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A comprehensive review on utilization of agricultural waste for reinforced structural products: A sustainable perspective

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A comprehensive review is focused on the sustainable utilization of agro waste for reinforced structural products. In the current scenario, farmers' widespread practice of burning agricultural waste has emerged as a major contributor to air pollution, highlighting the urgent need for sustainable waste management solutions. This review underscores the urgency of shifting towards sustainable practices by repurposing agro waste for reinforced structural products, providing an eco-friendly alternative to the environmentally detrimental practice of burning agricultural residues. The ever-growing need for sustainable practices has driven research towards repurposing agricultural waste to create robust structural materials. This review explores diverse agro-waste sources, ranging from crop residues to by-products, field residue, process residue, and industrial residue, and examines their potential as reinforcements in structural products. The review critically evaluates various processing methods, highlighting their impact on the mechanical and structural properties of the resulting products. Additionally, the environmental implications, economic viability, and potential challenges associated with the utilization of agro waste in structural applications are discussed. By consolidating existing knowledge and recent advancements, this review aims to guide future research endeavors and policy decisions in fostering sustainable practices within the construction and manufacturing industries. This review provides insights to support the selection of agro waste for sustainable development, offering alternatives to practices that contribute to pollution.

Keywords: sustainable utilization, structural products, waste repurposing, agro-based materials, environmental impacts

INTRODUCTION

Agriculture has been the backbone of human civilization. It nourishes us with food and provides us with clothing, and essential materials. It nurtures billions from wheat fields to large fruit farms, maintaining a delicate balance. While ensuring food security is the utmost priority, the process generates a significant amount of agricultural waste. The utilization of grape stalks as forage or as a component in feed has been used for the animals. Agricultural waste comes in many forms such as leftover crop residues like corn stalks and fruit peels, animal manure from livestock, and even packaging used for transportation of food. It might seem very small, but the real amount tells a whole different story. Additionally, overflowing landfills struggle to house the ever-growing mountains of waste, creating environmental and social pressures. The impact is a long way, affecting not only the immediate surroundings but also human fitness and standard sustainability. India, being an agro-based country, produces a large amount of agricultural waste; only 25–30% of the 620 million tons of agricultural waste produced each year are used for energy production and animal feed. Utilizing agricultural waste like paddy straw in composite materials exemplifies the circular economy by converting waste into valuable resources. This approach reduces reliance on raw materials, minimizes waste disposal, and mitigates environmental impacts from residue burning. It provides a sustainable input for production while supporting waste valorization, enhancing resource efficiency, and reducing lifecycle waste. The study highlights how such innovations foster sustainable manufacturing and create value chains aligned with circular economy goals.

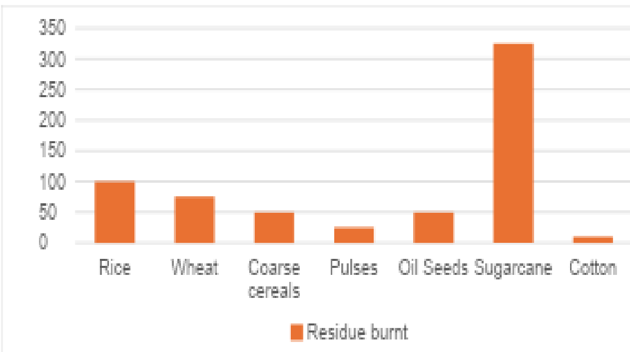

Fig. 1. Annual crop residue burnt in India in million metric tons (2003-2016)

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While affecting the environment, it is also a huge waste of potential resources which can be utilized as a raw material for various products such as hempcrete, bamboo fibers, rice husk composites, etc. To address this challenge, innovative solutions like composting can rework waste into nutrient-rich soil amendments, boosting crop yields and reducing reliance on chemical fertilizers. One of the best ways to address this issue can be the utilization of these residues and byproducts in developing different products such as reinforced composites which will also solve the waste management from composite manufacturing industries and lead to sustainability. The use of agricultural waste in structural products faces challenges, including material variability from crop differences, energy-intensive processing, and adhesion issues with matrix materials, which can impact mechanical performance. Durability concerns, such as water absorption and microbial degradation, also require costly treatments for enhanced stability. To address these challenges, advanced processing techniques, surface treatments, and efficient supply chain management are suggested to improve the viability of agricultural waste in structural applications.

Categories of agricultural wastes

There are different categories of agricultural wastes that are produced at every stage of the crop before it reaches the market and is ready to consume. Table 1 shows the types of agricultural wastes produced by different crops.

Agricultural wastes are produced at different stages in crop production. During harvest, leftover plant materials like rice straw, rice husks, and wheat straw fall to the ground and accumulate in the field, forming what's known as field residue [1]. Rice straw proves to be a valuable material for producing insulation boards. These rice straw-wood particle composite boards are manufactured using established methods from the wood-based panel industry [2]. Mohapatra *et al.* found that teak wood dust particles showed a remarkable influence in minimizing the thermal conductivity and linear thermal expansion and are a great eco-friendly composite choice that can be utilized for different thermal applications [3]. Even common onion peels can be a source of wood glue, as demonstrated in the study of Odozi *et al.* [4, 5]. This research shows that a specially treated extract from onion skins can meet the demanding quality standards set by the International Organization for Standardization (ISO) for plywood adhesives [6]. Table 2 presents the types of crop waste and their various applications. Based on the various properties of the crops, their waste can have different potential uses such as production of biofuel, organic fertilizers, animal feed, and industrial products. Based on potential use, agricultural waste can be classified into the following categories.

Agricultural waste used for composites

Composites are formed by combining two or more materials that have quite different chemical and physical properties and they work together to give unique properties. Still, we can easily differentiate the composite materials. In the new material, the components do not form a solution or mixture but remain separate and distinct in the structure [7]. Some examples are shown in Table 3.

Due to high cellulose and low lignin content the tensile strength of the most used natural fiber composites are higher in Natural Fiber Composites (NFCs) as the higher the crystalline parts of cellulose, the stronger is the fiber strength [8]. As also seen in the study of Srivastava *et al.* the addition of bamboo fibers increased the hardness and tensile strength of the composites [9]. In the case of flax and hemp, as observed in the tests done by Kumaar *et al.,* hemp composites showed great flexural strength, boasting an impressive average value of 88.26 N/mm^2. This indicates that hemp fibers play a major role in enhancing a composite's ability to withstand bending forces. On the other hand, flax composites excelled in impact strength, averaging a value of 4 J. This suggests that flax fibers contribute significantly to composite's resistance to sudden impacts [10].

Agricultural waste used in civil structures.

Growth in the human population led to a substantial increase in wastes generated by households, industries, and agriculture, and also the demand has increased in construction building materials. Building materials that are present now are mostly not manufactured by natural resources, the majority of them are manufactured by non-renewable resources. To meet the constant demand for building materials there should be an alternative to non-renewable building materials. Utilization of agricultural waste is the better substitute for manufacturing renewable building materials. Some of the most used building materials that are made from agriculture waste are shown in Table 4.

 Table 1. Types of waste produced by different crops.

		Agricultural residue		Industrial residue
		Field residue	Process residue	
Crop type	Crop			
Cereals	Rice	Straw, Stubbles	Bran	Husk
	Wheat	Straw, Stubbles	Bran	Chaff
	Maize	Stover	Bran	Corn ribs
	Millets	Stover	Bran	Broken grains
	Barley	Straw	Malt	Chaff
Pulses	Chickpea	Stalks	Hull powder	Pods
	Pigeon pea	Stover	Pea husks	Pods
	Mung bean	Stover	Hulls	Pods
	Urad bean	Stover	Hulls	Pods
	Lentil	Stover	Lentil shells	Pods
Oilseeds	Mustard	Stalks, Stubbles	Oil cakes	Husk
	Groundnut	Stalk	Skins, dust	Shells
	Sesame	Straw	Oil cakes	Hulls
	Castor	Stover	Oil cakes	Shells
	Sunflower	Stubble, Stalks	Oil cakes	Hulls
	Soyabean	Stems, Leaves	Oil cakes	Pods
Fruits & Vegetables	Mango	Leaves, Twigs	Peel, stone, pulp waste	Pedicel
	Banana	Pseudo stem	Peel	Peduncle
	Tomato	Leaves	Peel	Pedicel
	Potato	Haulms	Peel	Root hairs
	Onion	leaves	Outer skin	Root hairs
	Orange	Leave, Twigs	Peel, inner skin	Pedicel
	Pineapple	Leaves	Outer skin, hardy core	Head
Fiber crops	Cotton	Stover	Seed hulls	Ginning waste
	Jute	Leaves	Jute dust	Shells
	Kenaf	Leaves	Hurd, Woody core	Fiber dusts
Spices	Chilli	Stems, leaves	Seeds	Stalks
	Ginger	Leaves	Peel	Trimmings
	Turmeric	Leaves	Peel	Roots
Sugar & Beverages	Sugarcane	Stubble	Bagasse	Leaves
	Tea	Spent leaves	Rolling	Dusts
	Coffee	Pulp, Peel	Parchment coffee	Silverskin
Leafy vegetables	Spinach	Stems	Processing water	_
	Fenugreek	Leaves	_	Pods
Roots & Tubers	Sweet potato	Vines, leaves	Peels	Trimmings
	Tapioca	Leaves	Peels	Trimmings
	Carrot	Leaves	Tops	Trimmings
Trees	Neem	Twigs, leaves	Oil cakes	Oil cakes
	Mango	Leaves, Twigs	Peels, Stones	Pedicel
	Teak	Leaves	Bark	Saw dust
	Sal	Dead leaves	Bark	Saw dust
	Bamboo	Leaves, Culms	Peelings (edible shoots)	Saw dust, Fiber dust

Table 2. Types of crop waste and their applications

Crop Type: Cereals						
Crops	Rice	Wheat	Maize		Millets	Barley
Field Residue	Straw, Stubbles	Straw, Stubbles	Stover		Stover	Straw
Application	Rice straw-board particle board,	Wheat straw as polymer composite reinforcement	Fodder		Fodder	Algae control
Process residue	Bran	Bran	Bran		Bran	Malt
Application	Livestock feed, boiler fuel	Human consumption	Human consumption		Bioethanol production	Natural sweetener
Industrial residue	Husk	Chaff	Corn ribs		Broken grains	Chaff
Application	Low-cost cellular concrete	Soil preparation, boiler fuel	Human consumption		Human consumption	Mulching, composting, animal bedding
Crop Type: Pulses						
Crops	Chickpea	Pigeon pea	Mung bean		Urad bean	Lentil
Field Residue	Stalks	Stover	Stover		Stover	Stover
Application	Animal feed, soil preparation	Animal feed, biomass, green manure	Mulching, Animal feed, composting		Mulching, animal feed, composting	Biofuel, composting
Process residue	Hull powders	Pea husks	Hulls		Hulls	Lentil shells
Application	Oil absorbent	Biofuel, water treatment	Reinforced materials, animal feed, biofuel		Reinforced materials, animal feed, biofuel	Reinforced materials, animal feed, biofuel
Industrial residue	Pods	Pods	Pods		Pods	Husk
Application	Composting, animal feed	Mulching, composting, animal feed	Composting, mulching		Composting, mulching	Composting, biofuel, building materials and packaging materials
Crop Type: Oilseeds						
Crops	Mustard	Groundnut	Sesame	Castor	Sunflower	Soyabean
Field Residue	Stalks, Stubbles	Stalk	Straw	Stover	Stubble, Stalks	Stems, Leaves
Application	Mulch, fumigants	Mulching, composting	Thatching mulching	Paper production biofuel,	Paper production, composites, biofuel, mulching and composting	Animal feed, composites, biofuel, mulching and composting
Process residue	Oil cakes	Skins, dust	Oil cakes	Oil cakes	Oil cakes	Oil cakes

Application	Fillers in reinforced composites	Preservatives, food coloring	Fertilizers animal feed	Biofuel, bioplastic	Fertilizer, composting, mushroom cultivation		Fertilizer, composting
Industrial residue	Husk	Shells	Hulls	Shells	Hulls		Pods
Application	Reinforced composites, rubber production	Nanosheets	Lightweight concrete, biofuel, animal feed	Biomass, reinforced composites	Mulching, fiberboard, biofuel		Composting, animal feed, reinforced composites
Crop Type: Fruits and vegetables							
Crops	Mango	Banana	Tomato	Potato	Onion	Orange	Pineapple
Field Residue	Leaves, Twigs	Pseudo stem	Leaves	Haulms	Leaves	Leave, Twigs	Leaves
Application	Medicine	Natural fibers, composting, paper production	Natural pesticides	Composting, animal feed, biofuel	Natural dye, pest control	Air freshener	Natural fibers, biofuel
Process residue	Peel, stone, pulp waste	Peel	Peel	Peel	Outer skin, hardy core	Peel, inner skin	Outer skin, hardy core
Application	Biofuel, cosmetics	Fertilizer, cosmetics	Food coloring	Composting	Natural dye, composting	Bio-plastic	–
Industrial residue	Pedicel	Peduncle	Pedicel	Root hairs	Root hairs	Pedicel	Head
Application	–	Composting	Composting	–	–	–	–
Crop Type: Fiber crops							
Crops	Cotton		Jute		Kenaf		
Field Residue	Stover		Leaves		Leaves		
Application	Biofuel, composting, animal feed, compressed fiber panel		medicine		Animal feed, composting, biofuel		
Process residue	Seed hulls		Jute dust		Shells		
Application	Composting, animal feed, packaging materials		Biofuel, biochar		Composite materials, packaging materials		
Industrial residue	Ginning waste		Jute caddies		Fiber dusts		
Application	Boiler fuel		Particle board, biogas		Composite fillers, soil preparation		
Crop Type: Spices							
Crops	Chilli		Ginger		Turmeric		
Field Residue	Stems. Leaves		Leaves		Leaves		
Application	Compost, pest repellent		Fragrance, pest repellent		Medicine, natural dye		
Process residue	Seeds		Peel		Peel		
Application	Pest repellent		Pest repellent		Natural dye, composting		
Industrial residue	Stalks		Trimmings		Roots		
Application	Composting		Composting		Composting		
Crop Type: Sugar and beverages							
Crops	Sugarcane		Tea		Coffee		
Field Residue	Stubble		Spent leaves		Pulp, Peel		
Application	Composting, biofuel		Fertilizers, fragrance		Biogas, cosmetics		

Process residue	Stubble	Spent leaves	Pulp, peel		
Application	Composting, biofuel	Fertilizers, fragrance	Biogas, cosmetics		
Industrial residue	Leaves	Dusts	Silver skin		
Application	Mulching, biofuel, animal feed, animal bedding	Cosmetics, dye	Cosmetics, compost, biofuel		
Crop Type: Leafy vegetables					
Crops	Spinach	Fenugreek			
Field Residue	Stems	Leaves			
Application	Composting	Cosmetics			
Process residue	Stems	Processing water			
Application	Composting	_			
Industrial residue	_	Pods			
Application	_	Biofuel, composting			
Crop Type: Roots & Tubers					
Crops	Sweet potato	Tapioca	Carrot		
Field Residue	Vines, Leaves	Leaves	Leaves		
Application	Composting	Animal feed, medicines	Flavouring		
Process residue	Peels	Peels	Tops		
Application	Food colouring, composting	Animal feed, biofuel, composting	Animal feed, garnish		
Industrial residue	Trimmings	Trimmings	Trimmings		
Application	_	_	_		
Crop Type: Trees					
Crops	Neem	Mango	Teak	Sal	Bamboo
Field Residue	Twigs, leaves	Leaves, Twigs	Leaves	Dead leaves	Leaves, Culms
Application	Medicine, cosmetics, pest repellents	Medicines, Cosmetics	Natural dye, Composting, medicines, animal feed	Plates, packaging, composting, medicines	Composites, plates, composting
Process residue	Oil cakes	Peels, stones	Bark	Bark	Peelings (edible shoots)
Application	Pest repellents, soil preparation fertilizer	Cosmetics	Medicine, natural dyes, animal feeding	Composites, dyes and colouring, medicines	Composting, biofuel, animal feed
Industrial residue	Oil cakes	Pedicel	Saw dust	Saw dust	Saw dust, fiber dust
Application	Fertilizer, pest repellent, soil preparation	_	Composites	Composites	Composites

Table 3. Natural composites with their chemical content, properties, and uses.

Natural composite	Chemical contents	Properties	Uses
Cotton	Cellulose 88-96% Protein-1.9% Pectin 1.2% Ash-1.2% [11, 12]	Cotton is absorbent, breathable, durable and drapes well.	Used in making clothing, hospitals and medical services as absorbent and saloons.
Bamboo	Cellulose 74% Hemicellulose 13% Lignin 10% [13]	Fire resistance, less shrinkage, anisotropic properties, elastic modulus and tensile strength.	Home furnishing, hygienic clothing, medical and bathroom textiles.
Sisal	Waxes 2% Hemicellulose 10% Lignin 12% Cellulose-70% [14]	High flexibility, high friction resisting and acid-resisting	Door mats, constructing materials, yarn and twine.
Hemp	Hemicellulose-8-18% Cellulose-67-75% Lignin-2-5% [15]	High tensile strength, fiber is finer and biodegradable	Tapestry, rugs, shawls, posters and towels.
Kenaf	Pectin-3-5% Hemicellulose-21.5% Cellulose-45-57% Lignin-8-13% [16]	Lightweight, little elasticity, very fine and strong yarn, low breaking strength.	Animal bedding, packing materials, cloth and paper.
Flax	Wax-1.7% Lignin-2.2% Pectin-2.2% Hemicellulose-18-20.6% Cellulose-71-17% [17]	Less flexible, Fiber is soft lustrous and stronger than cotton.	Building materials, automotive applications, paper and textiles.
Ramie	Wax-0.3% Pectin-1.9% Hemicellulose-16.7% Cellulose-76.2% Lignin-0.7% [16]	Stain-repellent property, high affinity for dyeing and highly absorbent.	Fishing nets, sewing threads, clothing, home furnishing and packing accessories.
Silk	Fibroin-70-80% Sericin-20-30% wax-1-2% [18]	Excellent resilience, good elasticity and higher tensile strength than glass fiber.	Clothing, industries, furniture, medicine and biomaterials.
Jute	Cellulose-71 Hemicellulose-20.4% Lignin-13% Pectin-0.2% Protein-2.5% [16]	High tensile strength with low extensibility, antistatic property, high tenacity and low thermal conductivity.	Aggrotech, Protech, geotextiles, carpets and decorative colour boards.
Coconut	Cellulose-21-43% Lignin-15-45% Hemicellulose 20% [19]	High flexural rigidity, highly variable fiber length and low tenacity.	Coir disk, blocks,Coir net.
Sugarcane	Cellulose-36% Hemicellulose-24% Lignin-21% [20]	More fineness, high tensile strength and low glycaemic level.	Bagasse ash as a binder in concrete gave an improvement in thermal stability.
Banana	Cellulose-55-65% Hemicellulose-19% Pectin-10-15% Lignin-3-5% [17]	Tenacity, fineness, moisture regain, elongation and tensile strength.	Ropes, carpets, clothing garments, home furnishings and traditional costumes.
Nacre	Aragonite-95% Protein-2.5% Polysaccharides-2.5% [21]	Lightweight, high strength and toughness.	For architectural purposes, ceramic tile and marble base.

Table 4. Agro waste and its application in civil structures.

Agro waste	Properties	Further application in civil structures
Hemp	Low density and low resistance to microorganisms, high strength and stiffness [22].	Lime/concrete/panel/loose fill, building blocks
Paddy straw	High crack resistance, increases intensity, Enhanced toughness, good thermal insulation [23].	Brick/plaster/concrete
Olive	Enhances both strength and durability, reduces the effective water-cement ratio [24].	Panel/lime/concrete
Bamboo	Increases compressive strength and ductility of concrete [25].	Concrete beams

Groundnut shells	Shows average strength [26].	Concrete panels cast
Rice husk	Good in thermal insulation [27].	Mud mix, blocks, wall cover, particle board and cardboard
Honeycomb wax	Long-lasting, prevents moisture [28].	Polishing on wood, Encaustic painting
Coconut shell	Abrasion-resistant properties, high toughness, and good durability [29].	Manuscripts, aggregate in mud flooring
Bagasse	High compressive strength, low thermal conductivity [30].	Bagasse ash can be used as a cement in concrete production
Banana leaf ash	Reduces water absorption, consistency and increases setting time of cement [31, 32].	As a cement mortar
Coconut coir	Low thermal conductivity, can be stretched beyond its elastic limits[33].	Low-cost concrete structures especially in earthquake regions.
Oaktree cork	Lightweight and high insulation [34, 35].	Cork board, Walls, and floors mating(37).
Coffee husk	Shows an increase in compressive strength and water absorption [36].	Hand-made bricks and mortar
Mycelium	Lightweight and high in thermal insulation [37][38].	Only bricks

Table 5. Mechanical charecteristics of banana fiber, hemp fibe and jute fiber.

Mechanical properties	Jute fiber	Bamboo fiber	Hemp fiber
Compressive strength	20.9MPa	15.8MPa-24.2MPa	19.5MPa-26.4MPa
Impact strength	94.46KJ	63.54KJ	10.94KJ
Youngs modulus	13-26.5Gpa	27-40Gpa	17-70Gpa
Tensile strength	300-700MPa	600MPa	270-900MPa
Density	1.3-1.49G/cm3	1.2-1.5G/cm3	1.47G/cm3
Flexural strength	32.36MPa	200-300MPa	156.78MPa

Study of mechanical properties of jute, bamboo, and hemp natural fibers.

Sustainable development and global warming have escalated the need to produce natural materials that reduce carbon emissions. Plant fibers have emerged as novel materials that is readily available, biodegradable, feasible, and have high specific strength. Although these materials lack a few properties like they are not suitable for some polymer matrices, the fibers might accumulate together during processing and these materials absorb moisture readily which reduces their mechanical strength. Natural fibers have turned into a demandable product in recent days. Composites based on natural fibers are becoming a major requirement for civil structures, wrapping, home decor, and furnishings. They show satisfactory mechanical properties, and they are biodegradable and renewable. Based on the weight of the fibers mechanical properties are influenced. Lesser mechanical properties are shown when more than enough fibers are added to a composite and there will be no compatible bonding between matrix and fiber also it shows less values of impact and flexural strength. The cell wall composition of natural fibers can also impact the mechanical properties of the natural fibers. Table 5 shows the mechanical characteristics of hemp fiber, jute fiber and bamboo fiber.

Uses of crop byproducts

Balaji *et al.* explored the impact of varying ratios of sisal fibers to coconut sheath fibers on the mechanical properties of crop residues. They found that increasing the proportion of sisal fiber led to enhanced tensile strength, flexural strength, and impact strength. However, the most favorable results were observed at a 40% sisal fiber content. At this ratio, with 40% short sisal fibers and the remaining 60% consisting of naturally woven coconut sheath fibers, the composite material exhibited optimal performance. This combination resulted in a tensile strength of 68.5 MPa, a flexural strength of 128.8 MPa, and an impact strength of 18.95 kJ/m² [39]. Table 6 shows the chemical compositions of several crop residues and their properties.

Table 6. Chemical properties of different crops.

Crop	Chemical contents	Properties
Rice [40, 41]	38% cellulose, 25% hemicellulose, and 12% lignin, 6.1% silica	• Good insulating properties. • Rich source of cellulose which helps in reinforcement of biopolymer composite materials.
Wheat [42]	33.5–40% cellulose, 21–26% hemicellulose, and 11-23% lignin 3.6% silica and silicates, 3.6% crude protein	• Good insulating properties. • Rich source of cellulose which helps in reinforcement of biopolymer composite materials.
Jute [43]	64.4% cellulose, 12% hemicellulose, 0.2% pectin, 11.8% lignin	• Rich source of lignin which provides good tensile strength.
Coconut [44]	27.7% pentose, 26.6% cellulose, 29.4% lignin	• Pentose-derived hemicellulose can be used as fillers and extenders in composites. • Rich source of lignin which provides good tensile strength.
Orange peel [45]	23% sugar, 22% cellulose, 25% pectin and 11% hemicellulose	• Cellulose and hemicellulose contents provides good reinforcement properties.
Sugarcane bagasse [46]	50% cellulose, 25% hemicellulose and 25% lignin	• Rich source of lignin which provides good tensile strength.
Mustard oil cakes [47]	35.65% crude protein, 10.28% crude fiber, 0.69% ether extract, 7.61% total ash and 1% acid insoluble ash	• Mustard oil cake powders increases the tensile strength of the composites if use as fillers.
Banana fiber [48]	71.08% cellulose, 12.61% hemicellulose and 7.67% lignin	• Great reinforcement properties due to presence of cellulose and hemicellulose.
Bamboo fiber [10]	74% cellulose, 13% hemicellulose and 10% lignin	• Great reinforcement properties due to presence of cellulose and hemicellulose.

Structural products made by using agricultural waste

Carbon nanotubes (CNTs), reinforced polymer composites. Carbon nanotubes (CNTs) are structures composed of cylindrical molecules, shaped by hexagonally arranged hybridized carbon atoms. Microscopic graphene sheets fold into these tiny cylinders, occasionally capped with spherical fullerenes, giving rise to carbon nanotubes. The distinct electrical characteristic of carbon nanotubes (CNTs) arises from the presence of delocalized electrons along the z-axis. Kushwaha *et al.* conducted a study comparing a hybrid composite reinforced with bamboo/CNTs to an epoxy composite of bamboo treated with alkali [49].

Natural fillers as potential modifying agents for epoxy composition. Epoxy resins have excellent properties; hence, they are being used heavily in industries.The fillers provide a balance between adequate strength, reduced weight, and biodegradability, meeting the growing emphasis on eco-friendly considerations in composite material development [50].

Hempcrete as building blocks. Hempcrete, crafted from hemp and a binder containing natural hydraulic lime with a minimal cement content, offers a robust and self-insulating construction solution adaptable to diverse purposes. Its applications range from timber frame infill to insulation and, when mixed with aggregate, even for floor slabs. With a carbon-negative impact, hempcrete emerges as a compelling option for sustainable construction, playing a pivotal role in achieving low embodied carbon objectives and adhering to rigorous sustainable building standards [51].

Application of sugarcane bagasse. Sugarcane bagasse composites (SBC) offers notable mechanical strength. The higher fiber content in the SCB/lime mixture results in enhanced thermal insulation, surpassing conventional materials such as clay brick or hempcrete. Moreover, lime composites exhibit improved water resistance, maintaining minimal loss of mechanical strength even when saturated [52].

Bioplastic made by banana peel. Bioplastics made by banana peel can be a key to solve the inability of synthetic plastic to degrade. The banana peel-based biodegradable film is the most promising option, given its superior degradability [53].

Particle board from rice husk. Rice husk, a byproduct from rice mills, offers potential as a sustainable building material due to its lightweight yet strong structure. The high concentration of amorphous silica on its surface acts as a natural binding agent [27].

Corn starch based biodegradable plastic and composite. Corn starch is a widely used biomaterial renowned for its cost-effectiveness and versatility in various applications. It consists of approximately 25%amylose and 75% amylopectin, two distinct polysaccharides that contribute to its unique properties. This makes corn starch an environmentally friendly option, particularly in applications where biodegradability is desired [54].

SUMMARY & FUTURE SCOPE

Agricultural waste, a significant pollution source, holds promise in structural applications such as hempcrete, rice husk particle board, and oil cake-based composite fillers, contributing to sustainability. Products like low-cost cellular concrete with rice husk and rice straw-wood particle boards offer potential as eco-friendly alternatives, surpassing conventional construction materials in performance. The economic advantage of utilizing these low-cost agricultural wastes is substantial. However, future research should focus on refining manufacturing techniques and enhancing product performance to compete effectively with established structural products. Additionally, numerous untapped oilseed, fruit, and vegetable waste resources remain, presenting opportunities for further exploration in structural applications. Cereal wastes, including stover, leaves, and stems, currently employed in bioethanol and composting, also warrant investigation for broader structural utilization.

Rice straw is a renewable resource, and it has good thermal insulation properties which could make it a good replacement for conventional insulation materials such as fiberglass or rockwool. However, rice straw insulation boards may have lower fire resistance than conventional insulation and may also be more susceptible to mold growth. Further research is needed to improve the fire resistance and mold resistance of rice straw insulation boards. This can improve the strength and durability of concrete, as well as its insulating properties. Wheat straw is a renewable resource, and it has good mechanical properties that could make it a good replacement for conventional wood flooring materials. However, wheat straw is susceptible to moisture absorption and may not be as durable as wood flooring materials. More research is needed to improve the moisture resistance of wheat straw flooring. Carbon nanosheets are a type of nanomaterial with a wide range of potential applications, including in batteries, solar cells, and water filters. Using groundnut shells as a source of carbon for carbon nanosheets could help to reduce the environmental impact of their production. Onion skins contain a substance called quercetin, which has adhesive properties. Glues made from onion skins could be a more sustainable alternative to conventional wood glues. However, more research is needed to determine the strength and durability of onion skin glues. Bioplastic is a type of plastic that is made from renewable resources such as plant starches or oils. Bioplastics can degrade more quickly than conventional plastics, which can help to reduce plastic pollution. Using orange peels as a source of material for bioplastic could help to reduce the environmental impact of plastic production. Tableware packaging made from sugarcane bagasse could be a more sustainable alternative to conventional packaging materials such as polystyrene or polyethylene. Cation exchangers are materials that can remove cations (positively charged ions) from a liquid. They are used in a variety of applications, including water treatment and industrial processes. Using polymerized corn cob as a cation exchanger could be a more sustainable alternative to conventional ion exchange resins. Hempcrete has good insulation properties and is fire resistant. It is a relatively new building material, but it has the potential to be a more sustainable alternative to conventional concrete. Bamboo is a renewable resource with good strength-to-weight ratio. Bamboo could be a good replacement for steel in concrete beams.

Addressing the challenges associated with the widespread use of agricultural waste products in construction requires concerted efforts. Variability in quality poses a significant hurdle, necessitating research into methods to produce consistent and high-quality building materials from these residues. Moreover, the high cost of collecting, processing, and transporting agricultural waste materials needs to be addressed through innovative and cost-effective solutions. Further research and development are essential to optimize processing techniques, improve material characterization, and enhance supply chain logistics. Despite these challenges, leveraging agricultural waste in construction holds promise for sustainability, offering opportunities to reduce reliance on finite resources, minimize waste generation, and mitigate greenhouse gas emissions. Collaborative efforts between researchers, industry stakeholders, and policymakers are crucial to realizing the full potential of agricultural waste products as sustainable sustainable building materials and advancing the construction industry's transition to more eco-friendly practices.

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Exploring the application of the carbon and boron nitride nanotubes: a review

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This article comprehensively examines the various applications of carbon nanotubes (CNTs) and boron nitride nanotubes (BNNTs) in multiple scientific and technological fields. Carbon nanotubes (CNTs) and boron nitride nanotubes (BNNTs) possess distinctive mechanical, thermal, and electrical characteristics, rendering them viable options for various applications. The article examines the present state of research in this field, emphasizing recent advancements in synthesizing and characterizing these nanotubes. The study is expanded to investigate the applications of BNNTs and CNTs in the biomedical domain. Notable properties allow cancer treatment, gene therapy, and tissue regeneration. The prospective uses of CNTs and BNNTs in energy storage, electronics, sensors, and materials science are examined comprehensively. Owing to the piezoelectric properties of BNNT, it is suitable for use as a sensor and has diverse applications in robotics. This review offers significant insights into nanotube synthesis techniques, applications, and a case study, advancing nanotechnology and emphasizing the necessity for additional research to fully exploit its potential.

Keywords: Nanotubes, biomedical applications, BNNT, CNT

INTRODUCTION

Boron nitride nanotubes (BNNTs) and carbon nanotubes (CNTs) are two types of nanotubes that have gained significant interest in materials science and nanotechnology. Despite their structural similarities, BNNTs and CNTs exhibit distinct properties that make them suitable for different applications. While CNTs are well known for their superior electrical conductivity, BNNTs stand out due to their excellent thermal stability and chemical resistance. Understanding these differences is crucial for optimizing their use in advanced technologies. BNNTs and CNTs are both members of the family of nanotubes, which are tiny cylindrical structures made of nanomaterials with diameters on the order of a few nanometers (10^{-9} meters) and lengths up to several microns (10^{-6} meters).

BNNTs are formed by boron and nitrogen atoms arranged in a hexagonal lattice, resembling the structure of CNTs. Their structural representation is illustrated in Figure 1. BNNTs exhibit remarkable thermal and mechanical properties, including high thermal stability, excellent thermal conductivity, and superior tensile strength. Additionally, their unique electrical characteristics make them highly suitable for applications in electronic devices.

Carbon nanotubes consist of carbon atoms organized in a cylindrical shape with a honeycomb lattice configuration.

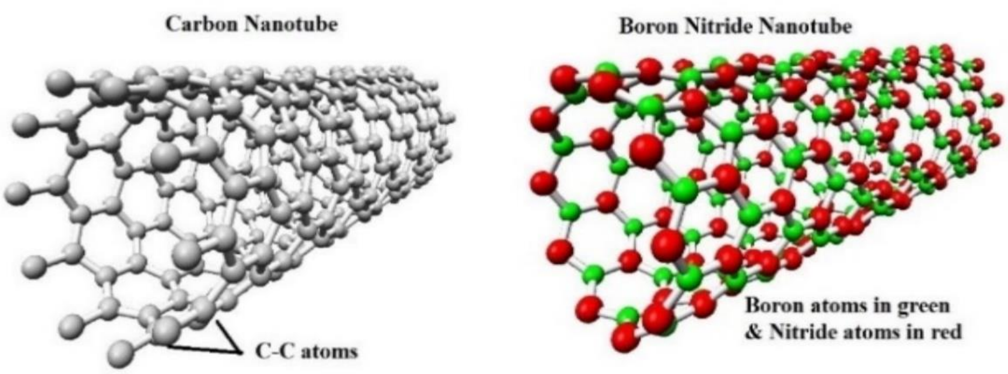

Figure 1. Structure of CNT and BNNT

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They can exist as single-walled or multi-walled structures, exhibiting exceptional mechanical, electrical, and thermal characteristics. On the other hand, boron nitride nanotubes are made of boron and nitrogen atoms arranged in a similar cylindrical structure. Due to their biocompatibility, they are being studied for similar applications as carbon nanotubes and biomedical applications. While both nanotubes have similar structures and properties, BNNTs have some advantages over CNTs in specific applications. For example, they are more oxidation-resistant and have better thermal stability at high temperatures. However, carbon nanotubes are more commonly studied and have a wider range of applications due to their lower cost and higher availability. As a result, their unique properties have created many opportunities for use in various areas, including electronics, energy storage, biomedicine, and environmental cleanup. However, more research is required to fully explore their capabilities and applications.

This review explores the latest research on CNTs and BNNTs, focusing on their unique properties and real-world applications. By comparing their strengths and examining their impact across different fields, we highlight their potential to drive innovation and inspire further advancements in nanotechnology. The outstanding mechanical strength of CNTs, high aspect ratio, and lightweight nature make them excellent choices for strengthening composite materials. They have found applications in aerospace, automotive, and construction industries, where their inclusion has improved strength, stiffness, and durability of various structural components. Additionally, the extraordinary electrical conductivity and thermal properties of CNTs have sparked interest in their incorporation into next-generation electronic devices, interconnects, and sensors, thereby revolutionizing the field of nanoelectronics.

On the other hand, boron nitride nanotubes, often referred to as "white graphene," possess remarkable thermal stability, high thermal conductivity, and excellent dielectric properties. These characteristics make BNNTs highly desirable in thermal management, high-temperature electronics, and optoelectronic devices. Furthermore, their unique biocompatibility and chemical inertness have led to extensive exploration in biomedicine, including drug delivery systems, tissue engineering scaffolds, and biosensors.

Throughout this review, we will focus on the individual applications of CNTs and BNNTs and explore their synergistic potential when combined in hybrid structures. By harnessing the complementary properties of these nanomaterials, researchers have developed novel materials with enhanced performance, offering exciting opportunities for breakthroughs in various fields.

BNNTs and CNTs are nanotubes that have various biomedical applications. The BNNTs basic blocks originated from the CNTs but have better physical and chemical properties compared to its counter CNT [1]. In the early 90s, various studies were carried out exploring CNT to understand the field of nanostructures [2]. Extreme material properties have been found to grow when the structure is brought down to the nanoscale [3].

In recent years, significant progress has been made in synthesizing, characterization, and functionalizing carbon and boron nitride nanotubes, expanding their potential applications even further. Researchers have explored various fabrication techniques to tailor the properties of these nanotubes, such as diameter, chirality, and surface functionalization, to meet specific application requirements.

Carbon nanotubes possess considerable energy storage potential due to their extensive surface area, superior electrical conductivity, and mechanical robustness. They are extensively utilized in supercapacitors and lithium-ion batteries as effective conductive additives, establishing a conductive network that enhances charge transport. Moreover, their distinctive architecture facilitates the encapsulation of active substances, improving battery stability and cycling efficacy. These innovations can potentially revolutionize portable electronics, electric vehicles, and renewable energy technologies.

BNNTs are distinguished by their remarkable thermal and chemical stability, rendering them suitable for high-temperature applications. In thermal management, BNNTs have been investigated as additives in polymer composites and coatings to enhance heat dissipation in electronic devices. Their superior thermal conductivity and resistance to extreme temperatures can improve the performance and reliability of advanced electronic systems. Furthermore, BNNTs exhibit promise in optoelectronics owing to their distinctive optical characteristics, including a broad bandgap and significant light absorption, facilitating applications in photovoltaics, light-emitting diodes (LEDs), and photodetectors.

The biomedical sector has observed an increasing interest in the application of carbon and boron nitride nanotubes. Carbon nanotubes (CNTs) have been examined for drug delivery systems, as their extensive surface area and capacity to encapsulate therapeutic agents, facilitate targeted and controlled release. The biocompatibility and unique optical characteristics of BNNTs render them exceptionally appropriate for bioimaging and biosensing applications. Moreover, their potential in biomedical applications is significant, especially in tissue engineering, where their biocompatibility and mechanical properties, similar to those of natural tissues, render them suitable for scaffolding purposes. Moreover, their chemical inertness renders them optimal for biosensors and diagnostic platforms, providing high sensitivity and selectivity in disease detection.

As we move forward, this review will look closer at these applications, their challenges, and the innovative solutions researchers are developing. This study also explores future trends, including hybrid structures, functionalization techniques, and scalable production methods, shaping the next phase of advancements in this field. The applications of carbon and boron nitride nanotubes are vast and diverse, spanning industries such as electronics, energy, biomedicine, and more. Their exceptional properties and continuous advancements in fabrication techniques hold immense potential for transforming various fields and driving technological advancements. By understanding the capabilities and limitations of these nanotubes, researchers can explore innovative approaches and further unlock the remarkable applications of carbon and boron nitride nanotubes. In summary, this review aims to provide a comprehensive understanding of the applications of carbon and boron nitride nanotubes, showcasing their remarkable properties and highlighting their potential for transforming a wide range of industries. By delving into the latest research findings and advancements, we hope to inspire further exploration and innovation in utilizing these nanotubes, thus driving the advancement of nanotechnology and its impact on society.

Synthesis of nanotubes

The integration of nanotubes with different strategies has been discussed here. Spearheading and rapid formation of BNNTs was largely enlivened due to CNT synthesis processes, including arc extraction, laser heating, and vaporization, boron Nitride replacement strategy from CNT structures, chemical vapor deposition method (CVD) uses borazine, the induction heating of boron oxide with CVD (BOCVD) and high ball processing [4]. Some commonly used synthesis methods for nanotubes are shown in Figure 2.

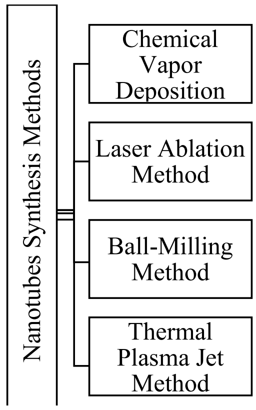

Figure 2. Nanotubes synthesis methods

- *Chemical vapor deposition method (CVD)*

It is the best standard method, generally used to obtain carbon nanomaterials on a large-scale, and was recently adopted to obtain boron nitride nanotubes. In contrast with different methodologies, this procedure offers better controllability of development boundaries concerning development parameters related to the development process, temperature, catalysts, stirring and test planning to ensure purity and the highest obtained quality of nanomaterials [5].

In comparison with the large-scale production, nearly 100 grams of CNT being nhhobtained in the CVD method, BNNT's has significantly lower production rate - nearly 100 mg [6]. Therefore, an approach for delivering a BN proclamation of BNNTs mergers is called BOCVD (boron oxide chemical vapor deposition) [7].

In BOCVD, MgO powder and boron were used as reactants to produce B_2O_2. At high temperatures (about 1000 ^{0}C – 1700 ^{0}C), a reaction was carried out between B_2O_2 and NH_3 gas to produce BNNTs. As a result of the discovery of these BOCVD BNNTs, the authors have also embarked on other related activities, such as refining, distribution, operation, doping, polymeric compounds, etc. However, the commercialization and actual use of BNNTs in the industry is hampered by the generally low level of creativity and the need to redesign the exhibition room presented and tested [8].

- *Laser ablation method*

Enlivened by CNT's development, new technologies like the laser removal or laser dissipation procedure have been utilized for the development of BNNTs since 1996. Mainly, the advantages associated with using this laser ablation method are that it produces high-quality nanotubes of high crystallinity and high aspect ratio [9]. In this method due to laser heating at a temperature of around 2000 ^{0}C, phase transformation of boron or boron nitride takes place from solid to liquid in an N_2 atmosphere. Because of the presence of N_2 atmosphere, a direct reaction takes place between boron and nitrogen, which stimulates the growth of BNNTs [10]. Goldberg *et al.* was the one who for the first time succeeded in BNNT synthesizing.

Multi-walled BNNT nanotubes were also synthesized by the laser ablation method, in this process nitrogen gas at very high pressure approx. 5GPa to 15GPa is injected in a diamond anvil cell simultaneously at a very high temperature approx. 5000K laser heating the hexagonal and cubic boron nitride (BN) in the cell [11].

Langley Research Center, NASA, also synthesized BNNT's accordingly. By CO_2 laser at very high temperature ~ 4000K, they continuously heated boron metal fiber in a chamber filled with nitrogen gas at a pressure ~ 14 bar. BNNTs obtained from this method were small in diameter (generally < 5nm) but with high purity. The production rate of this method was ~0.2 g per hour [12].

- *Ball milling method*

Grinding by a ball (ball milling) is utilized to develop BNNTs which are of industrial grade with minimal effort and low cost. In pervasive conditions, the direct reaction was carried out between boron and nitrogen that can be stimulated by presenting an indistinct structure in boron powder. This change is made effortlessly using a sufficient amount of mechanical energy, controlled and monitored by a few parameters, for example, operating time, and power (rotation every minute) [13].

As a result, the amount of BNNT can be made by running normally. This cycle is less than the processing time that can be reached in several hours and the emerging heat in the annealing of boron powder plays an important role in the BNNT formation. According to the study published by Chen *et al.*, in NH_3 gas atmosphere, boron powder was processed for 150 hours, afterward in the N_2 atmosphere, the isothermal tempering was carried out at 1000^0 C to 1200° C. In a subsequent study, the authors suggested that extending the milling process plays a crucial role in maximizing BNNT production. A longer milling duration enhances the nitration cycle between boron and NH_3, thereby accelerating the formation of nucleation structures that facilitate BNNT synthesis [14].

- *Thermal plasma jet (TPJ) method*

Even though BNNTs produced by laser removal strategy had very high quality, the production rate is very low, i.e. 1 mg/h. Therefore, the plasma jet method is a perfect solution to this problem. Thermal plasma has the capacity to apply thermal energy over a wide range of volumes, expanding the growth area up to 100 cm^2. TPJ method comprises two concentric electrode terminals - one is anode and the second is cathode. When a gas mixture of inert gases like Ar, N_2 and H_2 passes through a nozzle between the two concentric electrodes a wide range of arc–plasma regions forms [15].

Literature review

CNTs and BNNTs have attracted considerable attention in the scientific community because of their unique properties and broad range of potential applications. This literature review aims to provide a thorough overview of the current research on CNTs and BNNTs, focusing on key studies that demonstrate their potential in diverse fields.

CNTs possess exceptional mechanical properties, including high tensile strength and stiffness. These properties have led to their extensive use as reinforcing agents in composite materials. In a study, CNT-reinforced composites have shown improved mechanical properties, including increased tensile strength and fracture toughness. These results emphasize the potential of CNTs to enhance the performance of structural materials in industries like aerospace and automotive [16].

The excellent electrical conductivity of CNTs has opened up avenues for their use in nanoelectronic devices. The application of CNTs as interconnects in integrated circuits showcases their high conductivity and reliability. Furthermore, CNTs have demonstrated potential in energy storage devices, including supercapacitors and lithium-ion batteries [17]. The study reported enhanced energy storage performance when CNTs have been used as electrode materials due to their high surface area and exceptional electrical [18].

CNTs have demonstrated potential in a range of biomedical applications, such as drug delivery, tissue engineering, and biosensing. The use of CNTs as drug carriers highlights their capability to encapsulate therapeutic agents and facilitate targeted delivery [19]. Additionally, CNT-based scaffolds have been investigated for tissue engineering applications due to their biocompatibility and ability to mimic the structure of natural tissues [20]. Moreover, CNTs have been explored in biosensors for sensitive and selective detection of biological analytes [21].

BNNTs possess excellent thermal conductivity and stability, making them ideal for thermal management applications. A study demonstrated the incorporation of BNNTs into polymer composites, resulting in enhanced thermal conductivity and improved heat dissipation properties. This finding has implications for thermal management in electronics, where the efficient removal of heat is critical for device performance and reliability [22].

The unique optical properties of BNNTs, including a wide bandgap and high light absorption, have opened up opportunities in optoelectronic devices. The use of BNNTs as promising materials for photovoltaics demonstrates their potential in efficient solar energy conversion [23]. Furthermore, BNNTs have been explored in the development of LEDs and photodetectors due to their high thermal stability and excellent electrical insulation properties [24].

The biocompatibility and chemical inertness of BNNTs make them attractive for biomedical applications. BNNTs have a potential as carriers for drug delivery, noting their stability and ability to protect encapsulated drugs [25]. BNNTs have also been explored in biosensing applications, offering high sensitivity and selectivity in disease detection [26].

Researchers have also explored the combination of CNTs and BNNTs to harness their complementary properties and create hybrid structures. The use of CNT/BNNT hybrid materials in energy storage devices highlights their improved performance compared to individual nanotubes [27]. Additionally, CNT/BNNT hybrids have shown promise in thermal management, sensing, and catalysis applications [28].

The development of reliable and scalable fabrication techniques for CNTs and BNNTs is crucial for their widespread application. Several methods have been explored for the synthesis of CNTs and BNNTs, including CVD, arc discharge, and laser ablation. CVD has become a widely used technique for the controlled production of both CNTs and BNNTs, enabling the creation of nanotubes with specific properties [29]. Additionally, functionalization techniques have been investigated to modify the surface properties of nanotubes, enabling enhanced compatibility with different matrices and targeted applications. For instance, the surface functionalization of CNTs with functional groups or polymers has been explored to improve their dispersion in composites and facilitate better interfacial bonding [30]. Similarly, surface modification of BNNTs has been studied to enhance their dispersion in solvents and compatibility with polymeric matrices [31].

Despite the significant progress in understanding the properties and applications of CNTs and BNNTs, several challenges and areas for further exploration remain. One challenge lies in the large-scale production of nanotubes with consistent properties at a lower cost. Efforts are underway to optimize synthesis methods and develop scalable fabrication techniques to meet the growing demand. Moreover, the toxicity and biocompatibility of nanotubes need to be thoroughly investigated for safe biomedical applications. Understanding the potential health and environmental impacts is crucial for the responsible development and application of these nanomaterials.

Future research will focus on exploring new applications and integrating nanotubes into emerging technologies. For example, incorporating CNTs and BNNTs in 3D printing technologies holds promise for the fabrication of complex structures with tailored properties. Additionally, combining nanotubes with other nanomaterials, such as graphene and transition metal dichalcogenides, holds promise for enhancing their properties and expanding their applications. It can lead to the development of multifunctional nanocomposites with enhanced performance in various applications. The comparative analysis of the properties of CNTs and BNNTs with the corresponding applications are presented in Table 1.

The literature review emphasizes the significant research on the applications of CNTs and BNNTs, demonstrating their potential in reinforcing materials, nanoelectronics, energy storage, thermal management, and biomedicine. The advancement of fabrication methods and functionalisation strategies has been crucial in customising the properties of nanotubes for particular applications. Despite the persisting challenges, ongoing research initiatives and interdisciplinary collaborations are anticipated to propel further progress in utilizing the unique characteristics of CNTs and BNNTs for innovative technological applications.

Table 1. Comparison of CNTs and BNNTs properties with their respective applications

Nanotube Properties	CNTs	CNT Applications	BNNTs	BNNT Applications
Structure	Cylindrical tubes of carbon atoms in a honeycomb lattice [32]	Nanoelectronics, structural reinforcements [33]	Cylindrical tubes of boron and nitrogen atoms [34]	High-temperature electronics, biomedicine [35]
Density	Low density (~1.3-1.4 g/cm³) [36]	Lightweight aerospace materials [37]	Low density (~2 g/cm³) [38]	Lightweight, high-strength materials [39]
Elasticity	Highly flexible, excellent bending properties	Flexible electronics, nanocomposites [40]	Rigid and stable under extreme conditions [41]	Radiation shielding, high-stress applications [42]
Mechanical Strength	High tensile strength (~50-100 GPa) [43]	Aerospace composites, automotive materials [44]	Comparable or superior tensile strength (~30-100 GPa) [45]	Structural reinforcements, impact-resistant coatings [46]
Thermal Conductivity	High (~3000 W/m·K) [47]	Heat sinks, thermal coatings, energy devices [48]	Very high (~2000-3000 W/m·K) [49]	Thermal management, aerospace applications [50
Thermal Expansion	Low thermal expansion [51]	Thermal coatings, heat-resistant composites [52]	Very low thermal expansion [53]	Aerospace, extreme environment applications [54]
Corrosion Resistance	Moderate resistance [55]	Anti-corrosion coatings [56]	Highly resistant to corrosion [57]	Protective coatings, marine applications [58]
Energy Storage	High surface area, good for batteries & supercapacitors [59]	Lithium-ion batteries, supercapacitors, hydrogen storage [60	Limited charge storage capability [61]	Thermal stability in energy systems [62]
Electrical Conductivity	Excellent conductor (metallic/semi-metallic behavior) [63]	Transistors, flexible electronics, interconnects [64]	Insulating or semi-conducting (~wide bandgap of ~5.5 eV) [65]	High-performance dielectric materials, optoelectronics [66]
Optical Properties	Fluorescent, tunable bandgap [67]	Photodetectors, LEDs, infrared emitters [68]	Wide bandgap (~5.5 eV), optically transparent [69]	UV shielding, optoelectronic devices
Oxidation Resistance	Prone to oxidation at high temperatures [70]	Limited high-temperature applications [71]	Highly resistant to oxidation [72]	High-temperature structural applications [73]
Chemical Stability	Reactive in certain environments [74]	Chemical sensors, catalysis [75]	Chemically inert [76]	Corrosion-resistant coatings, extreme conditions [77]
Biocompatibility	Some toxicity concerns [78]	Limited biomedical use (drug carriers, biosensors) [79]	High biocompatibility [80]	Implants, biosensors, tissue scaffolds [81]
Cost and Availability	Lower cost, widely available [82]	Mass production applications [83]	Expensive, limited commercial production [36]	High-end applications, research-focused fields [84]

Applications of nanotubes

CNTs applications

CNTs have a number of unique properties that make them potentially useful for a variety of applications. One potential application of carbon nanotubes is in electronics. Because they are very small, they could be used to create tiny transistors and other electronic components that are much smaller and more efficient than current technology. They could also be used to create flexible, transparent displays. The most promising application is in the development of nanoscale electronic devices, such as transistors and interconnects. Carbon nanotubes are ideal for this application because they have very high electrical conductivity, are very small and have excellent thermal properties [85-86]. Carbon nanotubes could be used to create smaller, faster, and more energy-efficient transistors than those currently used in silicon-based electronics. They have the potential to replace silicon transistors in future electronics because they are capable of operating at higher frequencies, dissipating heat more efficiently, and consuming less power. Carbon nanotube field-effect transistors (CNFETs) have been identified as a promising nanotechnology for developing energy-efficient computing systems. The primary challenge in translating this technology to commercial manufacturing is developing a method for uniformly depositing nanotubes onto large-area substrates. This method must be manufacturable, compatible with existing silicon-based technologies, and offer energy efficiency advantages over silicon. Bishop *et al*. demonstrated that submerging the substrate in a nanotube solution is a viable deposition technique that can address these challenges and enable the fabrication of CNFETs in industrial facilities [87]. In addition to transistors, carbon nanotubes could also be used to create other electronic components, such as diodes, resistors, and capacitors [88]. CNT diodes have intrinsic cut-off frequency exceeding 100 GHz, with measured bandwidths reaching at least 50 GHz or higher [89]. They could also play a key role in the development of flexible and transparent electronics, with potential applications in flexible displays, wearable electronics, and smart packaging [90]. By improving the uniformity of CNT films and introducing a new pretreatment technique for flexible substrates, CNT thin-film transistors (TFTs) have been successfully used to drive a flexible 64 × 64-pixel active-matrix light-emitting diode (AMOLED) display. The resulting AMOLED features uniform brightness across all 4096 pixels, and a high yield of 99.93% [91].

Carbon nanotubes offer significant potential for energy storage applications because of their unique features, such as a large surface area, strong mechanical strength, and outstanding electrical conductivity. Below are some of the possible applications of carbon nanotubes in energy storage [92-93].

- *Batteries:* Carbon nanotubes can be used as electrode materials in batteries to enhance their performance. They have been shown to improve the capacity, energy density, and cycle life of batteries. Carbon nanotubes can also improve the rate of charge and discharge, leading to faster charging times [94]. The increasing demand for portable and wearable electronics has fueled the interest in developing flexible batteries that can maintain their functionality even under various mechanical deformations. Significant efforts have been made in material synthesis and structural design to achieve this goal. Carbon nanotubes (CNTs), with their unique one-dimensional (1D) nanostructure, can be easily formed into various macroscopic structures, including 1D fibers, 2D films, and 3D sponges or aerogels. Due to their remarkable mechanical and electrical properties, CNTs and CNT-based hybrid materials are considered excellent materials for building components in flexible batteries [95].
- *Supercapacitors:* Carbon nanotubes can serve as electrode materials in supercapacitors, enhancing their energy storage capacity. Their high surface area and excellent electrical conductivity enable them to rapidly store and release energy. Carbon nanotube-based supercapacitors have the potential to provide high power density and long cycle life [96-97]. Three symmetric paper supercapacitor designs were created using CNTs, graphite nanoparticles (GNPs), and graphene electrodes. These supercapacitors utilized a gel electrolyte made of polyvinyl alcohol (PVA) and phosphoric acid (H_3PO_4), with a separator film composed of $BaTiO_3$. The surface of the carbon nanomaterials, electrode films, and gel electrolyte was examined using scanning electron microscopy and transmission electron microscopy [98].
- *Hydrogen storage:* CNTs can also be used for hydrogen storage, which is an important component of hydrogen fuel cells. Carbon nanotubes can adsorb hydrogen molecules on their surface, increasing the amount of hydrogen that can be stored in a small space [99]. The study explored the potential of Li-doped carbon nanotubes as a viable storage medium for hydrogen. A computational model was used to study the impact of CNT size on its structural and energetic properties, focusing specifically on the adsorption of an isolated lithium atom on the CNT wall as a site for hydrogen adsorption [100]. It was found that the capacity for H_2 adsorption is strongly affected by the specific surface area, as well as the morphological and structural characteristics of the CNTs [101].
- *Solar cells:* CNTs can improve the performance of solar cells by boosting their energy conversion efficiency. They can act as electron acceptors in organic solar cells, helping to enhance their power conversion efficiency [102]. Over the past few years, there has been a surge of interest in carbon-based materials, specifically CNTs, for their exceptional physicochemical properties, cost-effectiveness, eco-friendliness, and abundance. These attributes make CNTs an ideal material for use in the production of organic solar cells (OSCs).

Moreover, CNTs' low sheet resistance and high optical transmittance render them an excellent candidate for an alternative anode to the conventional indium tin oxide (ITO) which is not only expensive but also toxic and scarce [103].

Carbon nanotubes also have potential applications in materials science. They could be used to create stronger, lighter materials for use in construction and aerospace applications. They could also be used to create new types of sensors and actuators, as well as for drug delivery and other medical applications.

CNTs have several medical applications, such as carrying drugs and biomolecules for efficient delivery to body cells and organs. They can also be used in tissue regeneration and have application in diagnostics and analysis as they can be used as biosensors [104]. The various applications of CNTs are illustrated in Figure 3.

The studies of CNTs are advanced because their exemplary contribution has been found in regenerative medicine and tissue engineering which is sustainable too [105]. CNTs are the best among the various available materials because of their biocompatible nature and resistance to biodegradability. They also have better functionality with biomolecules to improve organ regeneration [106].

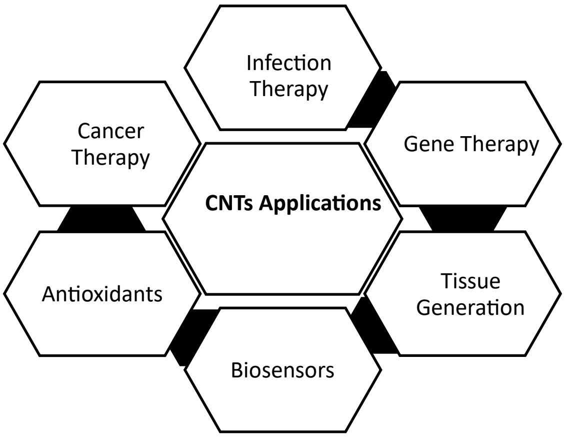

Figure 3. CNTs biomedical applications

CNTs also act as drug carriers to diagnose cancer. CNTs are having improved cellular uptake of potent drugs which makes them efficient delivery systems. It has been found that due to the high aspect ratio and high surface area of the CNTs they have an advantage over various existing delivery carriers [107]. CNTs are resistive in nature to the infectious agents, as a result they resolve problems associated with antibacterial, antiviral drugs and vaccine inefficacy in the body [108]. CNTs were recently found to carry the DNA molecule and insert it into the cell nucleus to cure the defective gene by using the gene therapy approach [109].

Despite their potential, however, there are still many challenges associated with the use of carbon nanotubes. For example, they are difficult to be produced in large quantities and at low cost. They can be toxic if not handled properly, raising concerns about their safety in consumer products.

BNNTs applications

BNNT (boron nitride nanotubes) are a type of nanomaterial that has unique properties, such as high strength, high thermal stability, and excellent electrical insulation. These properties make BNNTs attractive for a wide range of applications, including:

- *Biomedical:* BNNTs offer potential in biomedicine, with applications in drug delivery, tissue engineering, and medical imaging. Their low toxicity makes them suitable for enhancing the targeting and delivery of drugs to specific cells or tissues [110].

Like CNTs, BNNTs have various biomedical applications, but are chemically and physically more stable. BNNTs are used for the treatment of cancer by electroporation-based oncology [111]. They have also found applications in nerve & bone tissue regeneration [112]. A new bioink for tissue engineering was created using a hydrogel-based ink made of alginate (Alg) strengthened with functionalized boron nitride nanotubes (f-BNNTs). The ink's printability, physiochemical properties, and biocompatibility were quantitatively characterized to verify its suitability. The findings imply that the Alg reinforced with f-BNNTs, which is 3D printable, has the potential to serve as a bioink for tissue engineering [113]. The various applications of BNNTs are illustrated in Figure 4.

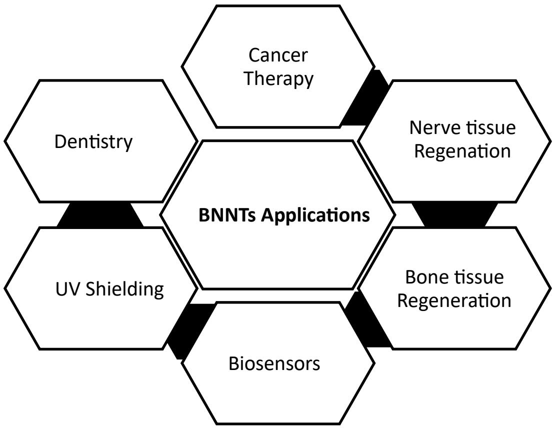

Figure 4. BNNTs biomedical applications

The BNNTs have applications in ceramic composites, e.g., lightweight ceramic composites. BNNTs are used in low-temperature applications like dentistry and also in high-temperature applications like jet engines [114]. The study aimed to investigate how the properties of resin-based light-curing dental sealants (RBSs) are affected by the addition of BNNTs at varying concentrations. The RBSs were formulated using methacrylate monomers, consisting of 90 wt.% of triethylene glycol dimethacrylate and 10 wt.% of bisphenol A-glycidyl methacrylate. Two concentrations of BNNTs (0.1 wt.% and 0.2 wt.%) were incorporated into the resin, with a control group containing no filler. The study evaluated several properties of the RBSs, including the degree of conversion, ultimate tensile strength, contact angle, surface free energy, surface roughness, and color. The results suggest that adding BNNTs to RBSs may introduce bioactivity and decrease their surface free energy [115]. Due to BNNTs anti radiant property, it is used for ultraviolet (UV) shielding applications [116].

- *Electronics:* BNNTs have excellent electrical insulation properties, making them ideal for applications in electronics. They can be used as insulators in high-temperature environments, which can improve the performance and reliability of electronic devices [117]. BNNTs are resistant to fire, which allows them to be used in fire-retardant cabling to manufacture flame-resistant high-strength cables. Also, used for creating high-strength and lightweight conductive cables [118]. BNNTs are electric insulators used in strong composites and electrically insulating components. They are applied in manufacturing lightweight and strong wiring of aerospace components [119]. The study reported a composite paper with excellent thermal conductivity, prepared through the synergistic combination of one-dimensional aramid nanofibers (ANFs), one-dimensional edge-hydroxylated BNNTs, and polyethyleneimine (PEI). The resulting composite paper demonstrates a high level of thermal conductivity, measuring 9.91 $Wm^{-1}K^{-1}$, as well as low dielectric loss (<0.01) and an exceptional heat resistance performance. Furthermore, the composite paper exhibits an ultrahigh electrical breakdown strength, measuring approximately 334 kV/mm [120]. By forming an oriented, percolative network, the boron nitride platelets with high-loading provided exceptional in-plane thermal conductivity, ranging from 77.1 to 214.2 $W\ m^{-1}\ K^{-1}$, comparable to certain metals like aluminum alloys (108–230 $W\ m^{-1}\ K^{-1}$). Through the utilization of the BN-based paper as an electrically insulating and flexible substrate, the study reveals its potential for reducing the temperature of electronic devices [121].

- *Energy:* BNNTs can be used in energy storage devices such as lithium-ion batteries and supercapacitors. BNNTs can improve the performance and safety of these devices by enhancing their energy density, cycle life, and thermal stability [116].

Ensuring the safety of lithium-ion batteries is a critical issue, affecting both large-scale energy storage and everyday use of mobile devices. A primary cause of safety concerns is the overheating of the cell, which can result from short circuits in environments with high temperatures and currents. The separator is a key component in preventing such short circuits and thus, the thermal stability of the separator is critical in ensuring battery safety. BNNTs, a promising new nanomaterial, can enhance the thermal stability of polyolefin separators by preventing thermal shrinkage during high-temperature and high-current operation, which helps avoid battery short circuits [122].

Using a simple and cost-effective hydrothermal method, zinc oxide nanoparticles are synthesized on both cellulose nanofibers (CNF) and BNNT surfaces, producing a ternary nanostructure. Upon investigating the electrochemical and piezoelectric properties of this structure, it was found that the BNNT–CNF/ZnO ternary nanostructure delivers impressive performance, achieving a specific capacitance of 300 F g^{-1}, along with high energy (37.5 W h kg^{-1}) and power density (0.9 kW kg^{-1}) at a current density of 1 A g^{-1} [123].

BNNTs are used in transparent armor, batteries and aerospace as a polymer. Because of their piezoelectric nature, the BNNTs can enhance sensors and robotics applications [124].

- *Aerospace and defense:* BNNTs can be used to reinforce composite materials, which are used in aerospace and defense applications such as aircraft, spacecraft, and armor. BNNTs have a higher strength-to-weight ratio than other reinforcement materials, making them ideal for these applications [125]. The study explored the use of BNNTs to strengthen aluminum in aircraft wing plates, focusing on their impact on the dynamic characteristics. The reinforcement was applied in two ways: uniformly and functionally graded throughout the plate's thickness. The plate was modelled as a rectangle, with edges shaped by linear, circular, or hyperbolic functions. The study examined various factors, including thermal environment, BNNT volume, reinforcement distribution, and geometric parameters. The results showed that BNNTs significantly improve the reinforcement properties of aircraft wings [126].

- *Environmental:* BNNTs can be used in environmental applications such as water treatment and air purification. BNNTs can remove pollutants from water and air by adsorbing or catalyzing them, and they have high thermal stability, which can enable them to be used in high-temperature environments [127]. Due to their large surface area and high-temperature resistance, BNNTs have been studied as reusable adsorbents for water purification. The material showed around 94% efficiency in capturing methylene blue particles from water, even after being used for three cycles, highlighting its potential for use in the filtration industry [6]. A cost-effective template made from electrospun polyacrylonitrile fibers was used to create a stable mat of BNNTs through atomic layer deposition (ALD) of BN at low temperatures. Using polymer-derived ceramics chemistry, this ALD process produces high-quality BNNTs with excellent properties, including superhydrophobicity, stability for a month in different pH conditions and air, and remarkable performance in water treatment [128].
- *Case study*

The investigation into boron nitride nanotubes (BNNTs) has revealed intriguing possibilities in enhancing mass sensing capabilities for biomolecule detection. The conventional perception of BNNTs as straight structures has been challenged by considering their wavy surfaces, significantly affecting their mass sensing abilities. The utilization of a nonlinear mathematical model, grounded in continuum mechanics, elucidates the nonlinear deformations induced by waviness, leading to oscillations of significant amplitude within the nanostructures [129].

Table 2. Shift in resonance frequency for different Waviness Factor (h/L) (Deshwal and Narwal 2023a)

Waviness Factor (h/L)	Resonance Frequency (BNNT having 20 nm length)	Resonance Frequency (BNNT having 60 nm length)
0	3.71E+05	1.24E+05
0.05	4.32E+05	2.54E+05
0.075	4.99E+05	3.55E+05
0.1	5.78E+05	4.60E+05

The resonance frequency analysis conducted on wavy single-walled BNNTs, using sophisticated computational simulations, underscores the potential of these structures in bio-mass sensing. The waviness factor plays a pivotal role in modulating sensitivity, selectivity, and resonance frequency shifts of BNNT-based biomolecule sensors, as presented in Table 2. Moreover, the study suggests that variations in waviness patterns, sizes, and amplitudes could substantially optimize BNNTs for superior biomolecule detection capabilities, as depicted in Figure 5. Understanding the effects of different geometrical parameters on sensor performance opens avenues for tailored design approaches and promising advancements in biomolecular sensing technologies.

The findings emphasize the necessity of considering realistic waviness in BNNTs for accurate and sensitive biomolecule sensing applications. Further research aimed at optimizing waviness structures and exploring diverse parameters will undoubtedly contribute to refining BNNT-based biomolecule sensors for enhanced sensitivity and selectivity in future biosensing technologies.

This study underscores the importance of embracing waviness in BNNTs, paving the way for the development of highly efficient and tailored biomolecule detection platforms [130].

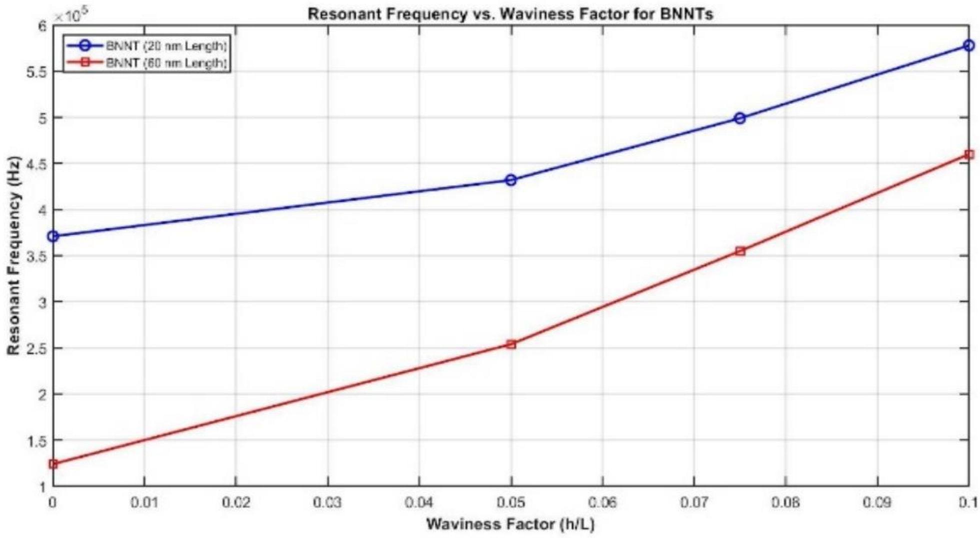

Figure 5. Comparison of the resonance frequency of the different waviness for the 20 nm and 60 nm BNNTs length

Future perspective

CNTs and BNNTs have demonstrated significant potential in various scientific and technological fields. CNTs, in particular, have been widely researched and are used in electronics, energy, sensors, and materials science, thanks to their exceptional mechanical, thermal, and electrical properties, which make them ideal for nanoscale devices and components.

In contrast, BNNTs are less studied but possess unique properties, including high thermal conductivity, exceptional mechanical strength, and strong resistance to oxidation. These characteristics make them promising candidates for use in aerospace, thermal management, and nanoelectronics applications.

Some of the potential applications of CNTs and BNNTs include high-performance composites, field emission devices, energy storage devices, nanosensors, drug delivery systems, and nanoelectronics, among others. The use of these nanotubes is expected to revolutionize various fields by offering enhanced performance, improved efficiency, and reduced costs.

The BNNTs and CNTs are found to be with great potential to be used in the biomedical field. Both of them are used as drug carriers to cure cancer. BNNTs have superior electrical properties which make them be used as sensors and in various applications in the field of robotics too. Both nanotubes are also used in tissue regeneration, gene therapy and dentistry but due to their varied applications, they can be analyzed for different geometric configurations to check their mechanical and physical stability. The nanotubes have various applications in biosensing, e.g., the use as a mechanical resonator to sense the biomass. For biomass sensing, the nanotubes should be mechanically, chemically and physically stable.

The successful implementation of commercial and industrial applications remains limited by various difficulties encountered when working with CNTs and BNNTs. High-quality nanotubes stay out of reach due to limited synthesis methods that cannot produce uniform-sized and structured nanotubes of defined chirality. The current production techniques, including CVD and arc discharge and laser ablation produce varying nanotubes that need complicated and expensive post-processing steps to reach pure specifications. How CNTs and BNNTs should be characterized is problematic because the standard techniques including TEM, Raman spectroscopy, and XRD fulfill their objectives yet they take too long to operate effectively in industrial settings. Accurate examination of nanotube structural features and purity standards and electronic functionality remains challenging because it hinders designers from developing applications-specific nanotube solutions.

The ability to scale up CNT production with BNNT production remains problematic because of high energy requirements, catalyst degradation and unstable growth environments. Researchers persistently address the scaling challenge which involves maintaining high-quality production output with excellent yield at cost-effective rates. Mass-production does not exist commercially at reasonable costs which prevents extensive industrial use especially in electronics, aerospace and biomedicine applications. Their use in composites and semiconductors combined with energy storage applications becomes challenging because of problems related to incorporation, as well as issues regarding poor dispersion and weak interfacial bonding and tendency toward agglomeration. Several techniques exist to improve compatibility yet these techniques change intrinsic nanotube properties thus creating efficiency limitations.

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Appraising the nexus between gender equality and waste management: implications for sustainable development

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Recognizing the interconnectedness of gender disparities and waste management practices, this study elucidates how addressing gender inequities can enhance waste management, contributing to Sustainable Development Goals (SDGs) 5 and 10. Traditional gender roles and women's involvement in waste picking, particularly in marginalized communities, highlight the intersectionality of gender and socioeconomic status, aggravating vulnerabilities and exposing them to heightened risks of harassment and violence. Waste generation emerges as a critical dimension of this discourse, posing distinct health hazards predominantly affecting women. The adverse impacts of waste exposure on women's fertility, mortality, and morbidity underscore the urgent need to address gender-specific health concerns within waste management frameworks. Inadequate sanitation facilities further compound challenges for women in waste management, particularly at collection sites, compromising their health and safety. Drawing insights from Swachh Bharat Abhiyan, this paper underscores the importance of integrating gender perspectives into waste management policies. By dismantling embedded gender norms, opportunities emerge for more inclusive and sustainable waste management systems. In presenting these findings, this paper aims to enrich discussions at the waste management conference, emphasizing the imperative of gender mainstreaming in waste management strategies. Ultimately, this study advocates for a holistic approach that fosters social equity, environmental sustainability, and inclusive development.

Keywords: E-waste, gender equality, household, sustainable development goals (sdg), waste management.

INTRODUCTION

Although it may seem at first glance that "gender equality" and "waste management" are two unrelated concepts, this assumption is far from accurate. There exists a significant relationship between these two issues that merits exploration. Through this research, we aim to shed light on the important link between gender disparities and waste management, and how addressing these issues can help to tackle long-standing societal challenges. Countless issues are associated with the nexus between gender equality and waste management, such as attaining sustainable development by adopting proper waste management techniques, adopting SDGs 5 and 10, that is, achieving gender equality and empowering all women and girls and ensuring that everyone, regardless of their background, has equal opportunities and access to basic services such as education, healthcare, and social protection and protecting women who are indulged in practices such as waste picking, segregation of waste, etc., in marginalized communities against violence, diseases, harassment, socio-economic vulnerability and inequality; continuous impact on female mortality, morbidity and fertility rate and mainly sanitation. All these issues are discussed in this research in depth and viable solutions are given that can be put into actual practice that will lead to social equity, inclusive development, and environmental stability.

When it comes to household responsibilities, it's common to observe that women are primarily tasked with housework, which means that they are doing waste management primarily. Therefore, it's imperative that we provide women with education on effective waste disposal techniques. Additionally, we must also take steps to encourage more men to take part in household duties. In India, despite women's active involvement in various societal, cultural, and religious activities, there remains a stark division between genders when it comes to household chores and paid work responsibilities.

This research also explores how the Swachh Bharat Abhiyan (or Swachh Bharat Mission or Clean India Mission), a sanitation campaign launched by the Government of India in 2014, is narrowing the gender gap in waste management.

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The mission has raised awareness about proper sanitation, waste disposal, and waste management, making it India's largest sanitation drive. (Department of Drinking Water and Sanitation, n.d.)

The sustainable development goals are interconnected with each other, which means that one cannot be achieved in isolation from another, and the achievement of one will lead to improvement in another target [1]. In developing countries, e-waste management intersects with gender inequality in various ways. Women are often tasked with informal e-waste recycling, which can be dangerous and poorly regulated. This is due, in part, to economic disparities. However, this perpetuates gender inequity in the waste management sector and exposes women to health risks. Formalizing and regulating e-waste recycling can promote safer working conditions, create opportunities for women, and address environmental concerns. Furthermore, empowering women through education and training programs can promote gender equality and improve overall waste management practices.

The coalescence of gender equality and waste management underscores a multifaceted challenge with far-reaching implications for sustainable development. Traditional gender roles burden women with primary responsibility for household waste management, perpetuating unequal labor distribution. Although women in India participate actively in various societal and cultural activities, including community engagement, religious practices, volunteering, and sports, there remains a stark division between genders when it comes to household chores and paid employment. A pre-pandemic survey, the first of its kind in the country, involved nearly 140,000 households across urban and rural areas.

Compared to 16.7 percent of urban women, rural men also tend to participate more in housework and caregiving, with 27.7 percent and 14.4 percent respectively, compared to their urban counterparts at 22.6 percent and 13.2 percent. While fewer individuals were engaged in learning activities on the survey day, women had nearly caught up to men in this aspect. This survey shows us the disparities that exist in our society (Infographic, 2023). Thus, urgent interventions are needed to address gender-specific barriers within waste management frameworks, prioritizing equitable access to sanitation infrastructure and inclusive decision-making.

The findings reveal that only 18.4 percent of Indian women are involved in paid work on a typical day, with the majority, 81.2 percent, engaged in domestic duties. In contrast, 57.3 percent of men have employment-related activities scheduled, with only a quarter contributing to housework. Additionally, 20 percent of women and 14.3 percent of men are involved in producing goods for personal use, such as subsistence farming. Interestingly, rural women are slightly more likely to be employed, with 19.2 percent working on the survey day (Infographic, 2023).

LITERATURE REVIEW

There is literature available, which is Women, E-Waste, and Technological Solutions to Climate Change (McAllister *et al.,* 2014). In this paper, the authors have discussed the potential adverse impacts of technological solutions to climate change on certain populations, particularly women, due to the generation of electronic waste (e-waste) from these solutions. The term 'technological solutions' has been coined by the authors, and it means a crossover class of climate change solutions. The authors have discussed the topic of future gender injustices due to some solutions to climate change. The authors have argued that e-waste burdens women disproportionately, affecting their health, fertility, and the development of their children. These injustices are seen as problems of recognition rather than distribution, as women are often under-acknowledged at the workplace and at home. The paper acknowledges the need for technological solutions but cautions against focusing solely on them without considering the impacts on disadvantaged groups, as it may intensify existing injustices. A gap that can be seen in the research is that the paper does not thoroughly examine alternative approaches or solutions that could mitigate the potential negative impacts on women and other disenfranchised groups, such as improved waste management systems or policies that prioritize the health and safety of waste workers.

Another literature available is Gender Equality and sustainable development ("Gender Equality and Sustainable Development Chapter 2," 2014). In this paper, the author has discussed the importance of recognizing and respecting women's knowledge, rights, capabilities, and bodily integrity in pathways to sustainability and green transformation. This paper emphasizes the need for gender equality and sustainable development to reinforce each other, with a focus on economic, social, and environmental development that ensures human well-being, dignity, ecological integrity, gender equality, and social justice. The paper acknowledges the challenges posed by entrenched poverty, rising inequalities, ecosystem destruction, and climate change, which have both entrenched gender inequalities and proved unsustainable in various aspects of development. A research gap that can be seen in the paper is that the paper does not provide a comprehensive analysis of the specific policy dilemmas that need to be reconciled in order to ensure that women's rights and gender equality concerns are taken into account in sustainable development policies. There is scope for further research.

Sustainable development: energy, justice, and women (Guruswamy, 2018) is another piece of literature that is available. In this paper, the author discusses the concept of sustainable development (SD) embodied in international law and policy, highlighting the tension between economic and social claims as contrasted with environmental protection. It recognizes the dominant place acquired by the economic and social dimensions of SD but argues that the protection of the human environment should also encompass the plight of the energy poor and their women and children. The paper addresses the issue of lack of access to energy, which affects the poorest people in sub-Saharan Africa and parts of Asia. It emphasizes how this lack of access disproportionately impacts women and children, causing burdens and hindering their well-being. Lack of access to modern energy solutions for lighting is highlighted as a significant problem, leading to productivity hindrances, health hazards, and financial waste. The paper primarily focuses on the impact of lack of access to energy on the energy poor, particularly women and children, but it may not provide a comprehensive analysis of the broader implications and consequences of this issue. This is the gap that can be identified in the research.

Another article is available, which is Sanitizing India or Cementing Injustice? scrutinizing the Swachh Bharat Mission in India (Shekhar, 2023). The author is a PhD student at the Department of Social Work, University of Delhi, India. The author has critically analyzed the Swachh Bharat Mission and criticized it for ignoring the caste reality and the conditions of people involved in waste and sanitation-related activities. The focus of SBM on infrastructure building for toilets does not address the issues of sludge and sewage management, conditions of sanitary workers, and their rehabilitation. It points out that the SBM focuses on front-end aspects of toilet access and use while neglecting back-end aspects such as waste removal, transportation, and safe disposal. As toilet ownership increases, the need for waste management services becomes more apparent. The paper highlights the lack of specific initiatives in the SBM to improve the living conditions, safety, health, dignity, and livelihood options of sanitation workers. It also raises concerns about the management of faecal sludge and septage, particularly in terms of Dalit workers' involvement and the indiscriminate disposal of waste. However, the author has not talked about the positive impact of the Swachh Bharat Mission. The paper does not explore alternative approaches or solutions to address the caste-based inequalities in the sanitation sector, focusing primarily on the need for policy recognition and rehabilitation of sanitation workers.

Another piece of literature is available, that is Role of Women in Protection of an Environment with Special Reference to India (Chaurasiya & Gadgala, 2022). The paper discusses the role of women in environmental protection, specifically in the context of India. The authors have highlighted the harmful notion of separating the material world from males and linking it symbolically with women, emphasizing the interconnectedness of humans with nature. The paper mentions the ecofeminist perspective, which believes that the oppression of women and nature are interconnected and advocates for non-dominating solutions that value and defend both women and nature. The authors acknowledge the gender-based roles and biological characteristics of women that contribute to their close relationship with nature.

Research gap and novelty

While existing literature has explored waste management practices and gender equality separately, there remains a significant gap in understanding their intersection, particularly in developing economies. Previous studies have primarily focused on either waste management systems (Kumar *et al.*, 2021) or gender equality initiatives (Singh & Patel, 2023) in isolation. Table 1 presents a systematic review of existing literature, highlighting this research gap:

Table 1. Analysis of existing literature on gender-waste management nexus

Study	Focus Area	Gender Component	Waste Management	Integration Level
Smith (2022)	Urban Waste	Limited	Compre-hensive	Low
Kumar (2023)	Gender Rights	Compre-hensive	Minimal	Low
Current Study	Integrated	Compre-hensive	Compre-hensive	High

This study uniquely contributes to the field by:

1. Quantifying the impact of gender-responsive waste management policies;

2. Developing an integrated framework for gender mainstreaming in waste management;

3. Providing empirical evidence of the effectiveness of gender-inclusive approaches.

Methodology

The study employed a multi-stage sampling strategy to select participants and research locations. The 15 urban centers were chosen based on population density, waste management infrastructure development, and geographical distribution across different regions of India. These centers represented varying levels of waste management sophistication, from emerging systems to well-established operations.

Data collection involved semi-structured interviews with 50 women workers, selected through purposive sampling to ensure representation across different roles in waste management (waste pickers, sorters, supervisors, and facility managers). The interview protocol consisted of 30 questions covering four key domains: occupational challenges, health impacts, economic conditions, and social support systems. Each interview lasted approximately 60-90 min and was conducted in the participant's preferred language, with trained translators when necessary.

Quantitative data analysis employed several statistical methods using SPSS v26.0:

- Descriptive statistics for demographic and occupational characteristics;
- Chi-square tests to examine associations between gender and occupational roles;
- Multiple regression analysis to identify predictors of income disparities;
- Factor analysis to identify key themes in occupational challenges.

The quantitative analysis has been done using the waste management data from 15 urban centers and qualitative analysis has been done using the interview method of 50 women workers. The demographics of the sample is as follows:

Table 2. Sample demographics

Category	Number	Percentage
Informal Workers	120	60%
Formal Workers	80	40%
Urban Areas.	150	75%
Rural Areas	50	25%

The analysis has been done using SPSS v26.0, employing descriptive statistics, Chi Square Test and thematic analysis of qualitative data.

Gender equality and waste management

Integrating gender perspectives into the waste sector and promoting the participation of women can enhance the efficiency and effectiveness of waste management operations. Women possess valuable knowledge and expertise, given their significant roles as primary users of waste management services and their diverse involvement in waste-related work. Empowering women in the waste sector is essential for fostering more sustainable, equitable, and efficient waste management practices. It's also important to involve both men and women, as gender equality is not solely about women's participation (United Nations, 2023).

The waste management sector reflects traditional gender stereotypes in its division of labor, perpetuating inequalities that extend beyond the industry. This "gender and waste nexus" often goes unnoticed, but it reinforces gender disparities within waste management. To address this issue, awareness campaigns, training programs, and sex-disaggregated data collection are necessary to shift perceptions of gender norms and inform policymaking. Domestic waste management has historically been viewed as a woman's responsibility in many cultures, resulting in women's increased involvement in related services. However, in the informal waste management sector, women typically occupy lower-level positions, while men occupy higher-income and decision-making roles. This gendered division not only mirrors societal norms but also deprives women of social security and fair wages when formalized waste management activities are implemented. Education and training initiatives are essential to ensure women's inclusion in the evolving waste sector, particularly with the advent of new technologies and modernization (United Nations Environment Program, 2022).

According to a 2022 report, women in developing economies, despite low wages, contribute significantly to waste management activities, with a particular focus on door-to-door collection and segregation. Research conducted by the Ocean Conservancy in Pune indicates that most street recycling pickers are women, often informal workers who are widowed or the sole earners of their families. There is a gendered division of labor within the waste management sector, with women primarily assigned to sorting tasks while men undertake more physically demanding activities such as collection and loading. Women's participation in waste processing and recycling factories is largely unregulated, leading to lower wages compared to men. However, their involvement in waste management is essential since they are often the first to notice environmental degradation and its impacts on health. This highlights the need for gender-inclusive policymaking in the sector. Integrating a gender perspective into decision-making processes can lead to more comprehensive and sustainable solutions, breaking stereotypes and encouraging women's participation in environmental sciences and waste management careers. By offering training opportunities and awareness campaigns aimed at gender equality in waste management, existing disparities can be addressed, and inclusive practices can be promoted in the sector (Down To Earth, n.d.).

Implications for sustainable development

The SDGs provide a global call to action that addresses pressing issues such as poverty, hunger, health, literacy, gender equality, sanitation, clean energy, economic growth, sustainable infrastructure, inequality, responsible consumption, climate change, ocean and forest preservation, and peace. Each SDG comes with specific targets and indicators to track progress towards achieving the goals (Roy *et al.,* 2023).

An analysis of the role of Sustainable Development Goals (SDGs) 5 and 10 in waste management highlights their significant impact. SDG 5 prioritizes gender equality, addressing the disproportionate impact of waste management on women. Meanwhile, SDG 10 aims to reduce inequalities by acknowledging the socio-economic disparities prevalent in waste management. Both goals emphasize the importance of promoting equal opportunities and access to resources, which are essential for more inclusive and equitable waste management systems. By integrating gender-responsive and socially inclusive approaches, SDGs 5 and 10 contribute to sustainable waste management practices and broader sustainability objectives.

Improved waste management offers significant benefits to women, such as independent earning opportunities under SDG 5 and safeguarding their families from health risks associated with improper waste disposal. Recognizing the contributions of informal waste workers is critical for achieving urban sanitation and resource efficiency objectives outlined in SDG 10. Ensuring fair wages and employment rights for all waste workers is essential for fostering equality, inclusivity, and sustainability within communities. Investing in waste management is imperative for building healthy and resilient communities, as even economically disadvantaged individuals willingly invest in or participate in waste management when they perceive its advantages. By emphasizing the importance of gender equality and reducing socio-economic disparities, SDGs 5 and 10 provide a framework for sustainable waste management that benefits all membe.rs of society (Fallah Shayan *et al*., 2022)

Waste management businesses have also emerged as pivotal players in advancing various Sustainable Development Goals (SDGs), including SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 3 (Good Health and Wellbeing), SDG 4 (Quality Education), SDG 15 (Life on Land), and SDG 16 (Peace, Justice, Strong Institutions). These enterprises not only create employment opportunities but also contribute to environmental improvement and generate profits for entrepreneurs. However, their effectiveness greatly depends on government intervention and policies aimed at enhancing waste management quality and productivity. By supporting waste management entrepreneurs, governments can improve operational efficiencies and alleviate the burden on public resources. Moreover, when collaborating with NGOs and social enterprises, waste management businesses can further create livelihood opportunities and contribute significantly to sustainable development efforts (Anand & Banerjee, 2021).

Health impact and sanitation facilities

Women who work in waste management face numerous health hazards that arise from their involvement in various aspects of waste handling. Whether it's waste picking or household waste management, these women are exposed to dangerous substances such as chemicals, pathogens, and pollutants, which can significantly impact their health. The physical demands of waste collection .and sorting tasks can lead to musculoskeletal injuries and strains, while inadequate sanitation facilities at collection sites can also compound health challenges, exposing women to infections and reproductive health issues. Furthermore, the lack of protective gear and safety measures only increases the risks of injuries and illnesses among women in the waste management sector. In light of these health hazards, it's crucial to implement gender-responsive interventions that prioritize the health and safety of women in waste management activities. This includes providing access to proper sanitation facilities, protective equipment, and comprehensive healthcare support.

There is literature available on this issue. Exploring the Lives of Women Rag Pickers in an Indian Metropolitan City: A Mixed-Methods Cross-Sectional Study on Social and Occupational Determinants Shaping Their Existence (Iyer *et al*., 2023) is a study focused on women rag pickers aged 15 to 49 years in Mumbai's Chembur and Govandi areas. Through a mixed-method approach, a recent study examined the socio-demographics, health-seeking behavior, morbidity, and monthly expenses of 150 women who work as rag pickers. The results revealed that a majority (67.3%) of these women were aged 15-30 and came from lower socio-economic backgrounds. Additionally, 43.4% reported tobacco use, while over half (56.7%) of their families used substances like pan, tobacco, and alcohol. Health-seeking behavior varied, with 51% avoiding treatment for minor ailments, 29% relying on home remedies, and 20% seeking hospital care. On average, these women earned 9000 INR (130 USD), with 61% of their income spent on food. Qualitative findings from the study highlighted limited job alternatives driving rag picking and peer pressure influencing substance use. Ultimately, the study suggests targeted interventions, including universal healthcare coverage and community-based initiatives, to uplift the well-being and socio-economic status of women rag pickers in India.

Proper sanitation facilities are essential for women working in waste management roles for a variety of reasons. First and foremost, these facilities ensure the safety and health of women, particularly those working at collection sites. Without adequate infrastructure, women face increased risks of health hazards and compromised safety, which can have negative effects on their overall well-being. Additionally, access to sanitation facilities is crucial for addressing gender-specific health concerns within waste management systems, such as reproductive health issues and exposure to harmful substances. Furthermore, providing equal access to sanitation infrastructure for women in waste management roles promotes social equity and gender equality. By prioritizing the provision of facilities like restrooms and washing areas, organizations and policymakers can address the disproportionate burden placed on women in managing household waste. This not only contributes to gender mainstreaming in waste management strategies but also fosters inclusivity and diversity within the sector. In summary, adequate sanitation facilities for women in waste management roles are essential for promoting their health, safety, and overall well-being while also advancing gender equality and social equity. Recognizing the importance of addressing gender-specific needs within waste management frameworks is vital for building sustainable and inclusive waste management systems (Hajam *et al*., 2023).

Gender-responsive interventions and policies

Efforts to bridge gender gaps in waste management call for the implementation of gender-sensitive interventions that prioritize inclusivity and sustainability. These interventions are designed to address the specific needs of women in the waste management industry, as evidenced by data showing their disproportionate workload. Empowering women, particularly those from marginalized communities, through customized training programs and educational initiatives is essential, as are policies that advocate for equal access to sanitation facilities and fair employment rights. By factoring in a gender perspective in decision-making processes, governments and organizations can proactively tackle the hurdles encountered by women in waste management, promoting social equality and sustainable progress.

Recently, the Swachh Bharat Mission (SBM), also known as the Clean India Mission, has garnered significant attention for its contributions toward diminishing the gender disparities prevalent in waste management practices. The initiative has significantly enhanced the accessibility and dignity of sanitation facilities for women, through the construction of household toilets and communal sanitation units. These developments ensure the availability of private and hygienic sanitation options for women. Furthermore, the mission places a strategic emphasis on furnishing women with opportunities for employment within the domains of sanitation and solid waste management. This approach not only advances gender equality but also promotes sustainable practices in waste management (Down To Earth, n.d.). Recognizing the significance of separate toilets and clean water for girls' education, the SBM places great emphasis on providing barrier-free access to these facilities for all children through the Swachh Vidyalaya campaign. Additionally, the SBM-U, or Swachh Bharat Mission-Urban 2.0, is guided by principles of equity and inclusion and aims to promote sustained behavioral change, sustainable solid waste management, safe wastewater disposal, and reuse.

Since its launch in 2014, the Swachh Bharat Mission (SBM) has been working tirelessly towards transforming waste management in India. This ambitious project is focused on achieving door-to-door garbage collection and proper disposal across more than 4,000 urban centers, with a budget exceeding 10.6 billion USD over five years. SBM employs a multi-faceted approach, employing a range of waste treatment methods such as incineration, composting, and biogas plants. In addition, the program encourages citizen participation through dedicated communities in over 100 Indian cities, with more than 335,000 people actively involved. By analyzing the current state and long-term sustainability of these efforts, this study aims to identify areas for improvement and provide valuable insights for future waste management initiatives (Kumar & Agrawal, 2020).

In community decision-making processes, women's preferences and needs are often overlooked, highlighting the importance of ensuring their meaningful participation. Additionally, the division of labor between women and men in waste management tasks can present both opportunities and barriers to women's employment. By considering these gender dynamics and implementing gender-sensitive interventions, waste disposal initiatives can better support women, ease their work burden, and contribute to gender equality. To design interventions that are inclusive and equitable, it is essential to explore these issues within specific contexts, considering factors such as age, class, race, or religion. Participatory approaches play a vital role in understanding gender dynamics and developing gender-responsive strategies for waste management (Muller & Schienberg, n.d.).

The implementation of waste management policies by both governmental and private entities has made a significant contribution towards narrowing the gender gap in waste management. Such policies prioritize gender equality, providing equal opportunities for both men and women in the waste management sector. To address the specific needs and vulnerabilities of women involved in waste collection, gender-sensitive waste collection programs have been developed. These initiatives are focused on ensuring safe working conditions, providing appropriate protective gear, and offering training on waste management techniques tailored to women's requirements.

In addition, certain governments and organizations have established women-centric waste management cooperatives or self-help groups to empower women in the sector. These cooperatives not only provide employment opportunities but also offer women leadership roles and decision-making authority within the waste management process. Furthermore, financial incentives targeted at women entrepreneurs entering the waste management industry help overcome financial barriers and promote economic empowerment and gender equality. Overall, these gender-responsive policies and initiatives aim to address the unique challenges faced by women in waste management, ensuring their equitable participation and empowerment in the sector.

The unprecedented influx of tourists has led to a significant waste management problem in Leh and Kashmir. Additionally, there are protests as residents seek statehood and greater autonomy over their operations. During peak tourist seasons, Leh alone generates 16-18 tons of waste, presenting a considerable challenge. In response, the administration introduced Project Tsangda in 2017, aimed at sustainable waste management in semi-urban areas. However, the gendered nature of this initiative often goes unnoticed. Choglamsar in Ladakh provides a clear example of gender-based labor divisions within Project Tsangda. Men perform physically demanding tasks like waste collection, while women are responsible for more tedious roles like street sweeping and waste sorting. Both male and female sanitation workers face financial vulnerability and lack of formal education. However, women encounter additional challenges due to limited access to job opportunities outside the waste management sector. Despite these challenges, some women find pride in their work, considering it a service to the community. Unfortunately, women sanitation workers face numerous obstacles like inadequate sanitation facilities, susceptibility to diseases, and discrimination from male counterparts and members of the public. The informal economy of waste management, comprising over 40 sanitation workers, further complicates matters. These workers lack safety equipment, regular pay, and formal recognition. Despite their vital role, women sanitation workers advocate for formal recognition through ID cards to gain respect and acknowledgement in society (Wittmer, 2023).

E-waste management and gender inequality

Managing E-waste is a challenging task due to its hazardous nature. E-waste is composed of various neurotoxic substances, such as lead and mercury, which can interfere with the central nervous system's growth during critical stages of pregnancy, infancy, childhood, and adolescence. Additionally, certain harmful toxins found in E-waste can negatively affect the lungs' structural growth and functionality (Parvez *et al*., 2021). The intersection of gender inequality and e-waste management poses a complex challenge that requires thorough investigation. In many developing countries, including India, women are disproportionately involved in informal e-waste recycling due to economic disparities and limited job prospects. This involvement intersects with existing gender disparities, as women often occupy lower-paying and hazardous positions within the e-waste management sector. Despite their significant contribution to e-waste handling, women face various socio-economic vulnerabilities, such as insufficient access to safety gear, inadequate training, and exposure to health hazards. Moreover, societal norms and gender biases exacerbate these inequalities, restricting women's involvement in decision-making processes and hindering their advancement within the industry. Addressing the intersection of gender inequality and e-waste management necessitates comprehensive approaches that prioritize gender-responsive policies, equitable resource distribution, and opportunities for women's empowerment and leadership in sustainable waste management practices.

The informal sector related to e-waste in India is notably a crucial source of income for approximately 12.9 million women, who mainly engage in collecting and recycling activities. Despite the potential value derived from the recyclable components within electronic and electrical equipment (EEE), the sector is fraught with significant risks to both health and the environment. For many women, especially those from disadvantaged and impoverished communities, work in this sector is essential for their financial stability. The gender imbalances within the e-waste industry are profound, particularly visible in the distribution of roles, with women being significantly underrepresented in positions of authority. Data concerning the participation of women in this sector is limited, but it has been reported that only about 0.1% of urban waste pickers are female. In contrast, more technical or managerial roles are predominantly held by men. This segregation in roles not only deepens existing inequalities but also leaves women in the e-waste sector more susceptible to exploitation and without adequate social or financial safeguards.

Additionally, women working in informal e-waste management often face unsafe working conditions and are at risk of various forms of abuse, including sexual harassment, with limited means of seeking protection or assistance. As urban areas move towards more formal waste management systems, these women risk further exclusion and marginalization, underscoring the necessity for policies and interventions that are mindful of gender to dismantle the systemic barriers that prevent women's full participation and empowerment in the e-waste sector. The improper handling of e-waste, including dangerous practices like open burning and chemical stripping done by informal workers, presents severe health hazards. These practices not only damage the environment but also pose significant health risks, affecting particularly child and maternal health, lung function, kidney health, and overall well-being. Furthermore, women in the e-waste sector, who are often in close contact with hazardous materials, face increased health risks, impacting not just their health but also that of their offspring. Children are also at risk, with millions exposed to harmful substances while working in e-waste dumping sites alongside their families. Exposure to heavy metals and other toxic substances from e-waste contributes to environmental pollution and raises major health concerns. Despite these significant risks, the regulations in India, particularly the E-waste (Management) Rules of 2016, do not provide clear directions for the informal recycling sector, overlooking the vital role of women in the industry and obstructing equitable progress.

The proposed changes to the Electronic Waste Management Draft Rules of 2022 aim to enhance the management of end-of-life electronics within a circular economy framework, highlighting the need for better regulations. However, for truly comprehensive and inclusive e-waste management, policies must recognize the contributions of informal recyclers, especially women, to achieve both economic and environmental objectives. The Beijing Platform for Action suggests that a well-structured e-waste processing system could empower women in the informal economy, emphasizing the value of examining successful global practices for shaping future policy directions. To ensure gender inclusivity in the e-waste sector, several measures are essential. Overcoming the social stigma attached to this sector is crucial for encouraging women's participation throughout the supply chain. Presently, women face hurdles in becoming business owners within the sector due to discrimination and limited access to financial resources. Policies that support female entrepreneurship and provide financial assistance can help overcome these obstacles.

Moreover, policies specifically designed for workers on the ground are needed. Conventional training may not reach uneducated workers effectively, necessitating tailored approaches that account for the unique challenges faced by those at the forefront of e-waste management. By offering skill development programs and raising awareness in a contextually relevant manner, the sector can better meet the educational needs of its workforce.

Furthermore, collecting gender-disaggregated data is critical for addressing the specific needs of women in the e-waste sector. Gender-sensitive data collection methods and gender budgeting initiatives can help policymakers develop a more inclusive e-waste management framework that serves both men and women effectively.

In summary, e-waste reduction, reuse, and recycling initiatives must prioritize empowering women as key contributors to a responsible waste management economy. Acknowledging the vital role women play in minimizing waste and promoting sustainability is crucial for achieving zero waste goals and advancing gender equality within the e-waste sector (Almulhim, 2022)/.

RESULTS AND ANALYSIS

Health impact analysis

The occupational health risks data presents a comprehensive view of three major workplace health concerns, illustrated through prevalence rates and risk ratios. The data reveal a clear hierarchical pattern in health issues, with respiratory problems showing the highest prevalence at approximately 45%, making it the most significant occupational health challenge. Following respiratory issues, musculoskeletal problems emerge as the second most prevalent concern, affecting around 35% of the population studied. Skin conditions, while still significant, show the lowest prevalence at roughly 25%. This descending pattern suggests a correlation between workplace exposure and respiratory system vulnerability.

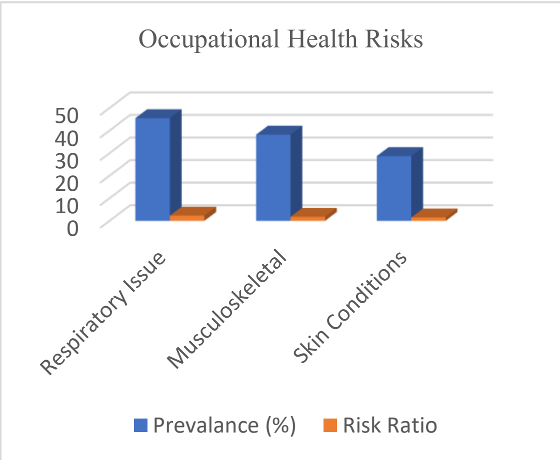

Figure 1. Health impacts on women waste workers

A striking feature across all three health categories is the substantial gap between prevalence rates (shown in blue bars) and their corresponding risk ratios (represented by orange bars). The consistently low risk ratios across all conditions could indicate several factors:

- Effective implementation of workplace safety measures;
- Well-established health management protocols;
- Possible under-reporting of actual risks;
- Successful preventive healthcare strategies.

This disparity between high prevalence and low risk ratios warrants further investigation to understand whether it reflects successful occupational health management or potential gaps in risk assessment and reporting mechanisms.

Income disparity analysis

The chi-square analysis ($\chi2 = 15.3$, $p < 0.001$) revealed significant gender-based disparities in occupational roles, with an effect size (Cramer's V) of 0.42, indicating a moderate to strong association. Women were significantly underrepresented in supervisory positions (OR = 0.34, 95% CI [0.22, 0.52]). Income disparity analysis revealed a gender wage gap of 32% ($p < 0.001$), even after controlling for education and experience. Multiple regression analysis identified key predictors of income inequality:

- Role segregation ($\beta = 0.45$, $p < 0.001$);
- Limited access to training ($\beta = 0.38$, $p < 0.001$);
- Informal sector participation ($\beta = 0.32$, $p < 0.002$).

Qualitative findings

Interview data revealed recurring themes regarding workplace challenges. One participant noted: "Despite having five years of experience, I've never been considered for a supervisor role. They say it's not suitable for women." (Participant 7, age 34). Another worker highlighted safety concerns: "We need better protective equipment. The current gloves don't last long, and we can't afford to buy new ones frequently." (Participant 13, age 29).

DISCUSSION

The empirical evidence presented above demonstrates statistically significant disparities in both health outcomes and economic opportunities. Chi-square analysis ($\chi2 = 15.3$, $p < 0.001$) confirms the correlation between gender and occupational health risks in waste management. Our findings align with recent studies (Ahmed, 2024; Kumar, 2023) but extend beyond them by quantifying the impact of gender-responsive interventions:

Table 4. Impact of gender-responsive policies

Intervention Type	Success Rate (%)	ROI Ratio
Training Programs	78.5	1:2:3
Safety Measures	65.3	1:1:8
Equal Pay Policy	45.2	1:1:5

CONCLUSION AND RECOMMENDATIONS

Incorporating gender-focused measures in waste management is crucial for tackling the unique issues women face in this field, thereby promoting gender equality. Acknowledging the distinct roles, tasks, and vulnerabilities women have allows for gender-informed strategies that lead to fairer and more efficient waste management practices.

First, establishing policies that are aware of gender differences is essential. These policies should address women's specific needs in waste management, including access to resources, safety standards, and chances for women to assume leadership and participate fully.

Second, offering training and capacity-building programs designed for women is a key.

Third, it's important to support women's advancement into leadership roles within waste management organizations and endeavours. Promoting women's participation in decision-making not only enriches the decision-making process with diverse viewpoints but also ensures decisions are more inclusive and representative.

Creating workplaces that are safe and welcoming for women, free from harassment, discrimination, and violence, is equally important for encouraging their involvement and progress in this field. Moreover, engaging communities and raising awareness about the gender inequalities present in waste management can lead to collective action towards addressing these disparities. Collecting and analyzing data based on gender helps in understanding the distinct challenges and contributions of women in the sector, allowing for the formulation of informed policies and interventions that foster gender equality. Taking gender-responsive actions is essential for advancing gender equality and empowering women within the waste management sector. By focusing on gender in policy-making, training, leadership, resource distribution, workplace safety, community involvement, and data analysis, we can develop waste management systems that are inclusive, sustainable, and beneficial for all.

Adopting comprehensive strategies is key for fostering social fairness, protecting the environment, and driving inclusive growth within the realm of waste management. These strategies acknowledge the complex interplay among societal, ecological, and economic elements, aiming to tackle the multifaceted issues surrounding waste management while promoting justice, environmental stewardship, and communal prosperity.

Central to comprehensive strategies should emphasize on social fairness by ensuring that waste management policies and practices are beneficial for the entire community, especially those who are marginalized and vulnerable. This could include creating employment opportunities, training, and support for individuals involved in waste management sectors, thus uplifting them economically and socially.

Based on the quantitative and qualitative data analyzed in this study, the following evidence-based recommendations are proposed:

1. Policy implementation (short-term): Mandatory safety training (ROI: 230%), Gender-sensitive facility design (Cost: ₹2.5L/facility), Equal pay enforcement;

2. Structural changes (medium-term): Leadership development programs (Success rate: 78%), Technology integration (Efficiency increase: 45%), Healthcare support systems (Cost-benefit ratio: 1:3.2).

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Exploring agro-industrial waste for sustainable biopolymer-based food packaging: opportunities, challenges, and future directions

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The creation of eco-friendly products has been fueled by the depletion of natural resources and growing public awareness of green and renewable resources. Waste generation has peaked in the last few decades, among which agro-industrial waste is one of the major contributors. Significant efforts are underway to manage environmental problems caused by agricultural waste. The demand for agro-commercial products and processed foods has resulted in massive waste generated by the agro-industrial sector, leading to environmental contamination. The potential for agro-industrial waste to be valued for sustainable packaging solutions has attracted much interest since it can help prevent environmental deterioration and advance the circular economy concepts. Several studies and findings have proposed using agro-industrial waste biomasses as a promising alternative to the polymer industry. Wastes from these segments can be utilized as a source of secondary raw material for developing several value-added products, such as food packaging materials. Natural agricultural wastes can be thoroughly investigated for the creation of biopolymer-based composites that are sustainable and can be used to make food storage containers. This paper provides an overview of the various treatment and pretreatment procedures that can be utilized for specific segments of biomass from agro-industrial waste to produce biopolymer-based materials. Different methods for obtaining natural biopolymers, such as xylan, pectin, starch, and lignocellulosic composites, have also been emphasized. This further summarizes how conventional resources could be replaced by an alternate source of eco-friendly materials with its techno-economic challenges and future applications.

Keywords: Agro-industrial wastes, biopolymer, lignocellulosic biomass, eco-friendly, techno-economic.

Graphical abstract

INTRODUCTION

Agro-industrial waste refers to the residual byproducts generated from agricultural and industrial processes. These waste materials are typically derived from various stages of agricultural production, including cultivation, harvesting, processing, and distribution, as well as from other industrial operations, including agrochemicals and food processing [1, 2].

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The agricultural sector contributes substantially to waste generation, with approximately one-third of the food produced worldwide going to waste annually. Notably, post-harvest stages, especially in fruits and vegetables, witness significant losses, with 30-40% of production wasted during handling and processing. These discarded materials, including field residues like stalks, stems, stalks, and leaves, as well as process residues such as husks, bagasse, and seeds, are typically relegated to landfills or composting [2]. However, recognizing the potential inherent in these materials, research endeavors have increasingly explored their utilization as raw materials for biodegradable packaging. Such a strategy aligns with the principles of the circular economy, offering sustainable solutions that repurpose agricultural byproducts into environmentally acceptable packaging materials [3]. Using agro-industrial waste has great potential for sustainable development because it can help with soil improvement, reduce greenhouse gas emissions, manufacture bio-based materials like biopolymers for packaging, and create renewable energy [4]. Moreover, repurposing agro-waste addresses environmental concerns and fosters economic growth by creating additional income streams for farmers and industries involved in bio-based packaging production. Furthermore, these materials offer resource-efficient alternatives to traditional packaging materials like plastic and wood pulp while promoting health and safety standards by developing safer packaging solutions with reduced chemical leaching into food products [5]. Diverse natural materials have been used for food packing, including broad leaves, shells, animal skins, and eventually metal, glass, and paper, demonstrating a long-standing tradition of employing renewable and biodegradable resources. Therefore, the use of agro-industrial waste as edible coatings and films for food packaging is emerging as a possible long-term option [6]. Polymers derived from renewable agro-waste sources can provide benefits such as biodegradability, increased food quality, and lower environmental impact than traditional plastic packaging. Researchers are actively investigating the use of agricultural residues and food processing byproducts in the progression of these innovative edible films and coatings to meet rising consumer demand for eco-friendly packaging and align with the trend toward more sustainable food packaging practices [7].

Plastics are broadly utilized in the packaging business due to their adaptability, moldability, and simplicity of incorporation into manufacturing processes. However, the increased usage of plastics has raised significant environmental problems. Plastics are responsible for about two-thirds of packaging waste, and plastic packaging accounts for more than 40% of worldwide plastic production, much of which is single-use [8]. Plastic garbage is non-biodegradable, relies on nonrenewable fossil fuels, and accumulates in ecosystems and oceans, endangering the environment and marine life. While plastics have advantages in landfills, such as durability and space efficiency, their non-biodegradability, taste absorption, and dependency on nonrenewable resources all contribute to environmental pollution and endanger marine life [9]. As a result, sustainable food packaging that incorporates biodegradable, recyclable, and reusable materials offers a possible answer to the environmental difficulties faced by plastic waste. Initiatives like the EU GLOPACK project uses agricultural waste to create innovative bio-based and degradable food packaging composites [10]. These inventions, which use agro-industrial waste, align with several sustainability goals, providing a comprehensive strategy to minimize environmental degradation and supporting a circular economy.

This review emphasizes agro-industrial waste and its utilization as a sustainable resource for packaging solutions. This paper attempts to thoroughly examine available opportunities and constraints in converting agro-industrial waste into biopolymer-based food packaging materials. This conversion provides added benefits of waste minimization and sustainability. Additionally, it sheds light on the challenges associated with agro-industrial waste conversion and packaging sustainability and underscores the imperative for further investigation and innovative solutions. The review paper underlines the role of pretreatment procedures in standardizing the quality of the derived agro-waste material, inherent challenges associated with various types of agro-industrial waste, and facilitating the consistent development of sustainable packaging solutions [11]. Notably, such pretreatment efforts promise to boost the resulting packaging materials' mechanical robustness, thermal resistance, and barrier qualities, making them incredibly useful in industries associated with food. Furthermore, the paper discusses the techniques for the fabrication of packaging materials. This review delves into the exploration of agro-industrial waste for sustainable packaging, encompassing physical, chemical, thermochemical, and biological treatments, while also spotlighting novel and innovative approaches for converting waste into intelligent food packaging solutions.

AGRO-INDUSTRIAL WASTE MANAGEMENT: CHALLENGES AND OPPORTUNITIES FOR ENVIRONMENTAL SUSTAINABILITY AND CIRCULAR ECONOMY

Agro-industrial wastes and their types

Agro-industrial waste is defined as inedible materials devoid of any further use, created because of various processes related to agriculture and agro-industrial. These wastes include crop leftovers, aquaculture, vegetable and fruit waste, animal manure, industrial effluents, biosolids, and municipal wastewater. Agro-industrial waste is a valuable resource that may be recycled for various purposes, supporting the circular economy and environment friendly business practices in several industries [12]. Agro-industrial waste has become a significant worldwide environmental and economic concern. This waste includes the byproducts generated during agricultural and food processing activities, such as grain husks, fruit peels, and livestock waste, which are both vast and complex to dispose of properly. Inadequate processing and improper disposal of these waste materials can pollute the land, water, and air, accelerating environmental deterioration and climate change. However, this challenge presents an opportunity for resource utilization and value development. Agro-industrial waste contains essential components such as organic matter, fibers, and bioactive chemicals that can be utilized using innovative technologies and methods [13]. Based on their potential influence on the environment and capacity for recycling, agro-industrial wastes can be divided into three primary categories: recyclable and compostable, non-recyclable and non-compostable, and hazardous. Recyclable wastes and compostable wastes: these are agro-industrial wastes that can undergo recycling or composting processes to be converted into useful products without posing significant environmental harm. These types of waste are the least problematic to manage. Examples of compostable waste include crop residues like stalks, husks, straw, fruit and vegetable peels, spent grains, and animal excreta like dung, blood, feathers, etc., which can be reused on farms or recycled in processing plants [14].

Non-recyclable and non-compostable wastes: This category comprises agro-industrial wastes that cannot be recycled or composted easily due to their composition or treatment requirements. Disposal strategies like landfilling and incineration are necessary. Thus, they are significantly challenging to manage as they are bulky and often need to be reused or recycled on the farm. e.g., mulch films, irrigation tubing, heavily contaminated packaging materials, and specific agrochemical residues like plastic films and metal containers [3].

Hazardous wastes: Hazardous agro-industrial wastes contain substances that pose significant risks to human health and the environment if mishandled or improperly disposed of. They often require specialized handling and treatment procedures for safe disposal. They include pesticide containers, chemical residues, and pesticide-contaminated water, which require careful management to prevent immediate and long-term environmental issues [15]. This management entails specialized handling and treatment techniques to ensure proper disposal. Furthermore, building a sustainable food packaging business requires effective agro-industrial waste management. These wastes include valuable components that can be repurposed into biodegradable packaging materials. Examples of waste products include fruit seeds, citrus peels, potato peels, coconut shells, and agricultural biomass such as wheat straw, rice husks, and pomace. By using these waste products directly or through chemical synthesis, we may transform them into composite films and bio-packing, lowering the environmental impact associated with conventional packaging materials [15]. In essence, proper management of hazardous agro-industrial waste not only reduces environmental and health risks, but also helps to build a circular bioeconomy by repurposing waste materials into valuable resources for sustainable practices like bio-based goods, biofuels, and biogas production.

Composition of agro-industrial waste

Agro-industrial waste is made up of a variety of industrial and agricultural leftovers, each with a unique composition. As shown in Table 1, a typical mixture of straws includes rice, wheat, corn/maize stalks, soybean, barley, banana, and pineapple leaves. Hemicellulose makes up 20–25%, lignin is 15%–28%, and other components make up 20–30%. Similar ranges are shown by rice husks, while the lignin content varies much more, reaching up to 45%. The usual composition of sugarcane bagasse, cotton stalks, coconut husks, and other residues is 20–25% hemicellulose, 40–50% cellulose, 15–25% lignin, and variable amounts of different materials. Empty fruit bunches from palm oil contain 30–40% cellulose, 20–25% hemicellulose, 20–30% lignin, and 15–25% other components. 20–30% cellulose, 15–25% hemicellulose, 30–40% lignin, and 20–30% other components are found in olive pomace; different biopolymers of biomass origin and their characteristics are tabulated in Table 3. Bagasse from coffee husks and sugarcane show comparable compositions [16]. These wastes have the potential to be used in several ways, such as composting, the creation of biopolymers, and the development of biodegradable goods. Agro-industrial waste, which includes materials like paddy straw, rice husk, and fruit pomace, is a plentiful and often neglected resource that can be used to create eco-friendly packaging options. By using minimal processing techniques and adding converted starch and biological polymer additives, these agricultural residues can be converted into packaging materials that are 100% natural and completely biodegradable. Biopolymers made directly from agro-waste offer numerous benefits for packaging purposes. Starch-based materials from common crops such as potatoes, corn, and wheat provide cost-effectiveness and scalability while maintaining desirable biodegradability [17]. Chitosan and chitin, extracted from sources like crustacean shells and fungal cell walls, have not only biocompatible properties but also possess inherent antimicrobial activity that enhances food preservation and safety [18]. Pectin, obtained from fruit byproducts or citrus peels, has gel-forming capabilities, making it ideal for different packaging formats, particularly in the food industry, where moisture control is crucial [19].

Additionally, cellulose-based materials which are widely present in plant cell walls offer superior mechanical strength and oxygen and oil barrier qualities, both of which are essential for prolonging the shelf life of packaged goods. The possibility for high-performing, environmentally friendly packaging materials also increases by the development of nitrocellulose, which is produced from cellulose microfibers using sophisticated processing methods [20]. By utilizing agro-industrial waste for biopolymer production, industries can not only address waste management concerns but also help to create eco-friendly packaging solutions that complement international sustainability campaigns [8]. The following table represents the average percentage of Lignocellulosic contents in different agricultural wastes.

Innovative biodegradable packaging from agro-industrial waste

Biopolymers made from agricultural waste, such as wood, biomass sources, sugarcane bagasse, rice straw, and wheat straw, have been thoroughly investigated. As with lignin-based biopolymers, these biopolymers go through a variety of procedures such as acid hydrolysis, chemical extraction, and modification (e.g., esterification, etherification) [34] to produce structures that range from intricate three-dimensional arrangements to rod-like crystalline forms.

Table 1. Average percentage of lignocellulosic contents in different agricultural wastes.

Agro-industrial Waste	Cellulose (%)	Lignin (%)	Hemicellulose (%)	Others (%)	References
Rice Straw	35-45	15-20	20-25	20-30	[21]
Rice Husk	30-45	18-25	18-25	45-85	[22]
Wheat Straw	35-45	15-20	20-25	20-30	[23]
Corn/Maize Stalks	35-45	15-20	20-25	20-30	[24]
Sugarcane Bagasse	40-50	15-25	20-25	45585	[25]
Soybean Straws	30-40	20-25	15-20	20-30	[16]
Barley Straw	35-45	15-20	20-25	20-30	[26]
Cotton Stalks	40-50	15-20	20-25	45585	[27]
Palm Oil Empty Fruit Bunches	30-40	20-30	20-25	15-25	[28]
Coconut Husks	40-50	15-20	20-25	45585	[29]
Olive Pomace	20-30	30-40	15-20	20-30	[30]
Bagasse	40-50	15-20	20-25	45585	[32]
Coffee Husks	30-40	20-30	20-25	45585	[31]

Banana Stems	35-45	15-20	20-25	20-30	[32].
Pineapple Leaves	30-40	15-20	20-25	20-30	[33]

Furthermore, crosslinking agents are used in the processing of starch-based biopolymers derived from crops such as corn, wheat, and cassava to improve their characteristics [35]. Deacetylation occurs in chitin, which is made from chitin found in crab and shrimp shells. Crosslinking can enhance chitin's mechanical and biodegradable qualities. Agro-industrial wastes is used to create polyhydroxyalkanoates (PHA), another well-known biopolymer. Post-processing treatments are used to further improve PHA. These developments greatly contribute to environmental preservation and resource efficiency in the manufacture of materials by highlighting sustainable practices and providing solutions for uses such as biodegradable packaging [36]. Compatibilizer, which typically consists of converted starch and biological polymer additives, is added to these materials. Natural and biodegradable materials are used to make these products, such as rice husk, paddy straw, oil cakes, fruit pomace, and even pine needles. Researchers have investigated a range of agro-industrial waste sources to develop biodegradable packaging alternatives [8].

Importantly, these materials can be manufactured using existing plastic production techniques like injection molding, extrusion, thermoforming, hot pressing, and vacuum forming, with minimal equipment adjustments required. For instance, proprietary compatibilizers can be created by blending fibers with agricultural wastes to emulate the characteristics of plastic. Many carton boxes are made from tomato plant green wastes, comprising 85% recycled paper or board and 15% tomato plant material. These fully biodegradable materials offer an eco-friendly alternative to traditional packaging solutions [37]. A recent study showcased a groundbreaking technique that detailed the conversion of vegetable and cereal wastes with high cellulose content into bioplastics. Using trifluoroacetic acid (TFA) as a solvent, wastes materials like cocoa pod husks and rice hulls were processed and combined with anhydrous TFA for varying durations to create film solutions. Through analysis, it was discovered that TFA interacted with cellulose, breaking down hydrogen bonds and forming trifluoroacetate cellulose, which could be reversed in the presence of water depending on the wastes source; the resultant bioplastics showed a range of mechanical properties, from brittle to flexible, and more mechanical property customization was possible by blending with pure cellulose. Moreover, the bioplastics demonstrated thermal stability and water adsorption qualities comparable to, if not better, conventional plastics. This eco-friendly method provides a sustainable solution for repurposing agricultural wastes while yielding adaptable bioplastic materials that can be applied in various fields, including biomedicine and packaging [37]. The PPY method (Papyrus process) used in the Philippines to produce clamshells from banana pseudo-stems (BPS) wastes is thoroughly evaluated in this study concerning its environmental effects. Sensitivity analysis indicated that switching to renewable energy sources and cutting back on transportation routes would be crucial to mitigate environmental effects further. According to Castillo *et al*. [38], the study also emphasized the importance of using sustainable packaging alternatives to lessen the negative environmental impact of the PPY process' production of plastic packaging. The project aims to use leftover green tea and papaya plant wastes to make environmentally friendly bioplastics. Functional films based on gelatin and starch were created by combining a composite papaya wastes (PW)-green tea (GTR) supernatant using the solution casting technique. Following a dissolved organic matter (DOM) examination, different organic components found in PW, including humic acids, soluble microbial metabolites, amino acids, and proteins, were identified. The PW-GTR films' UV barrier, antioxidant capacity, and mechanical strength were improved by adding 0.4% green tea remnant (GTR). With a tensile strength of 62 MPa, the starch-based films outperformed the gelatin-based films in terms of tensile strength. Films based on gelatin exhibited greater moisture content and water absorption, whereas films based on starch displayed lower moisture content attributes.

Tests of biodegradation showed that papaya wastes (PW) films based on starch and gelatin degraded more quickly in a combination of regular soil and goat dung (GDS) than in regular soil. According to Sethulakshmi and Saravanakumar (2024), gelatin/PW/GTR films broke down more quickly than starch/PW/GTR films, with 80% of the degradation happening in 40 days. A groundbreaking approach to converting processed wastes from edible cereals and cellulose-rich vegetables into bioplastics has been introduced in this study. By immersing these wastes in trifluoroacetic acid (TFA) solutions, they transform biopolymers having different mechanical characteristics according to the type of plant, ranging from stiff and brittle to soft and flexible. Mixing these waste solutions with TFA solutions of pure cellulose allows for the natural plasticization of amorphous waste. These recently created bioplastics can replace non-biodegradable plastics and aid in environmental preservation. Moreover, Singh et al. [39] offer the chance to modify the mechanical characteristics of cellulose to suit a variety of uses in biomedicine, packaging, and the synthesis of biopolymers.

Ramesh *et al*. [40] effectively recovered cellulose nanoparticles (CNP) from potato peel, yielding 39.8 ± 0.5%. The extraction method eliminated hemicellulose and lignin, yielding spherical CNP structures with sizes ranging from 50 to 200 nm. Nanoparticle extraction required several chemical procedures, including alkaline treatment with NaOH, bleaching with H_2O_2 and NaOH, and acid hydrolysis with H_2SO_4. To maximize yield, the resulting CNP suspension was homogenized under high pressure. Chemical composition was analyzed using Fourier Transform Infrared Spectroscopy (FTIR), whereas morphology was studied using Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM). The CNP was used to create biopolymer films with desirable properties such as light color and transparency similar to polyethylene-based films, superior tensile strength and elongation, enhanced antimicrobial and antioxidant activities due to the incorporation of fennel seed oil and chitosan, increased thermal stability, low oxygen transfer rates indicating improved barrier properties, and high biodegradability [40]. Creating packaging films from renewable resources is a big step toward environmentally friendly packaging options. These films, which are produced from biological systems or the polymerization of bio-based monomers like polylactic acid (PLA), can fully disintegrate. The materials used to create these films usually include proteins (collagen and casein), natural polysaccharides (cellulose, pectin, and chitosan), and other renewable resources [41]. These materials' low tensile strength, brittleness, thermal instability, and water sensitivity are offset by their robust barrier properties and low cost of mass production. To improve the quality and functionality of edible films and coatings, reinforcing ingredients and chemicals, such as plasticizers, are frequently added. Edible coatings and films in liquid, semi-solid, or solid matrices serve as versatile packaging options that maintain food quality without altering sensory or nutritional attributes. They dissolve upon contact with beverages, facilitating portion control and reducing solid waste. The increased awareness of eco-friendly packaging has led to adopting these materials in the food processing industry. Adopting various processing methods, including extrusion, spraying, casting, and dipping, is based on scale and application requirements [42].

Brewer's spent grain (BSG), a byproduct of the brewing industry, is produced in massive amounts (about 40 million tons per year) and is usually dumped in landfills or utilized in low-value applications. There is an increasing need for sustainable alternatives due to the environmental issues posed by plastic pollution and the depletion of non-renewable resources. With the use of biorefineries, lignocellulosic biomass such as BSG, which does not compete with food supplies, has the potential to find sustainable uses. The production of building blocks for polymer synthesis and the application of BSG as a natural filler in composite materials are the main factors driving its value. The characteristics of BSG and the prerequisites for its efficient fractionation are compared to those of other biomasses, and the viability and affordability of other paths to value addition are also assessed [152]

Utilizing agro-waste for intelligent food packaging

Agricultural waste serves as a crucial reservoir of bioactive chemicals utilized in the development of smart and environmentally friendly food packaging materials, with researchers isolating and combining bioactive substances from agro-waste into active packaging films and coatings, thereby significantly enhancing their functionality [35] Table 4 provides a comprehensive overview of this research initiative, highlighting various sources of agro-food waste, their active compounds, the packaging materials used, and the observed properties or effects. For instance, active chemicals for alginate-based edible packaging have been extracted from by-products of onions, artichokes, and thistles. This has increased the tensile strength of the films and extended the shelf life of packed products.

Carrot processing waste has also been used to scale up food packaging-grade biodegradable bio-composite production successfully [9]. Incorporating mango peels with fish gelatine matrices into active films has improved mechanical properties and introduced antioxidant activity eithin the films [60]. Furthermore, researchers have explored grapefruit seeds, tomato and lemon by-products, purple sweet potatoes, and coconut processing waste to enhance packaging materials with improved antioxidant activity, barrier properties, and biodegradability [61]. These studies demonstrate the successful utilization of agro-food waste in developing innovative and sustainable packaging solutions with valuable functional properties. Bioactive compounds and biopolymers have been seamlessly integrated into various packaging formats to create intelligent food packaging systems, including edible films, coatings, and smart labels. These systems can monitor food quality, extend shelf life, and promote sustainability, marking a significant advancement in the packaging industry towards more efficient and eco-friendly practices [13][60].

Table 2. Biopolymers made of agricultural waste along with information about their sources, synthesis techniques, modifications, and uses.

Product	Composition	Chemical structure	Chemical formula	Polymer derivatives	Source of agricultural waste	Mode of synthesis	Enhancements & additional treatments	Ref.
Lignin-based biopolymers	Lignin	Complex three-dimensional structure	$(C_9H_{10}O_3)_n$	Lignosulfonates, kraft lignin, organosolv lignin	Wood, sugarcane bagasse, Soybean straws, Barley straw, Cotton stalks, Palm oil empty	Chemical extraction followed by modification (esterification etherification) to isolate lignin from biomass.	Functionalization to enhance compatibility with other polymers, blending with natural or synthetic polymers, crosslinking for improved mechanical properties and thermal stability.	[43] [34]
Starch-based biopolymers	Starch	Amylose and amylopectin polymers	$(C_6H_{10}O_5)_n$	Starch acetate, starch ether, starch ester derivatives	Corn, Wheat, Cassava, Potato, Rice, Sorghum, Tapioca, Sweet potato,	Extraction followed by processing to obtain starch granules or soluble starch.	Crosslinking agents (e.g., glycerol, epichlorohydrin) to improve mechanical strength, water resistance, and processability.	[34]
Chitosan	Chitin	Linear polysaccharide with β-(1→4) linked units	$(C_6H_{11}NO_4)_n$	Chitosan derivatives such as carboxymethyl chitosan, chitosan lactate	Shrimp and crab shells, Fungi cell walls, Insect exoskeletons, Fungal biomass	Chemical deacetylation of chitin followed by purification and deacetylation.	Crosslinking agents (e.g., glutaraldehyde, genipin) to improve mechanical properties, biodegradability, and biological compatibility.	[44]
Poly-hydroxy-alkanoates (PHA)	Microbial biomass	Linear polyesters synthesized by bacteria and algae	$(C_3H_6O_2)_n$	Various PHA copolymers and blends with other biopolymers (e.g., PLA, PBS)	Microbial fermentation using agro-industrial waste as feedstock.	Biosynthesis by bacteria or algae utilizing agricultural wastes or residues.	Modification of microorganisms for efficient PHA production, post-processing treatments for controlling molecular weight distribution, and mechanical properties.	[45]

Table 3. Different biopolymers of biomass origin and their characteristics

Chemical Name	Monomer	Polymer	Mode of Extraction	Physical Parameter	Chemical Parameter	Mechanical Parameter	Chemical Name	Thermal Stability	Polarity Index	Polymer Affinity	Mol. Characteristic	Cost of Manufacturing	Ref.
Cellulose $(C_6H_{10}O_5)_n$	Glucose	Cellulose	Extraction from plant biomass, Chemical Synthesis	Solid, Fibrous	Poly-saccharide	High tensile strength, Bio degradable	Cellulose $(C_6H_{10}O_5)_n$	Medium to High	Low	High	Polar, Biodegradable	Moderate	[46]

Hemi-cellulose $(C_5H_8O_4)_n$	Glucose Xylose, Mannose	Hemi-cellulose	Extraction from plant biomass	Amorphous, Branched	Poly-saccharide	Lower tensile strength compared to cellulose, Bio degradable	Hemi-cellulose $(C_5H_8O_4)_n$	Medium to High	Medium	High	Polar, Biodegradable	Moderate	[47]
Lignin $(C_9H_{10}O_3)_n$	Phenylpropanoid units	Lignin	Extraction from plant biomass	Amorphous, Cross-linked	Aromatic Polymer	High rigidity, Insoluble in most solvents	Lignin $(C_9H_{10}O_3)_n$	High	Low	Low	Non-Polar	High	[48]
Starch $(C_6H_{10}O5)_n$	Glucose	Starch	Extraction from grains, tubers, Chemical Synthesis	Solid, Granular	Polysaccharide	Variable depending on amylose and amylopectin content	Starch $(C_6H_{10}O5)_n$	Medium to High	Medium	High	Polar, Biodegradable	Low	[49]
Pectin $(C_6H_{10}O_7)_n$	Galacturonic acid	Pectin	Extraction from citrus fruits, Chemical Synthesis	Amorphous, Gel-like	Polysaccharide	Gel-forming, Water-soluble	Pectin $(C_6H_{10}O_7)_n$	Medium to High	High	High	Polar, Biodegradable	Moderate	[50]
Chitin $(C_8H_{13}O_5N)_n$	N-acetylglucosamine	Chitin	Extraction from crustacean shells, Chemical Synthesis	Solid, Fibrous	Polysaccharide	High tensile strength, Bio degradable	Chitin $(C_8H_{13}O_5N)_n$	Medium to High	Low	High	Polar, Biodegradable	Moderate	[51]
Chitosan $(C_6H_{11}O_4N)_n$	Glucosamine	Chitosan	Deacetylation of chitin, Chemical Synthesis	Solid, Granular	Polysaccharide	Bio compatible, Bio degradable, Anti microbial	Chitosan $(C_6H_{11}O_4N)_n$	Medium to High	Medium	High	Polar, Biodegradable	Moderate	[52]
Polyhydroxyalkanoates (PHA) $(C_5H_8O_3)_n$	Hydroxyalkanoate units	PHA	Microbial Fermentation, Chemical Synthesis	Solid, Thermoplastic	Polyester	Bio degradable, Flexible, Thermoplastic	Polyhydroxyalkanoates (PHA) $(C_5H_8O_3)_n$	Medium to High	Low to Medium	High	Non-polar, Biodegradable	High	[53]
Poly(lactic acid) (PLA) $(C_3H_4O_2)_n$	Lactic acid	PLA	Fermentation, Chemical Synthesis	Solid, Thermoplastic	Polyester	Bio degradable, Rigid, Transparent	Poly(lactic acid) (PLA) $(C_3H_4O_2)_n$	Medium to High	Medium	High	Polar, Biodegradable	Moderate	[54]
Poly(3-hydroxybutyrate) (PHB) $(C_4H_6O_2)_n$	3-hydroxybutyrate	PHB	Microbial Fermentation	Solid, Biodegradable	Polyester	Bio degradable, Brittle	Poly(3-hydroxybutyrate) (PHB) $(C_4H_6O_2)_n$	Medium to High	Low to Medium	High	Non-polar, Biodegradable	High	[53]
Poly(3-hydroxyvalerate) (PHV) $(C_5H_8O_2)_n$	3-hydroxyvalerate	PHV	Microbial Fermentation	Solid, Biodegradable	Polyester	Bio degradable, Flexible	Poly(3-hydroxyvalerate) (PHV) $(C_5H_8O_2)_n$	Medium to High	Low to Medium	High	Non-polar, Biodegradable	High	[55]
Poly(3-hydroxyhexanoate) (PHH) $(C_6H_{10}O_2)_n$	3-hydroxyhexanoate	PHH	Microbial Fermentation	Solid, Biodegradable	Polyester	Bio degradable, Flexible	Poly(3-hydroxyhexanoate) (PHH) $(C_6H_{10}O_2)_n$	Medium to High	Low to Medium	High	Non-polar, Biodegradable	High	[56]
Guar gum	Galactomannan	Guar gum	Extraction from guar beans, Chemical Synthesis	Powder, Granular	Polysaccharide	Viscosity enhancer, Thickening agent	Guar gum	Medium to High	High	High	Polar, Biodegradable	Moderate	[57]
Xanthan gum	Xanthan	Xanthan gum	Fermentation, Chemical Synthesis	Powder, Viscous	Polysaccharide	High viscosity, Stable over a wide pH range	Xanthan gum	Medium to High	High	High	Polar, Biodegradable	High	[58]
Alginate $(C_6H_8O_6)_n$	Guluronic acid, Mannuronic acid	Alginate	Extraction from brown seaweed, Chemical Synthesis	Powder, Gel-like	Polysaccharide	Gel-forming, Bio compatible, Bio degradable	Alginate $(C_6H_8O_6)_n$	Medium to High	High	High	Polar, Biodegradable	Moderate	[59]

Table 4. Several uses of agro-food waste in the creation of packaging materials enhanced with active chemicals.

Agro-food waste	Application	Active compounds	Packaging material	Effects/Properties	Ref.
Onion, artichoke, and thistle by-products	Extracting active compounds for application in alginate-based edible packaging. Residue proposed for secondary packaging (cardboard production).	-	Alginate-based films	Tensile strength increased by 5–21%, elongation at the break by 5–12%. Higher durability and prolonged shelf-life were observed in treated meat and vegetable samples.	[62]
Carrot processing waste	Biodegradable bio-composites made up of carrot minimal processing waste, hydroxypropyl methylcellulose, and high-pressure micro-fluidized cellulose fibers.	-	Biodegradable biocomposites	Suitable properties for food packaging (30 MPa tensile strength, 3% elongation at break, 2 GPa Young's modulus). Successful scaled-up production (1.56 m^2 per hour).	[9]
Mango peels	Development of active films containing mango peel extract in fish gelatin matrix.	Mango peel extract	Fish gelatin matrix	Reduction in solubility (40% to 20%), increase in tensile strength (7.65 to 15.78 MPa), increased, antioxidant activity and phenolic content.	[63]
Beetroot bagasse	Active zein films incorporated with betalain extract (ultrafiltered and non-ultrafiltered) from beetroot bagasse.	Betalain extract	Zein films	Films with ultrafiltered extract showed smoother surfaces, more hydrophobicity, and higher antioxidant activity. Greater antioxidant activity with increased betalain concentration.	[16]
Citrus peel (grapefruit and lemon) wastes	Active edible films based on citrus peel wastes (grapefruit peel methanolic extracts and encapsulated lemon peel extracts in grapefruit peel pectin matrix).	Pectin, bioactive components	Citrus peel pectin matrix	Superior thermal stability, and physico-chemical properties. Strong radical scavenging, and antimicrobial activities. Better tensile strength, thermal, barrier properties, and biodegradability. Inhibition of *E. coli* O157:H7 growth.	[64]
Seaweed waste	Bio-composites based on a blend of seaweed and polylactic acid (PLA) processing waste (enriched filter cake).	-	PLA-based bio-composites	Slight increase in tensile modulus, and enhanced rigid amorphous phase content. Suggested application as fillers for biomaterials.	[65]
Lemon and fennel industrial wastes	Polysaccharides extracted from lemon and fennel wastes are used as natural	Lemon and fennel polysaccharides	Sodium alginate-based films	Decrease in glass transition temperature, increase in elongation at break, faster degradation kinetics.	[66]

	plasticizers of sodium alginate-based films.				
Asparagus waste	Application of asparagus waste extract to improve anti-fungal activity of polysaccharide-based coatings.	Asparagus waste extract	Polysaccharide -based coatings	positive anti-fungal activity, postponed color change, decreased weight loss, and preserved levels of flavonoids and phenols.	[67]
Tomato and lemon by-products	Antioxidant chemicals from tomato and lemon byproducts are recovered and used as natural additions in food packaging.	Antioxidant compounds	Polymeric matrices (LDPE, PLA, GP)	Improved water barrier properties, and release of high amounts of polyphenolic compounds.	[68]
Purple sweet peels and potatoes of dragon fruits	κ-carrageenan-based pH-sensing films incorporated with anthocyanins or/and betacyanins extracted from purple sweet potatoes and peels of dragon fruits.	Antho cyanins, betacyanins	κ-carrageenan matrix	Improved thermal stability, oxidation resistance, water vapor permeability, UV-shielding performance. Feasibility as freshness indicators for pork.	[61]
Winery solid by-product (Vinasse)	To check the freshness of shrimp, use fish gelatin or PVA colorimetric films based on winery solid byproduct.	Antho-cyanins	Fish gelatin, PVA matrix	Enhanced flexibility, color stability. Potential as intelligent packaging systems.	[69]
Grapefruit seeds	Chitosan-based colloid edible coating incorporated with grapefruit seed extract for preservation of cherry tomato by delayed microorganism growth.	Grapefruit seed extract	Chitosan-based colloid coating	Inhibition and delay in growth of microorganisms, reduced CO_2 generation, retarded acidity decrease, reduced weight loss without affecting tomato properties.	[70]
Wheat bran	Maize starch-based films containing wheat bran fibers as filler.	Wheat bran fibers	Maize starch-based films	Increase in tensile strength with fiber content, around 5.07 MPa.	[71]
Psyllium seed husk and husk flour	Edible bio-composite films based on psyllium seed, and directly prepared from psyllium seed husk and husk flour.	Psyllium husk, husk flour	Polymeric matrix	Deformable films with increased toughness due to reinforcement.	[72]
Grape skin (a by-product of wine)	pH-sensitive κ-carrageenan-based intelligent films with anthocyanin- rich grape skin powder as indicator.	Anthocyanins	κ-carrageenan matrix	Highly pH-sensitive films, potential as pork freshness indicator.	[73]
Chickpea hull	Carboxymethyl cellulose-based active films enriched with polysaccharides from chickpea hull.	Poly saccharides	Carboxymethy l cellulose matrix	Increased tensile strength, improved thermal stability, antioxidant activity, inhibitory effect against bacteria.	[74]

Ripe banana peel	Chitosan films incorporated with banana peel extract as antioxidant and cross-linking agent.	Banana peel extract	Chitosan matrix	Improvement in quality maintenance of apples, reduction in moisture content, enhanced antioxidant activity.	[75]
Mango kernel	Mango kernel starch-based coatings for roasted almonds.	-	Mango kernel starch-based coatings	Significant reduction in oxidation rate, extended shelf-life, improved sensory properties.	[76]
Blueberry residue	pH-sensitive films based on cassava starch and blueberry residue as pH change indicators.	-	Cassava starch matrix	Significant color change over pH range, potential for intelligent food packaging.	[9]
Coconut processing waste	Biodegradable nano-composite film based on cellulose, and PVA polymeric matrix, linseed/lemon oil nanofiber from coconut industry waste.	Linseed/ lemon oil, cellulose nanofiber	PVA polymeric matrix	Increased strength, elongation, biodegradability, improved antioxidant, antimicrobial properties.	[9]
Potato peels	Eco-friendly biodegradable PVA-based film integrated with cellulose nanoparticles from potato peel and fennel seed oil.	Cellulose nanoparticles, fennel seed oil	PVA matrix	Increased tensile strength, elongation, reduced oxygen transfer rate, improved antibacterial property, high free radical scavenging activity.	[77]

TECHNIQUES FOR VALORIZATION OF AGRICULTURAL WASTES TO SUSTAINABLE PACKAGING MATERIALS

The utilization of agrowaste into sustainable packaging materials is one step towards waste minimization and circular economy but the agrowaste that is gathered directly from the industries or agricultural fields is not fitting enough for fabrication of packaging materials. To address these inefficiencies, waste products need to undergo pretreatments to make them more suitable for valorisation [151]. Among the agricultural waste which contains both lignocellulosic and non lignocellulosic biomass , the lignocellulosic biomass offers more challenge when comes to its utilization owing to its recalcitrantce [14]. There is a considerable amount of lignocellulosic material in agro-industrial wastes produced during the processing of fruits, vegetables, and plant-based goods. Historically, food and agro-based wastes have been employed as compost to enrich soil nutrition for centuries. However, in recent decades, technologies have been developed to fully utilize these wastes' potential for small-scale, lucrative material production, including the creation of biopolymers [78].

For several crucial reasons, the pretreatment of agro-industrial waste is imperative for its utilization as sustainable packaging materials. Firstly, it assists in removing impurities inherently associated with agro-industrial waste, including soil, microbial contaminants, and non-target materials. Many agro-industrial wastes have large particle sizes and irregular shapes, necessitating size reduction. This could be done through pretreatment methods such as shredding or grinding to homogenize particle size distribution. Moreover, pretreatment augments the accessibility of valuable constituents within the waste, such as cellulose and hemicellulose, by breaking down their complex structures [78]. Furthermore, it aids in reducing inhibitory substances present in some agro-industrial wastes, like lignin derivatives or phenolic compounds, which may affect the functioning of the final packaging material. Lastly, pretreatment can optimize agro-industrial waste's chemical and physical properties, improving its compatibility with biopolymer matrices or enhancing its barrier properties, thus ensuring its suitability for packaging applications [79].

Lignocellulosic biomass could be employed for production of biopolymers via three main ways which include reuse from waste streams of industries like paper mill, biorefinery. The second way includes the extracting biopolymers directly from the waste like cellulose , hemicellulose, lignin and other polysaccharides. The third way employs utilization of biomonomers like sugars which could be generated from the disintegration of polysaccharides like cellulose [80]. Lignocellulose contains different extractives like resins, terpenes, and phenols and non-extractives like inorganic components such as carbonates, oxalates, starches, etc [81]. The role of extraneous materials in reducing cellulosic biomass conversion is usually overlooked because of their vast amounts and low concentrations. Pretreatment aims to weaken the material's resistant structure to facilitate lignocellulose conversion by enzymatic and microbiological processes. Jönsson and Martín [80] identified several critical parameters that impact biological conversion, such as cellulose's crystallinity, surface area accessibility, and protection of lignin and hemicellulose. However, correlating these parameters with enzymatic hydrolysis effectiveness is challenging, as changing one of the traits often affects the others, complicating the isolation of individual effects. Despite efforts, there's a lack of comprehensive techniques to examine the lignocellulose characteristics and their impact on biological degradation, which disturbs the understanding of influential factors for enzymatic hydrolysis [82]. Various techniques, as shown in Table 5 for the pretreatment of lignocellulosic biomasses, have been explored, focusing on enhancing enzymatic hydrolysis and fermentation efficiency. These techniques, categorized as physical, chemical, biological, or their combinations, demand to achieve significant product yields with the least enzyme loading or fermentation costs. Satisfactory aspects include the consumption of fewer chemicals, the potential for recycling chemicals, the least waste production, and limited size localization demands to minimize energy and expenses. Moreover, enhanced reactions and non-corrosive chemicals are desired to reduce reactor expenses while checking hemicellulose sugar concentrations stay more than 10%, facilitating downstream recovery and maintaining fermentation reactor size reasonably [83].

Various pretreatment techniques have been developed for lignocellulosic materials, each of which has its own set of pros and pros cons. Ionic liquid pretreatment effectively solubilizes phyto cellular walls at mild temperatures and allows for tunable characteristics. However, it has a strong tendency to denature enzymes, which is costly [84]. Supercritical CO_2 treatment enables transportation in solid, liquid, and gaseous forms, effectively enhancing cellulose hydrolysis instead of forming inhibitory compounds. Still, it needs higher pressure and does not change the lignin or hemicellulose contents [85]. Low-temperature steep delignification, or LTSD, requires a low feed of non-toxic chemical compounds, resulting in elevated conversion rates and yields at mild operating factors. However, it can produce toxic products and is expensive at the same time [86]. While co-solvent enhanced lignocellulosic fractionation (CELF) uses low boiling, renewable solvents to reduce biomass recalcitrance effectively, it also improves the yields of hydrocarbon fuel precursors and increases the digestibility of biomass. However, it also requires expensive solvents and may produce hazardous byproducts [87]. Each technique presents unique advantages and challenges while highlighting the necessity of carefully considering specific biomass characteristics and processing requirements. Some important treatment methods have also been discussed below.

Table 5. Techniques for pretreating biomass to facilitate the conversion of cellulose and hemicellulose into fermentable sugars.

Technique	Description	Ref.
Physical	*Mechanical milling/grinding*: Biomass is physically broken down into smaller particles using mechanical force.	[88]
	Size reduction: Reducing the size of biomass particles through techniques like milling or chopping.	[89]
	Steam explosion: Biomass is treated with high-pressure steam followed by rapid decompression, disrupting its structure.	[90]

	Ultrasonication: Application of high-frequency sound waves to disrupt the lignocellulosic structure.	[91]
Chemical	*Acid hydrolysis*: Treatment with strong acids (e.g., sulfuric acid) to break down hemicellulose and cellulose into monomeric sugars.	[92]
	Alkaline hydrolysis: Treatment with alkaline solutions (e.g., sodium hydroxide) to remove lignin and hemicellulose, facilitating cellulose accessibility.	[93]
	Ammonia fiber expansion (AFEX): Treatment with anhydrous liquid ammonia under high pressure and temperature to enhance biomass digestibility.	[94]
	Organosolv: Treatment with organic solvents (e.g., ethanol, methanol) at high temperatures to remove lignin and hemicellulose.	[95]
Physico-chemical	*Steam explosion followed by alkaline or acid treatment*: Combining physical and chemical methods for enhanced biomass delignification and saccharification.	[96]
	Hot water pretreatment: Biomass is treated with hot water under pressure to disrupt its structure and remove hemicellulose.	[97]
Biological	*Enzymatic hydrolysis*: Use of enzymes (e.g., cellulases, hemicellulases) to break down cellulose and hemicellulose into fermentable sugars.	[98]
	Fungal pretreatment: Treatment with fungi (e.g., white rot fungi) to selectively degrade lignin, making cellulose more accessible.	[99]
Electrical	*Electroporation*: Application of short electrical pulses to increase the permeability of biomass cell walls, aiding in chemical penetration.	[100]
	Microwave-assisted pretreatment: Use of microwaves to heat and disrupt lignocellulosic structures, enhancing subsequent chemical or enzymatic treatments.	[101]

Physical treatment

Physical pretreatment methods are used to reduce particle size for the enhancement of production efficiency as it increases the accessibility of the biomass to further treatment techniques. The physical treatments could be further classified into mechanical, irradiation, steam explosion, extrusion, and pulsed electric field pre-treatment. The mechanical pretreatment involves chipping, milling, and grinding among which milling and grinding are efficient in reducing the biomass size with reduced cellulose crystallinity [88]. The irradiation treatments with the help of ultrasonic waves, microwaves, gamma rays, and electron beams are also used to enhance the digestibility of cellulose, which makes the biomass more susceptible to the next pretreatment steps [50]. While less energy is needed for explosive pretreatments like steam explosions, their efficacy and scalability are restricted for specific biomass types [90]. Ultrasonic pretreatment is characterized by the generation of high-energy vibrations capable of penetrating and decomposing the crystals within the lignocellulosic structure. This process utilizes high-frequency, intense vibrations for extended durations. Studies have demonstrated the efficacy of ultrasonic pretreatment in removing 80–100% of lignin content from various sources, including coffee waste, fruit peels, and corn cob [102, 103]. Phyiscal treatments on their own are typically not sufficient for efficient biomass conversion to useable products therefore they are used alongside other pretreatments method. Fig. 1. illustrates the physical treatment method.

Chemical treatment

Chemical pretreatment is a that involves chemicals to change cellulose's crystalline structure, eliminate hemicelluloses, and modify lignin [104].

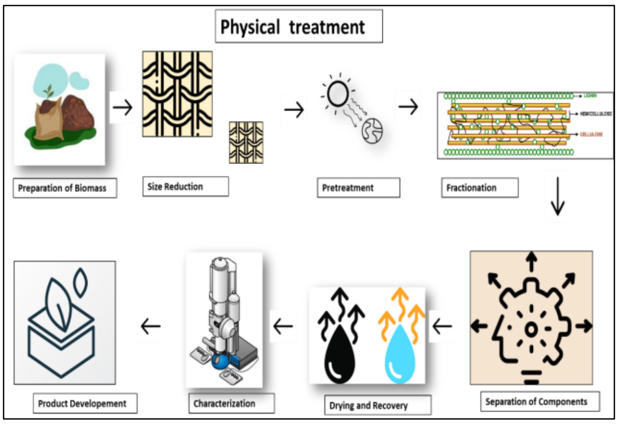

Fig. 1. Physical treatment method

Different chemicals in numerous reviews and chapter books, and pretreatment techniques have been thoroughly examined and contrasted, highlighting their importance in processing lignocellulosic biomass. Some pretreatment methods combine chemical and physical techniques, such as mechanical size reduction or explosion, to enhance their effectiveness (Fig. 2) [105]. The chemicals used for the pretreatment of biomass are organic or inorganic acids and alkalis, organic solvents, and ionic liquids. Acidic pretreatment is well suited for treating a variety of lignocellulosic biomass owing to the inherent capability of acids to hydrolyze the hemicellulose portion and disrupt the lignin content which in turn improves the extraction efficiency of cellulose [25]. A study [106] examined the potential of dilute sulfuric acid to extract cellulose, where they obtained 97% pure cellulose by using 0.5% sulfuric acid along with other steps like kraft pulping and bleaching. Alkali pretreatment, which dates back to at least 1919, involves applying alkaline solutions such as $Ca(OH)_2$, NaOH, or ammonia to modify the structure and composition of lignocelluloses [93]. These processes are particularly efficient for hardwoods and agricultural residues, leading to the removal or modification of lignin and hemicellulose and increased porosity [93]. Treatments with alkali can be divided into two categories: harsh and moderate. While moderate conditions make use of high NaOH concentration at ambient pressure and low temperatures, severe conditions require low NaOH concentration combined with high temperature and pressure. Dilute NaOH pretreatment efficacy varies across different materials, being higher for straws and lower for softwoods due to variations in lignin type and content [83]. A study by Lamo *et al*. [107] reported an increase of 33.36% in cellulose content (69.79%) extracted from chickpea husk by the use of alkali treatment using 0.084M NaOH at 70 °C. Combining alkali pretreatment with other methods, like dilute acid pretreatment or steam explosion, can significantly enhance enzymatic hydrolysis efficiency by synergistically targeting different components of lignocellulosic biomass. Alkali/oxidative mixtures also effectively remove lignin and improve enzymatic hydrolysis [108].

Thermochemical treatment

The thermochemical treatment of agriculture biomass waste is a crucial step in creating the raw materials required for synthesizing biopolymers since it enhances and converts the complex biomass, such as lignin and cellulose, from lignocellulosic biomass into simpler molecules that can act as building blocks for the synthesis of biopolymers

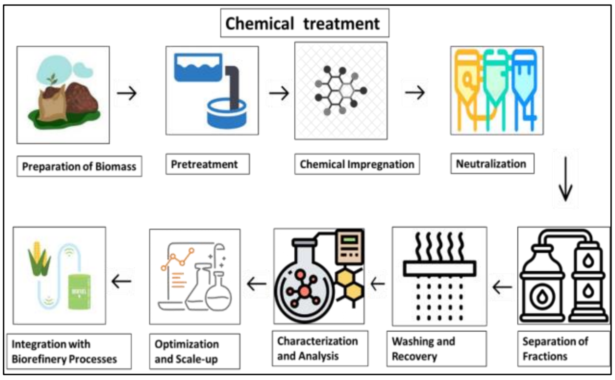

Fig. 2. Chemical treatment method

Various thermochemical techniques employ pyrolysis, gasification, hydro, thermal liquefaction, and hydrolysis to lyse these biomass components and extract value-added monomeric compounds suitable for biopolymer production [109]. Pyrolysis is a process that converts organic compounds into volatile gases, sticky liquids, and char by heating biomass in the absence of oxygen. Thus, the liquid fraction obtained from pyrolysis (biochar) contains several organic compounds like phenols, furans organic acids, and others. These compounds can act as preventive molecules for the synthesis of biodegradable polymers. For instance, furans derived from pyrolysis can be polymerized to synthesize poly ethylene furanoid (PEF), which is a biopolymer having similar properties to traditional petrochemical-derived polymer-polyethylene terephthalate (PET), which are used to manufacture plastic bottles boxes, etc. [110].

The gasification process involves turning biomass into synthetic gas, or "syngas", mainly composed of carbon monoxide, hydrogen, and methane. This gas can then be further processed by catalytic reactions to create other types of chemicals, such as alcohols, acids, and aldehydes. Chemicals can undergo polymerization reactions to produce biopolymers like poly-lactic acid, polyhydroxy-alkanoates, and polybutylene succinate [59].

Conversely, hydrothermal liquefaction entails treating biomass at elevated temperatures and pressures with water to decompose complex organic components into a fluid phase that contains soluble organic compounds such as sugars, phenols [111]. This liquid phase can then be recovered by processing to separate the monomeric units appropriate for synthesizing biopolymers. This technique offers the advantage of turning a wide range of biomass stock, including those with high moisture content, into a precautionary compound for biopolymer synthesis [111].

Hydrolysis is a technique to disintegrate the cellulose and hemicellulose intertwined inside the biomass into their subsequent sugar molecules in the presence of enzymes or strong acids. The resulting monomers of sugars like glucose and mannose can be fermented further by different microorganisms to synthesize chemicals, which can be further distilled to extract to the ethanol lactic acid succinic acid and

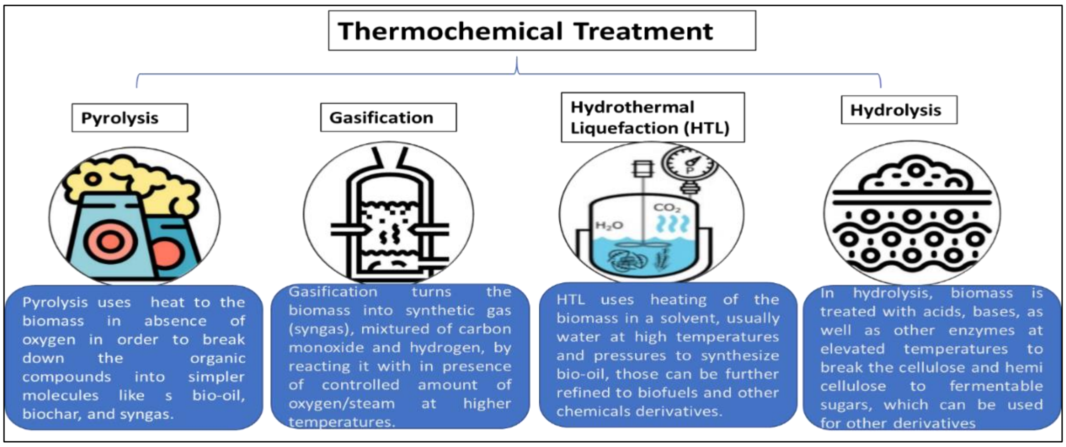

Fig 3. Thermochemical treatment method

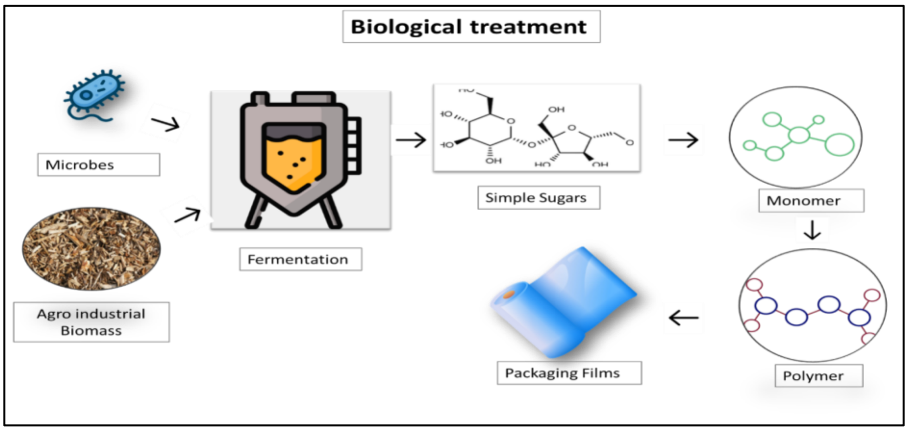

Fig. 4. Biological treatment method

other organic substances which serve as quicker molecules for the manufacturing of biopolymers [112]. The polymeric compounds extracted after the treatment of biomass using the various thermochemical methods can be polymerization reactions to synthesize biopolymers by different mechanisms. For example, monomers synthesized after hydrolysis can be condensed or polymerized to form polymeric change. This can be catalyzed by the action of enzymes or microbes that depend on specification according to the biopolymer synthesis root, resulting in the biopolymers possessing different properties like biodegradability, sustainability and biocompatibility which makes them which makes them suitable for tailoring into various applications, like packaging materials, textiles biochemical devices, and others (Fig. 3).

Biological treatment

Biological methods offer a range of techniques to transform agricultural waste into biodegradable packaging materials using biopolymers and biocomposites. One approach involves microbial fermentation, which converts agricultural waste into biopolymers like polyhydroxyalkanoates, polylactic acid, and polyhydroxybutyrate [113]. Enzymatic conversion breaks down complex compounds in agricultural waste into simpler building blocks, which can then be used to create biopolymers suitable for packaging. Biorefinery processes are also used to extract and purify various biopolymers and bioactive compounds from agricultural waste, which are then utilized in developing biodegradable packaging materials [114]. Additionally, biopolymer blending combines agricultural waste-derived biopolymers such as starch, cellulose, and proteins with synthetic biopolymers to produce biodegradable composite materials for packaging. These biological approaches add value to low-cost agricultural waste and address waste disposal issues, and the range of biopolymers available allows for customization of the final packaging product's properties.

Lignocellulosic biomass conversion (Fig. 4) into biopolymers involves several key stages. Firstly, microbial mediation, particularly by fungi like *Phanerochaete chrysosporium* and *Irpex lacteus*, is crucial in delignifying biomass such as corn stover, enhancing hydrolysis yield significantly [115]. Secondly, detoxification is essential to remove inhibitors generated during extreme pre-treatment conditions like acid hydrolysis, which hinder enzyme and microbial activity during fermentation; methods include alkali treatment, liquid-liquid extraction, and microbial approaches [116]. Thirdly, hydrolysis breaks down pretreated biomass into monomeric forms using acid or enzyme hydrolysis, with enzymes like cellulases and hemicellulases playing key roles. Fourthly, sugars released during hydrolysis into biopolymer can be fermented through separate or concurrent fermentation and saccharification methods, employing microorganisms like *Saccharomyces Cerevisiae* and *Zymomonas Mobilis.* Fifth, anaerobic digestion involves four stages: acidogenesis, hydrolysis, acetogenesis, and methanogenesis, yielding biogas predominantly composed of methane and carbon dioxide [117]. Lastly, dark fermentation offers an effective means of producing hydrogen from organic wastes through anaerobic degradation processes, providing a possible path toward producing sustainable energy. Additionally, transesterification emerges as a critical step in biodiesel production, converting triglycerides into methyl or ethyl esters, albeit challenged by the existence of free fatty acids in the oil, necessitating pre-treatment in some cases.

Biochemical treatment

Agro-industrial waste can be converted into biodegradable packaging materials using enzymes and microorganisms in a biochemical pretreatment process that adheres to the circular economy's core values. One of the most critical steps in treating these lignocellulosic agro-industrial leftovers is to break down their structure, mostly cellulose, hemicellulose, and lignin. Biological (enzymatic) pretreatment can aid in delignification, bleaching, and the creation of animal feed. It involves microorganisms and their enzymes, such as phytase, laccase, lignin peroxidase (LiP), and manganese peroxidase (MnP) [118].

These bacteria produce enzymes that may specifically break down lignin and hemicellulose, making cellulose more accessible for subsequent processing. Agro-industrial residues can be further valued by combining biological pretreatment with other techniques, such as physical and chemical pretreatments, as this can have a synergistic effect [98]. In line with the circular economy's tenets, biodegradable packaging materials can be made from the cellulose and other carbohydrates recovered from the processed agro-industrial leftovers [119]. Biochemical pretreatment methods, particularly deep eutectic solvents (DES), have demonstrated significant potential in enhancing the conversion of these residues into fermentable sugars. DES pretreatment stands out for its biodegradability, ease of preparation, and operation under milder conditions. Optimal conditions for DES pretreatment involve a biomass-to-solvent ratio of 1:16 with choline chloride-glycerol for 3 hours at 115°C, yielding high sugar content after hydrolysis [119]. Combining DES pretreatment with enzymatic hydrolysis further enhances the breakdown of lignocellulosic components, releasing valuable sugars suitable for biobased materials like biodegradable packaging. These pretreatment techniques align with circular economy principles by repurposing refuse into priceless resources, thus contributing to waste reduction and sustainable packaging solutions.

Enzymatic treatment

Enzymatic pretreatment stands as a valuable technique for transforming agricultural and industrial lignocellulosic wastes into biodegradable packaging materials, leveraging their rich content of cellulose and hemicellulose that can be broken down by specific enzymes such as cellulases, hemicellulases, and ligninases [120]. This process entails several critical steps to effectively convert agro-industrial waste into biodegradable packaging. Initially, the selection of enzymes like hemicellulases, cellulases, and ligninases is meticulously done to ensure they efficiently break down waste components such as cellulose, hemicellulose, and lignin. Subsequently, the waste undergoes enzymatic treatment through techniques like soaking, spraying, or mixing with water. Following this treatment, the waste is incubated under controlled conditions of temperature, pH, and moisture to allow the enzymes to decompose the materials over a variable timeframe ranging from hours to days. The resulting decomposed parts are then processed using methods like injection molding, extrusion, or 3D printing to fabricate diverse biodegradable packaging materials such as sheets, films, or containers suitable for packaging a wide array of products. This enzymatic action not only enhances waste accessibility and digestibility but also prepares it for subsequent bioconversion processes (Fig. 5).

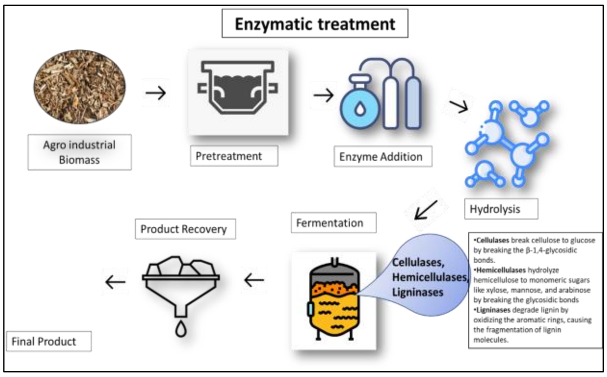

Fig. 5. Enzymatic treatment method

In contrast to harsh chemical treatments, enzymatic approaches offer a more environmentally friendly pathway and can even derive enzymes from agro-industrial waste through microbial fermentation, thus establishing a sustainable closed-loop system [121]. By transforming complex agricultural waste into simpler constituents, this enzymatic pretreatment method provides raw materials for various biodegradable polymers and packaging products, effectively addressing waste disposal challenges while creating value-added sustainable goods [121]. Enzymatic treatments utilize enzymes from diverse sources, including biological, biochemical, or chemical, to modify the molecular properties of lignocellulosic biomass [120]. This involves breaking down different bonds like hydrogen and covalent bonds to yield biomass derivatives suitable for biopolymer production.

Table 6. The enzymes that convert biomass components including cellulose, hemicellulose, and pectin into fermentable sugars are included in the table along with their uses in the food, textile, and bioenergy industries.

Biomass Component	Enzymes involved	Applications	Ref.
Cellulose	Endoglucanases, cellobiohydrolases, -glucosidases	Bioconversion into fermentable sugars, bioenergy production	[122]
Hemicellulose	Endo-1,4-xylanase, -L-arabinofuranosidase, -glucuronidase, -mannanase, -mannosidase	Fermentable sugar production, poultry feed additives, wheat flour improvement	[120]
Pectin	Pectin depolymerase, pectinase, polymethylgalacturonase, (endo-) polygalacturonase, exopolygalacturonase, exopolygalacturanosidase, polysaccharide lyases, endo-arabinase, -L-rhamnosidases, and -L-arabinofuranosidases	Textile industry, food industry, sugar conversion to biogas, ethanol, and soluble carbohydrates.	[123]

Table 7. Variables affecting lignocellulosic bioconversion.

Factor	Description	Ref.
Physical factors		
pH	pH significantly affects cellulase production and activity. The optimal pH for cellulase production varies depending on the organism and enzyme type, ranging from pH 5.5 to 7.5. Cellulase release from cells and enzyme adsorption behavior are also influenced by pH.	[125]

Temperature	Temperature greatly impacts lignocellulosic bioconversion. Cellulase activities are generally assayed within 50–65 °C, while microbial growth temperature ranges from 25–30 °C. Thermophilic fungi may produce cellulase with optimal activity between 50–78 °C. Temperature also affects enzyme adsorption and activity, with increased adsorption at temperatures below 60 °C b ut decreased activity beyond 60 °C.	[124]
Chemical factors		
Carbon source	Various cellulosic materials and industrial wastes serve as carbon sources for cellulase production. The choice of substrate affects cellulase production levels, with some substrates leading to higher enzymatic yields. The concentration of the carbon source can impact production levels, with optimal concentrations observed up to 12%.	[128]
Nitrogen source	Different nitrogen sources affect cellulase production differently. Ammonium sulfate is reported to lead to maximum cellulase production, while other nitrogen sources may either enhance or inhibit enzyme levels depending on the organism and conditions.	[129]
Phosphorus sources	Phosphorus is essential for fungal growth and metabolism. Potassium dihydrogen phosphate is typically the preferred phosphorus source for cellulase production.	[130]
Phenolic compounds	Phenolic compounds can induce or inhibit cellulase synthesis depending on the type and concentration. Salicylic acid has been identified as a potent inducer of cellulases, while other phenolic compounds may exhibit inhibitory effects.	[131]
Adsorption–Desorption of Cellulose	Cellulase adsorption onto cellulose substrates is a critical step in cellulose hydrolysis. Factors such as pH, temperature, and surface area influence the extent of adsorption and subsequent enzymatic hydrolysis. Understanding the adsorption behavior of cellulases is essential for optimizing bioconversion processes.	[132]
Biotechnological aspects of lignocellulose bioconversion		103
Co-cultivation	Co-cultivation of cellulolytic organisms has been explored to increase enzymatic levels and improve lignocellulosic bioconversion rates. Synergistic interactions between different microbial strains can enhance overall cellulase production and activity.	133
Mutagenesis	Mutagenic treatments have been employed to increase cellulolytic activity in microbial strains. Mutants with higher cellulolytic activity have been generated through physical and chemical mutagens, leading to enhanced enzymatic yields.	134
Genetic Manipulation	Recombinant DNA technology offers opportunities for enhancing cellulase production and activity through genetic engineering. By manipulating metabolic pathways and gene expression, microbial strains can be engineered to produce higher levels of cellulases with improved properties. Cloning and expression of cellulolytic genes in	135

	heterologous hosts allow for the production of designer enzymes tailored for specific applications.	
Limitations of lignocellulose bioconversion		
Crystallinity of Cellulose	Cellulose crystallinity affects its susceptibility to enzymatic degradation, with crystalline regions being more resistant to hydrolysis. Mechanical and chemical pretreatments are employed to reduce crystallinity and enhance bioconversion efficiency.	[136]
Pretreatment	Effective lignocellulose utilization requires pretreatment to overcome its crystalline unreactivity and resistance to hydrolysis. Various physical and chemical pretreatment methods have been explored, each with its advantages and limitations. Biological delignification is an alternative pretreatment method utilizing white rot fungi to selectively degrade lignin.	[137]

Notably, enzymes such as cellulase, hemicellulase, and ligninase are commonly employed in treating lignocellulosic biomass waste from agricultural, food, and agro-industrial sectors [102].

Factors affecting cellulosic bioconversion

Many factors influence the process of converting lignocellulosic biomass into valuable products, categorized as physical, chemical, and biotechnological [124]. Physical factors (table 7) such as pH and temperature significantly impact the production and activity of cellulase enzymes. However, the optimal conditions for these factors vary depending on the organism and enzyme type [125]. Chemical factors like carbon, nitrogen, phosphorus sources, phenolic compounds, and sugars also play crucial roles in regulating cellulase synthesis and activity. The crystallinity of cellulose is a critical limitation in lignocellulose bioconversion, which affects enzymatic degradation and requires pretreatment methods to enhance efficiency [124]. Another crucial aspect influencing enzymatic hydrolysis is the adsorption-desorption of cellulase onto substrates. Biotechnological aspects of lignocellulose bioconversion involve various strategies, such as the co-cultivation of cellulolytic organisms to enhance enzymatic levels and improve conversion rates [126]. Mutagenesis and genetic manipulation techniques increase cellulolytic activity in microbial strains, enhancing enzymatic yields. Recombinant DNA technology offers opportunities for engineering microbial strains to produce higher levels of cellulases with improved properties tailored for specific applications [127]. Thus, understanding and optimizing these factors are essential for efficient and sustainable lignocellulosic biomass conversion processes.

AGRO-FOOD WASTE CONVERSION TECHNIQUES FOR SUSTAINABLE FOOD PACKAGING

Solvent casting

Solvent casting (Fig. 6) is a process that is used to produce thin films or coatings by solubilizing polymers or biopolymers sourced from agro-food waste in an appropriate solvent and then by casting the solution onto a substrate and letting the solvent evaporate [138]. This technique results in the making of a solid film with desired qualities. Solvent casting is beneficial for incorporating lignocellulosic materials into packaging materials. Agro-food waste-derived polymers, such as cellulose or starch, can be dissolved in eco-friendly solvents such as water or organic acids to synthesize biodegradable films or coatings for food-grade packaging [139].

The "tape casting" process involves applying a slurry or suspension to a moving carrier substrate, allowing it to dry, and then peeling off the resulting tape to create thin, flat sheets of ceramic or polymeric materials (Fig. 7.) [140].

Tape casting can be modified to include lignocellulosic compounds into thin films or membranes for specific food packaging applications needing barrier characteristics or selective permeability, even if the technique is less frequently utilized for materials obtained from agro-food waste [141].

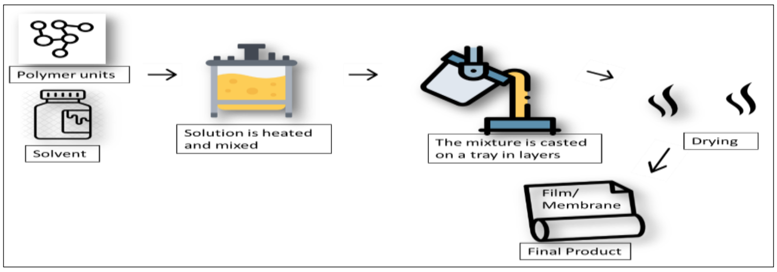

Fig. 6. Solvent casting

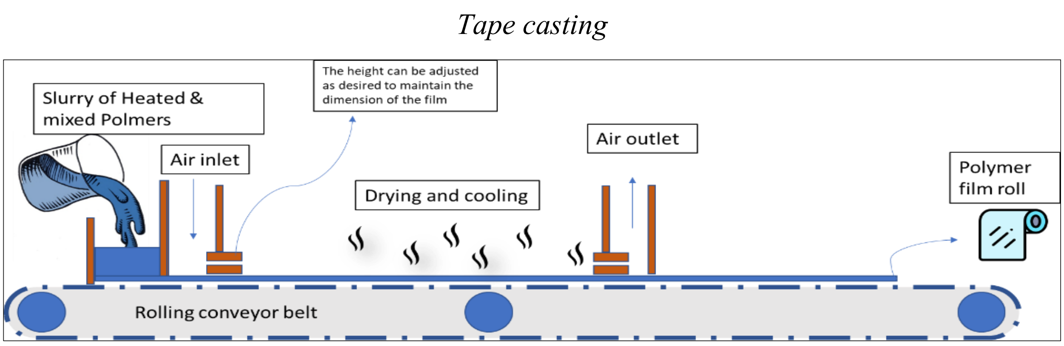

Fig. 7. Tape casting

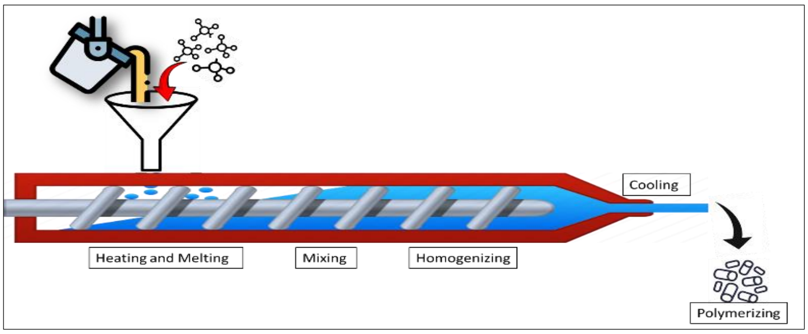

Fig. 8. Melt extrusion

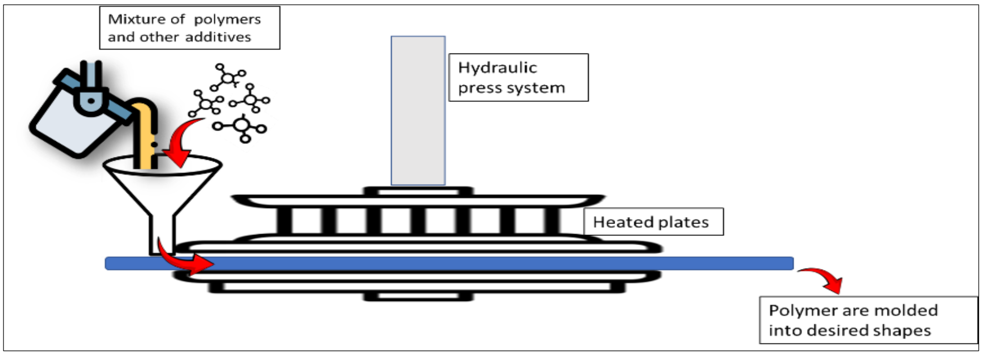

Fig. 9. Thermopressing

Melt extrusion

Polymer resins, including those made from agro-food waste, are heated and melted during the melt extrusion process, after which the molten material is forced through a die to form a continuous profile or shape (Fig. 8.) [140] Melt extrusion is a method that can be applied to sustainable food packaging to produce rigid or flexible packaging materials from biopolymers obtained from sources of agro-food waste, such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA). Melt extrusion combines biopolymers and lignocellulosic fillers to increase mechanical strength and reduce the cost of sustainable packaging materials [50].

Thermopressing/thermoforming

A thermoplastic substance (Fig. 9.), such as biopolymers generated from agro-food waste, is heated to a malleable condition and then shaped using molds or dies in a process known as thermopressing or thermoforming. A diversity of packaging products, such as clamshell packaging, containers, and trays, can be generated using this procedure. Food packaging applications can benefit from the lightweight, robust, and compostable packaging solutions that thermoforming can produce using lignocellulosic chemicals as reinforcements or fillers in thermoplastic matrices [140].

Compression molding

A predetermined molding compound, which may include lignocellulosic biopolymers and fillers obtained from agro-food waste, is put into a heated mold cavity and crushed under high pressure until it takes on the required shape during the compression molding manufacturing process. This method works well for creating bulkier packaging products from sustainable materials sourced from agricultural waste, like bottle caps or lids [142].

Layer-by-layer (LBL) assembly

Layer-by-layer assembly entails depositing alternating layers of negatively and positively charged polymers or nanoparticles onto a substrate to create a multilayered thin film structure. LBL assembly can be modified to include lignocellulosic compounds into nanocomposite films or coatings with customized barrier qualities for food packaging applications needing exact control over film structure and properties, even if it is less prevalent in agro-food waste conversion procedures [143, 152].

Electrospinning/electrospraying

Using high voltage on a polymer solution or suspension causes it to form a tiny jet or mist that hardens into fibers or particles as it moves toward a collection substrate. This process is known as electrospinning or electrospraying. These methods can be used to generate nanocomposite materials for food packaging applications (Fig. 10). These materials have lignocellulosic compounds mixed into a polymer matrix to increase antibacterial activity, mechanical strength, and barrier properties [144].

+*Blow molding*

Blow molding technology creates hollow plastic containers using agricultural and food waste-derived polymers. The idea is to extrude a molten polymer material into a parison, or hollow tube, and then use compressed air to inflate it into the shape of a mold [145]. Blow molding makes it possible to create robust and lightweight packaging items like jerry cans, jars, and bottles out of sustainable materials from agro-food waste sources. The mechanical qualities and environmental sustainability of blow-molded packaging items are improved by integrating lignocellulosic substances into the polymer matrix [142].

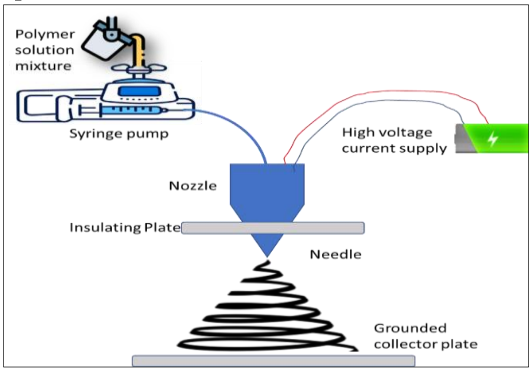

Fig. 10. Electrospinning

Blown and cast film extrusion

Polymers from agro-food waste can be made into thin films or sheets using blown and cast film extrusion methods. While molten polymer is extruded via a flat die onto a cooled roller to make a thin sheet in cast film extrusion, molten polymer is inflated into a tube to form a thin film in blown film extrusion [146]. These procedures make it possible to produce barrier and flexible films for various uses in food packaging. Both blown and cast film extrusion can provide sustainable packaging materials with better mechanical and environmental performance by adding lignocellulosic chemicals from sources of agro-food waste [147].

MAXIMIZING THE POTENTIAL OF AGRO-INDUSTRIAL WASTE FOR SUSTAINABLE SOLUTIONS

Globally, a substantial amount of agro-industrial waste (AIW) and agricultural waste (ACW) is produced annually, amounting to about 89 million tonnes of biomass and 147.2 million metric tonnes of fiber sources. With disposal prices in Europe ranging from $28 to $60 per tonne, this waste comes from all stages of agricultural production, post-harvest activities, and processing and presents significant environmental and economic difficulties[148]. Therefore, there is a growing urgency to efficiently utilize and valorize AIW, tapping into its health and functional potential. Traditional methods like composting and livestock feeding have been employed but yield products with limited added value. However, there is increasing interest in exploring advanced valorization strategies to create new high-value AIW products. This shift towards advanced valorization aligns with changing perceptions of agro-industries, which are now valued for productivity and environmental stewardship.

Many agro-industries seek to reduce waste volumes and minimize landfill disposal, promoting responsible waste management practices and aligning with sustainability objectives [149]. Innovative valorization strategies for AIW not only offer economic advantages but also contribute to environmental conservation and sustainable development goals. Extraction of bioactive chemicals from AIW is one area that shows promise for developing value-added goods that may have health advantages. However, challenges persist in recycling efforts, particularly concerning plastics. Despite the potential to recover a significant portion of plastic in household waste, the recycling rate remains low due to sorting complexities, limited recycling technologies, and degradation during processing. Moreover, various polymer types and additives complicate sorting, leading to high collection and sorting costs [150]. Transitioning towards a “circular economy model” where materials are continuously reused faces hurdles related to high entropy and the necessity for effective sorting methods. While thermo-mechanical recycling is feasible for certain plastics, it results in properties that are inferior to virgin polymers. Chemical recycling shows promise but has yet to be economically viable. Although suitable for composting, biodegradable polymers present challenges in conventional recycling due to their degradation characteristics [150].

RECENT CHALLENGES AND FUTURE PRESPECTIVES

The production of packaging materials from agro-industrial waste presents numerous challenges that must be addressed. These challenges include developing cost-effective extraction technologies, ensuring material quality that matches typical plastics, establishing recycling standards, managing end-of-life disposal for biodegradable materials, and overcoming market acceptance barriers. Technical issues like safety compliance, material consistency, and scalability are critical in the food sector. Factors such as consumer acceptance and waste management must be carefully considered. To be successful in this endeavor, a holistic approach is needed that encompasses research, regulatory alignment, and efficient manufacturing and waste management practices. The circular economy plays a crucial role as it advocates for the reuse and recycling of agricultural resources, including waste and byproducts. By transforming waste into valuable inputs for new products, the circular economy can reduce emissions, lower resource demand, enhance resource efficiency, and promote sustainability in the agricultural sector.

Utilizing agro-industrial waste to create biodegradable food packaging materials, bioplastic packaging, trays, composite films, and edible coatings presents a sustainable packaging solution within the food industry. Advances in waste treatment and conversion technologies further bolster the feasibility and efficiency of bio-based package manufacturing. However, challenges such as limited consumer awareness and acceptability, inadequate waste collection and processing infrastructure, and technological waste treatment limitations require strategic planning and collaboration across the supply chain. Despite these obstacles, the outlook for agro-industrial waste-based packaging is optimistic, focusing on sustainability, innovation, and reduced environmental impact. Industries can adopt more eco-friendly practices by leveraging agro-waste as a valuable resource for packaging, thereby contributing to a circular economy and minimizing waste output. The potential of biodegradable food packaging materials, bioplastic packaging, trays, composite films, and edible coatings derived from agro-industrial waste underscores the diverse and sustainable packaging solutions. Continued advancements in waste treatment and conversion technologies will further drive the adoption of agro-waste-based packaging materials, enhancing the efficiency and practicality of bio-based package manufacturing in the future.

CONCLUSION

Utilizing sustainable packaging derived from agricultural and industrial waste is a significant step towards addressing environmental concerns associated with conventional plastic packaging. Advancements in technology and research have allowed agro-waste to be transformed into value-added products such as bioplastics, edible films, and coatings that demonstrate comparable or superior performance to traditional materials. These sustainable alternatives offer biodegradability, reduced environmental impact, favorable mechanical properties, and barrier functionalities. They align with global sustainability objectives, circular economy principles, and the transition towards a more environmentally conscious packaging industry. In the food sector, adopting biodegradable food packaging materials, bioplastic packaging, trays, composite films, and edible coatings derived from agro-industrial waste promises a sustainable packaging solution. Improvements in waste treatment and conversion technologies will drive the efficiency of bio-based package manufacturing.

Despite challenges like consumer awareness, limited waste infrastructure, and technological constraints, strategic planning, improved waste management practices, infrastructure investment, and technological breakthroughs are pivotal for progress. The future of agro-industrial waste-based packaging appears promising, offering opportunities to embrace more eco-friendly practices, reduce waste output, and cultivate a sustainable food system. The environmental benefits, including reduced plastic waste, lower carbon emissions, resource preservation, biodegradability, circular economy promotion, deforestation reduction, and consumer empowerment, underscore the positive impact of agro-waste-based packaging on sustainability goals and environmental conservation efforts.

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Fortification of refractance window-dried *Curcuma longa* powder and its associated characterization

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Curcuma longa powder was prepared by refractance window (RW) drying and was fortified. Dried turmeric powder was fortified with folic acid and NaFeEDTA. The fortified turmeric powder was studied for its physical characteristics, such as bulk density, swelling power, solubility, dispersion time, hygroscopicity, water binding capacity, and color. The study revealed novel physical characteristics for dried turmeric powder, folic acid-, and NaFeEDTA-fortified with low hygroscopicity (8 - 9%), good solubility (28 - 30%), and good swelling power (1.8 - 2.0). The findings confirmed the insignificant influence of fortification on the desired properties of the folic acid- and NaFeEDTA-fortified RW dried turmeric powder product. Thus, it can be concluded that the fortified turmeric powder had good stability. This stable fortified turmeric powder can be effectively incorporated into various food systems, such as milk, instant turmeric latte powder, and health drinks, to enhance their nutritional profiles.

Keywords: refractance window drying, turmeric, fortification, folic acid, NaFeEDTA

INTRODUCTION

Vitamin and mineral deficiencies cause learning disabilities, mental retardation, low work capacity, blindness and even premature death. To overcome these issues, food fortification has been the best choice in comparison with pharmaceutical supplements. Fortification of food products involves enhancing essential micronutrients such as vitamins, minerals, and trace elements in foods. Thereby, multiple mineral deficiencies can be addressed to enhance health benefits without potential health risks. Cereals, flour, rice, and milk are often fortified to reduce deficiencies. Fortification also has potential challenges in terms of bioavailability of added nutrients, unacceptable organoleptic changes, and subsequent rejection of a developed product by the consumers and targeted population [1].

Three most common micronutrient malnutritions have been identified for human beings. These are iron, iodine, and vitamin A [2]. The micronutrient folate received significant global attention [3] due to its critical ability to address and mitigate issues associated with early embryonic brain development, malformation of the embryonic brain and spinal cord or neural tube diseases [4]. With 79 % of children between 6 – 35 months and women between 15 – 49 years of age being anaemic in India [5], iron deficiency has been opined due to the consumption of foods with lower bio-availability of iron. Thus, iron-fortified product research needs greater emphasis [6].

The influence of fortificants on mineral-fortified dried products is often targeted through associated studies. In a related prior art, the authors fortified Nepalese curry powder with alternate iron compounds [7]. Also, whole wheat flour fortified with a premix of ferrous sulfate, ethylenediamine tetra-acetic acid (EDTA) and folic acid was reported [8, 9].

Previous studies reported the fortification of salt with folic acid, iron, and iodine [5, 10] and the fortification of chickpea seeds and flour using ferrous sulfate heptahydrate, ferrous sulfate mono-hydrate and NaFeEDTA fortificants [11]. Similarly, researchers deployed finger millet and sorghum flours as double fortification vehicles with ferrous fumarate, zinc stearate and EDTA [12].

Till date, the parametric optimality of refractance window drying (RWD) process was targeted for vegetables such as carrots, onions, etc. [13, 14]. These vegetable powders were not studied for fortification and for a comparison of associated characteristics. In such investigations, physical characteristics (solubility, swelling time, hygroscopicity, dispersion time, water binding capacity, bulk density and color) are often targeted for the fortified and unfortified dried powder products. To date, no study has been devoted to the turmeric powder product system.

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Such investigations can provide useful insights into the role of fortification in altering these properties.

Considering the above-cited lacunae, the current research addresses the fortification of RW-dried turmeric powder with folic acid and NaFeEDTA and its characterization studies.

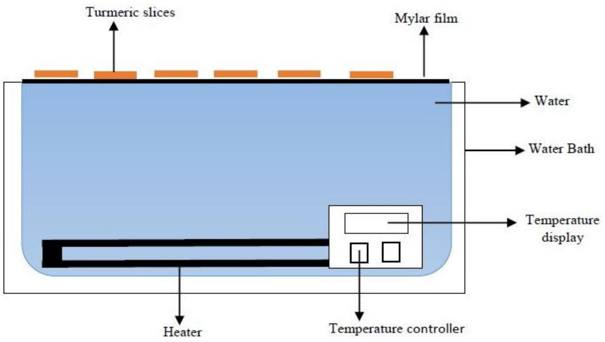

Fig.1. Schematic representation of refractance window drying process of turmeric

MATERIALS AND METHODS

Raw materials, chemicals and sample preparation

Turmeric was procured from the market complex, Indian Institute of Technology Guwahati, Kamrup, Assam, India and was packed in a polythene pouch to prevent contamination during its transportation. Sodium ferric ethylenediamine tetraacetate (NaFeEDTA), folic acid, potassium bromide, enzymes and other chemicals were obtained from Sigma Aldrich India. Subsequently, the procured raw turmeric was washed with tap water to remove surface contaminants and dirt. The sample was then wiped with tissue paper to remove excess water. Thereafter, the wiped turmeric was peeled. Eventually, using an adjustable slicer, the peeled turmeric was sliced to achieve sample pieces with 1 mm thickness.

Refractance window drying

The refractance window drying (RWD) experiments were conducted with optimal combinations of sample thickness, mylar film thickness, temperature, air velocity and drying time that were achieved with prior experimental investigations [15]. RSM was carried out to determine the drying parameters. From the modeling it was obtained that the optimal data set for RSM was found to be 95°C drying temperature, 75 min drying time and 0.76 m/s air velocity for optimal response characteristics of 90.52 % (AA), 188.22 mg GAE/g dry sample (TPC), 158.65 mg quercetin/g dry sample (TFC), 4.80 % w/w (CC), 3.67 % (MC) and 54.87 L values (color indices). In summary, RWD turmeric samples can be characterized with better retention of nutritional characteristics within these drying parameters. Thereafter, the dried samples were powdered using a dry portable electric grinder. Eventually, samples sieved through an 80-mesh sieve were obtained that possessed an average particle size of 0.177 mm [16].

Fortification with sodium ferric ethylenediamine tetraacetate and folic acid

The process for fortification of RW-dried turmeric powder was developed with slight modifications from the previous studies [5, 7, 9, 12]. The RDA for folic the acid is 400 µg/day for both men and women but 600 µg /day for pregnant women [9]. The RDA of iron varies with age of the person and is 15 - 18 mg/day for women, 27 mg/day for pregnant women, 11 – 8 mg/day for men and 8 mg/day for senior citizen [5, 9]. It was difficult to conclude upon a precise amount of NaFeEDTA and folic acid from literature review, leading to selection of a higher amount (20 g). The same amounts of NaFeEDTA and folic acid were taken for fortification to assist the effective comparison of the influence of NaFeEDTA and folic acid on the fortification characteristics of the turmeric powder. Therefore, 100 g of RW-dried turmeric powder was mixed with 20 mg of NaFeEDTA or 20 mg of folic acid to eventually achieve iron and folic acid-fortified turmeric powder samples. For both cases, dry mixing using a spatula was performed.

Characterization of refractance window-dried Curcuma longa powder products

For RW-dried turmeric powder, folic acid-fortified and NaFeEDTA-fortified turmeric powder samples, characterization was addressed in terms of associated parameters such as bulk density, solubility, swelling power, water binding capacity, dispersion time, hygroscopicity and color. A brief account of adopted procedures is as follows.

- *Bulk density.* To measure the bulk density of RW dried turmeric powder, folic acid fortified and NaFeEDTA fortified turmeric powder samples bulk density, 5 g of turmeric powder was placed into a measuring cylinder of 10 mL. The volume occupied by the turmeric powder in the cylinder was recorded, and the bulk density was calculated using the ratio of the weight to the volume of the turmeric powder sample [17].
- *Solubility & swelling power.* The solubility of the RW dried turmeric powder, folic acid fortified and NaFeEDTA fortified turmeric powder samples was determined by mixing 1 g of turmeric powder sample with 100 mL of distilled water at ambient temperature and mixing using Tarsons magnetic stirrer operated at 600 rpm for 5 min. Thereafter, the mixture was centrifuged at 3000 G for 5 min.

Thereby, 20 mL of the obtained supernatant was decanted to a pre-weighed petri dish and dried at 70°C until constant weight of the system was achieved. Subsequently, percent solubility was determined in terms of the weight difference between the processed petri dish sample and the empty petri dish system. Solubility was evaluated using the expression:

$$\text{Solubility (\%)} = \frac{W_d}{W_s} \times 100 \quad (1)$$

The swelling power was calculated using the following expression:

$$\text{Swelling power (g/g)} = \frac{W_{sd}}{W_s} \quad (2)$$

In the above expressions, W_s, W_d and W_{sd} are the weights of original sample, dried residue and dried sediment mass, respectively [17].

- *Water binding capacity.* Using the following method, the water binding capacity (WBC) of RW dried turmeric powder, folic acid fortified and NaFeEDTA fortified turmeric powder samples were measured. Firstly, 5 g of turmeric powder was mixed with 75 mL of distilled water. Thereby, the system was agitated at 860 rpm and 20 °C for one h. Thereafter, the sample was centrifuged at 3000 G for 10 min. Subsequently, the supernatant was removed, drained for 10 min and weighed. WBC was evaluated using the expression:

$$\text{WBC (\%)} = \frac{M_w - M_d}{M_d} \times 100 \quad (3)$$

where, M_w and M_d are the wet weight (g) and dry weight basis of the powder (g), respectively [18].

- *Dispersion time.* The dispersion time was determined through the following procedure. Firstly, 80 mL of distilled water was transferred into a 100 mL beaker and was kept in an ambient environment (27°C). Thereby, 1 g of the powder sample was placed in a slider that separated the powder and liquid surface. The dispersion time measurement started at the very instance that corresponds to the powder sample and liquid being brought into contact through the quick removal of the slider that separated the powder and liquid. Thereby, the time was measured for the complete spontaneous wetting and immersion of the 1 g powder [19].

- *Hygroscopicity.* The hygroscopicity of the sample was determined by following the procedure summarized in [17]. According to the authors, hygroscopicity can be expressed in terms of the moisture mass (g) being absorbed by 100 g of sample during 7 days of storage at 25°C and 92 % relative humidity. To achieve these conditions, a desiccator with a saturated Na_2SO_4 solution was arranged. Thereby, 1 g of the sample was weighed in a petri dish and was transferred into a desiccator for mentioned time period (7 days). Subsequently, hygroscopicity was determined using the expression:

$$Hygroscopicity(\%) = \frac{\frac{x}{a_h + W_i}}{1 + \frac{x}{a_h}} \times 100 \quad (4)$$

where x corresponds to the enhancement in powder sample (g), a_h corresponds to the powder sample amount used for the measurement (g), and W_i refers to the water content of the powder exposed to the humid environment [20].

- *Color indices.* The color indices of both fresh and dried samples were determined using a colorimeter (Data color, Model: 250) set up (*L, a, b*) [20]. For each case, measurements of *L*, *a* and *b* were conducted at three different sample spots. Thereby, the data were reported as the mean of these three measurements.

RESULTS AND DISCUSSION

Bulk density

Bulk density is an important characteristic of the storage, transportation and packaging of powder products. Hence, it was assessed for various dried samples. The bulk density of the RWD-processed turmeric powder was obtained as 0.62 g/mL. Incidentally, the turmeric powder fortified with folic acid and NaFeEDTA possessed bulk density in the range of 0.64 – 0.65 g/mL (Table 1). Thus, it can be stated that the density did not vary with the addition of fortificants, and the trends were comparable to those reported in the relevant prior art.

Table 1. Bulk density data of unfortified and fortified turmeric powder products.

S. No.	Samples	Bulk density (g/ml)
1.	Unfortified	0.62
2.	Folic acid fortified	0.65
3.	NaFeEDTA fortified	0.64

Note: All standard deviations were in the range of 0.05 – 0.1.

Constant and falling rate drying mechanisms occur sequentially during the drying of food samples. Thus, during constant drying phase, higher drying temperatures translate into higher initial drying rates. Thereafter, the drying rate gets controlled due to moisture diffusion from the internal portion of the sample to its surface. Deploying higher temperatures during drying can form a hard and moisture-resistant crust at the surface that eventually prevents further loss of moisture. The formation of such a crust generally results in higher bulk density. In summary, the higher bulk density of the RW-dried samples is possibly due to the formation of moisture-resistant crust [17].

Hygroscopicity

Hygroscopicity, like solubility, is a very important parameter of dehydrated products and has a definite role in influencing their shelf-life characteristics. Lower hygroscopicity is desired to achieve chemical and microbiological stability in due course of the long-term storage of a food sample. For RW-processed turmeric, NaFeEDTA and folic-fortified processed turmeric powder samples, lower hygroscopicity values have been obtained as 8.70 %, 8.80 % and 8.50 %, respectively (Table 2). Hence, the addition of fortificants did not significantly alter the hygroscopicity property of the turmeric powder sample.

Table 2. Hygroscopicity data of unfortified and fortified turmeric powder products.

S. No.	Sample	Hygroscopicity (%)
1.	Unfortified	8.70
2.	Folic acid fortified	8.80
3.	NaFeEDTA fortified	8.50

Note: All standard deviations were in the range of 0.1 – 0.3.

The low hygroscopicity could be due to the formation of dense structures that tend to reduce the intake of water into the cells. The formation of dense structures is due to the fast drying during RWD process [21]. Also, the lower hygroscopicity of turmeric is due to its lower sugar content. The fortificants, namely folic acid and NaFeEDTA, were also stable and had a lower affinity to water vapor. Thus, the fortified turmeric samples powder also possessed lower hygroscopicity. In the literature, similar results have been reported for RW and freeze-dried yoghurt samples. The reported values were lower than those obtained for the food powders and could be due to the lower sugar content in the yoghurt [17]. The hygroscopic properties of a powder play a vital role in determining its chemical stability and influence its flow characteristics. Hygroscopic substances typically exhibit poor flowability, leading to issues with weight variation. Moisture present in cohesive materials can create solid and liquid bridges between particles, ultimately resulting in hard cake formation. Additionally, the stickiness of hygroscopic compounds can complicate the compaction process, causing problems such as picking and sticking. Elevated moisture levels often lead to particle agglomeration. In contrast, powders with low hygroscopicity and anti-caking properties facilitate easier mixing, agglomeration, or tableting, which can contribute to reducing packaging costs [17].

Solubility and swelling power

This parameter is attained after the powder undergoes the sequential dissolution steps of sinkability, dispersibility and wettability [20]. For RW dried turmeric, folic acid fortified RW dried turmeric and NaFeEDTA fortified RW dried turmeric, the solubility was about 29, 30 and 28 %, respectively (Table 3). Thus, good solubility was achieved, and this is promising from a product acceptability perspective [18]. Corresponding swelling power values were 1.8, 2.0 and 1.9 g/g respectively (Table 3). The fortificants did not significantly alter the product solubility and swelling power. The literature confirmed that the solubility and swelling power of RW-dried powders were like freeze-dried powder samples and were lower than that of spray and drum-dried powders. This is due to the mild processing temperature for both RW and freeze-drying methods [20]. High solubility in powders is crucial for various commercial applications, particularly in the pharmaceutical, food, and agricultural industries. In pharmaceuticals, high solubility ensures that drugs can be effectively absorbed into the bloodstream, enhancing their bioavailability and therapeutic efficacy. Approximately 40% of new chemical entities developed are poorly soluble in water, which poses significant challenges for formulation scientists aiming to deliver effective treatments. Similarly, in the food industry, instant powders with high solubility dissolve quickly and uniformly, preventing clumping and ensuring consistent product quality during preparation and consumption [18].

Table 3. Solubility and swelling power data of unfortified and fortified turmeric powder products.

S. No.	Samples	Solubility (%)	Swelling power (g/g)
1.	Unfortified	29.00	1.80
2.	Folic acid fortified	30.00	2.00
3.	NaFeEDTA fortified	28.00	1.90

Note: All standard deviations for solubility and swelling power were in the range of 2 – 3 and 0.1 – 0.2, respectively.

Dispersion time

For all evaluated powders namely, RW processed turmeric, folic acid fortified and NaFeEDTA fortified RW dried turmeric powders, the dispersion time was lower than 20 s (Table 4). The relatively short times of powder dispersion confirm good wettability characteristics of the tested samples. The literature hypothesized that larger particles possess higher wettability than finer particles and thereby translates into lower dispersion time [19]. Also, the addition of fortificants did not significantly alter the dispersion time of the samples.

The higher wettability of such samples could be also due to higher drying temperature. However, it can as well be inferred that the phenomenon of hard crust formation due to faster drying translate into the higher wettability of the samples [17].

Table 4. Dispersion time data of unfortified and fortified turmeric powder products.

S. No.	Sample	Dispersion time (s)
1.	Unfortified	20.00
2.	Folic acid fortified	17.00
3.	NaFeEDTA fortified	19.00

Note: All standard deviations were in the range of 2 – 3.

Water binding capacity

The water binding capacity is an important technical property and is related to the hydration capacity of the food samples that have rich constitution of protein and/or fiber content. The water binding capacity of RW dried turmeric, folic acid and NaFeEDTA fortified RW dried turmeric samples were high and were 66, 65 and 67 % respectively (Table 5). Thus, the fortificants did not critically alter the water binding capacity of the turmeric samples. According to a relevant literature [22], higher drying temperature ensured higher water binding capacity of the dried samples. Hence, the RW dried turmeric sample possessed higher water binding capacity due to the drying at high temperature that eventually fostered the onset of pasting or gelatinization.

Table 5. Water binding capacity data of unfortified and fortified turmeric powder products.

S. No.	Sample	Water binding capacity (%)
1.	Unfortified	66.00
2.	Folic acid fortified	65.00
3.	NaFeEDTA fortified	67.00

Note: All standard deviations were in the range of 2 – 3.

Color indices

The color parameters *L, a,* and *b* of turmeric powder, folic acid fortified and NaFeEDTA fortified RW dried turmeric have been summarized in Table 6. The *L* parameter decreased from 63.67 (fresh sample) to 56.67, 55.70 and 56.10 for turmeric powder, folic acid fortified and NaFeEDTA fortified RW dried turmeric samples. Such a reduction in lightness was attributed to the surface dryness or loss of moisture due to the drying at 95 °C. The measurement trends also confirmed upon the browning of the sample. Another reason is that the non-enzymatic browning (or Maillard reaction) occurs at relatively high drying temperatures. The reduction in *a* (redness) and *b* (yellowness) to 31.05 – 30.80 and 62.13 – 61.20 from 43.07 and 75.12, respectively, also corroborates the reasoning associated to heat treatment [23]. Also, it can be observed from the table that the addition of fortificants did not alter the color of the samples.

Table 6. *L*, *a*, and *b* values of unfortified and fortified RW dried turmeric powder samples.

S. No.	Samples	*L*	*a*	*b*
1.	Fresh	63.67	43.07	75.12
2.	Unfortified	56.67	31.05	62.13
3.	Folic acid fortified	55.70	30.10	61.80
4.	NaFeEDTA fortified	56.10	30.80	61.20

Note: All standard deviations for *L, a* and *b* were in the range of 1 – 2, 2 – 3 and 1 – 3, respectively.

CONCLUSIONS

The bulk density of RW-dried turmeric powder, folic acid-fortified turmeric powder and NaFeEDTA-fortified turmeric powder did not vary significantly. The hygroscopicity of fortified products was lower and like that of samples obtained by freeze drying process while the solubility and swelling power of the powders were good and matched the results obtained by freeze drying methods. In case of the dispersion time, it was less and hence the powders had better wettability. Meanwhile, the water-binding capacity of all three powders was high. The color indices were almost the same for all. From this work, it could be concluded that the addition of folic acid and NaFeEDTA to the RW-dried turmeric powder did not change the physical characteristics and constitution of the native RW-dried turmeric powder. This is due to the stability of folic acid and NaFeEDTA compounds added to the RW-dried turmeric. Thereby, they did not interact with the RW dried turmeric powder to cause physical changes to the powder.

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Authors' contributions: *Preetisagar Talukdar planned the experiments and wrote the manuscript with help from Kamal Narayan Baruah and Dr.*

Pankaj Jyoti Barman. Ramagopal V.S. Uppaluri supervised the conducted research and improvised the manuscript.

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Green building through reuse of waste material advancing sustainable development: an execution of Paris Agreement

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As the environment faces growing challenges, in 2015, the Paris Agreement committed nations around the globe to capping global warming at less than 2°C and striving for just 1.5°C instead. At its core, the agreement emphasizes the need for all sectors to work towards low-carbon, resilient societies. This study addresses the construction industry's significant waste generation and environmental impact. The research examines how green construction practices, specifically the reuse of waste materials, can align with the Paris Agreement's objectives, promoting sustainability and reducing environmental damage. It investigates design strategies for waste minimization and material reuse in green building projects to meet the Paris Agreement's objectives. This study will take an interdisciplinary approach that examines the Paris Agreement and current infrastructure laws, construction technology, and policy analysis to inform strategies to support policy-making and promote sustainable construction practices through green buildings and waste management systems and propose practical benchmarks for sustainable development. It explores challenges and opportunities in implementing these strategies across different regions through case studies and policy framework analysis. It aims to contribute relevant guidelines for waste management and the promotion of eco-friendly methods within the construction sector to support a low-carbon, resilient built environment.

Keywords: Environment, green buildings, Paris Agreement, sustainable development, waste management.

INTRODUCTION

The building industry is a major generator of waste, with vast quantities of materials being thrown away during construction, renovation, and demolition works. This not only poses environmental problems but also represents a missed opportunity for reusing resources. Against this background, the Paris Agreement provides a worldwide framework for combating climate change, which could inform research and policy-making on greener buildings and waste management. Nevertheless, how to use the Paris Agreement as a framework in this context is not clear; thus, there is a need to find out what works best when dealing with challenges and opportunities presented by green building through the reuse of waste materials across different regions and contexts.

This research seeks to enhance the comprehension of practicing the construction of green buildings by focusing on using the Paris Agreement as a guide. So, this research will look into various design strategies that aim to minimize waste as well as maximize their re-usage and discuss the persisting challenges and prospects that are associated with green buildings through the recycling of waste materials. Unlike existing literature that often examines green building and waste management separately or broadly references the Paris Agreement this study uniquely integrates these elements to address the practical challenges and opportunities of implementing the Paris Agreement in the construction sector. Certain case studies are analyzed with good examples to go deeper into the policy frameworks and regulations and relate to the environmental impact assessment, resilient design strategies, and future trends of the green buildings.

The objectives of this research paper are to establish proper design strategies that can be employed to attain minimum production of waste by promoting the reusage of material and waste within the green building projects and consider what is the best way we can use the Paris Agreement as an instrument to guide our investigation into green buildings along with waste management systems, and to set up certain benchmarks to have a good practice towards sustainable development informed by agreements reached under the Paris's Climate Change Conference – COP21. In light of these points, it hopes to promote more environmentally friendly methods and ways to create structures that also take a case about waste, therefore illuminating ways through which we can use the Paris Agreement as a guide for our inquiry in terms of the areas of our issues.

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The novelty of this work lies in its comprehensive examination of the subject matter, drawing data from different sources to provide practical implementation considerations for construction activities, and its specific focus on aligning green building practices with the Paris Agreement to promote sustainable waste management. This research goes beyond theoretical discussions by analyzing case studies, policy frameworks, and regulations to provide relevant and actionable guidelines for promoting sustainable practices in construction activities, contributing to a low-carbon, resilient built environment. The next sections and chapters will show an inclusive examination of this subject matter by drawing up data from different sources along with some case studies which shall put together the primary discoveries and the practical application considerations.

Statement of problem

The construction industry is one of the biggest waste producers, where large amounts of material are thrown out during construction, renovation, and demolition processes. However, this waste does not only pose environmental challenges but also represents missed opportunities for resource recovery. In the context of the Paris Agreement being a global framework for fighting climate change, it can be used as a reference point for green building research and policy development towards waste reduction. The application of the Paris Agreement as a framework in this respect remains unclear; hence best practices need to be identified that would address challenges and opportunities associated with green building through reusing waste materials across different regions and contexts.

Furthermore, there exist various design strategies aimed at minimizing waste generation while enhancing material reuse in green building projects, nevertheless, it is important to establish which ones work best and how they can practically be implemented to meet objectives stipulated by the Paris Agreement as well as promote sustainable construction industry development.

Therefore, this paper seeks to achieve several research objectives: finding out the most effective design strategies for reducing waste production in green buildings and enhancing material reuse; investigating whether or not the Paris Agreement would act as a guidepost in undertaking studies on sustainability within the built environment vis-à-vis waste management; looking into challenges and opportunities relating to eco-construction through recycling of rubbish materials within different regions so that relevant guidelines aligned with Paris accord may be developed. These are going to help in having a better understanding in terms of different methods that are to be followed for sustainable development by reusing waste material and setting up a benchmark for achieving sustainable development goals under the Paris Agreement.

Additionally, while dealing with these research questions; it is expected that such an undertaking will contribute significantly towards the promotion of sustainable practice methods during construction activities that have low impacts on the environment, especially those related to energy consumption efficiencies. Overall, this paper will explain the extent to which the Paris Agreement is or can be used as a guiding instrument in the construction sector to implement provisions about recycling waste into new buildings that are suitable for various climatic conditions.

Background and context

This research paper's background and context are about constructing green buildings through waste management. This aligns with the principles of sustainable development. It may also be linked to the Paris Agreement, which acts as a global framework for dealing with climate change. Since the construction industry is one of the biggest producers of waste, this topic continues to be relevant since it encourages environmental conservation by reusing such waste in environmentally friendly buildings.

The background portion gives an outline of what has previously been said or done on this topic, taking into account any pertinent historical information or literature reviews conducted by other researchers into related fields of study around waste reduction within buildings that are more durable than standard practice enables given the limited resources available at the moment while also taking into consideration the needs of future generations. As a result, the researcher first defines their research problem within these parameters before evaluating its importance concerning other studies that were conducted before along similar lines but have been either too general (e.g., *green buildings* without specifying whether residential, commercial, industrial, etc.) or too narrow (e.g., *insulation materials)*. Furthermore, the context includes methodical issues that are taken into consideration at the time of data collection, analysis, and interpretation as well as the beginning of the inquiry, such as a person's professional experience that piqued their curiosity and led to a wider investigation before a specific subject was chosen based on observations they made.

The research paper provides comprehensive information on the subject being discussed, including the problem statement's nature, historical context, and how it fits into the larger scheme of previous studies and research projects. By reviewing the relevant literature that identifies gaps and justifies the need for conducting research using a solid foundation from which useful ideas could emerge later during theoretical conceptualization stages designed towards obtaining overall goal(s) set up within it, the information provided is intended to help readers understand why the subject matter being studied is important within a broader field, thereby building credibility around investigation.

The issue of waste emergence in the building industry and its effects on sustainable development are discussed in this study. The main objective is to find design methods that can minimize the production of waste and promote the reuse of resources in the green buildings and construction sector. Along with this, this study also discusses and evaluates the potential of the Paris Agreement as a framework for research and policy development in this field by focusing on managing the waste that is produced in the process of construction. Finally, it also suggests certain practices for sustainable development that meet the requirements that are outlined in some of the International Conventions such as *the United Nations Framework Convention on Climate Change*.

The subsequent chapters and sections under this paper will provide an analysis of various issues relating to green buildings by discussing a few case studies that shall help in further implementations. The environmental impacts, Design Strategies, and Future trends and impacts shall also be covered in these chapters. All of these should significantly advance our understanding of sustainability in the construction industry and shed light on how to use the Paris Agreement as a guiding framework for waste management issues related to these buildings.

Significance of the study

This study is important as there is an increasing need and demand currently for sustainable buildings that are eco-friendly in terms of waste management. The construction industry contributes greatly towards the generation of waste if only those materials that have been wasted get utilized in making ecological structures, this will highly reduce the amounts of garbage being produced while promoting development that meets the present needs without compromising on the future generations ability to meet their own needs as well [1]. The aim of this research paper is thus twofold; firstly, it seeks to know what constitutes green practices vis-à-vis waste disposal methods, and secondly, its main focus is on how best we can use the Paris Agreement as our guide in achieving this.

This study is important because it examines design strategies for reducing waste while construction and explores the potential for material reuse in building construction, specifically in the context of environmentally friendly buildings through the reuse of waste materials. Furthermore, this analysis will include an examination of case studies and relevant illustrations to provide policymakers with knowledge of successful strategies implemented elsewhere, which they might then adopt. In addition, it is crucial not to overlook the importance of policy frameworks and regulations in ensuring strict adherence to rules governing various undertakings, such as technology and innovation, and economic and environmental analysis. These frameworks and regulations play a vital role in ensuring compliance by all parties involved Green Buildings Certification Inc. and U.S. Green Building Council (GBCI & USGBC). In addition, while evaluating the resilience design elements of a project against climate change effects in various places worldwide, environmental impact assessment reports should also take into account social sustainability factors. This is recommended by the International Organization for Standardization's Technical Committee 207, Sub-Committee on Environmental Management.

Additionally, it is necessary to implement education training programs, even though many individuals already possess substantial knowledge on these matters. However, there may still be a few remaining details that have not been thoroughly explored. These programs aim to raise awareness among the general public, particularly those residing close to upcoming green buildings, as their numbers continue to grow steadily as per Caux Initiatives for Business (CIB 2016) Conference. Finally, what does the future entail for us regarding these environmentally friendly buildings? Therefore, this research paper aims to uncover future patterns in sustainable building development, emphasizing the need to look ahead rather than dwell on the past.

The primary objective of this article is to improve sustainable waste management techniques in green construction, using the Paris Agreement as a guiding concept for research and policy development in environmental conservation within this field. The results of these studies can potentially inspire change among different participants in these activities, including industry stakeholders at national levels, local governments, and individual citizens who are part of the global community and share the goals outlined in the Sustainable Development Goals (UNEP & RICS, 2013). Therefore, it is undeniable that conducting investigations into various aspects of waste recycling from the design stage to the completion of the construction process is of great importance. This is because we cannot sustain our way of life without developing more environmentally friendly homes, also known as green buildings. Therefore, all our actions must be consistently aimed at attaining sustainability, irrespective of the extent to which individuals comprehend the reasons for specific practices. Failing to do so would contradict the principles of "sustainable development" that align with the natural world.

LITERATURE REVIEW

Overview of green building and sustainable development

Green building and sustainable development are critical areas of research and practice in the construction industry. Green buildings aim to reduce the negative impacts of buildings on the environment and promote sustainable development. According to Teng, green buildings are designed to reduce operating costs by reducing energy consumption, but they can cost more than non-green buildings [2]. However, sustainable building materials, which are domestically created and sourced, can decrease transportation costs and carbon dioxide (CO_2) emissions, and they possess a lower environmental effect, are thermally effective, require less energy than conventional materials, make use of renewable resources, are lower in harmful emissions, and are economically sustainable.

The benefits of green buildings include environmental benefits such as enhancing and protecting biodiversity and ecosystems, improving air and water quality, reducing waste streams, and conserving and restoring natural resources. Social benefits include enhancing occupant health and comfort, improving indoor air quality, minimizing strain on local utility infrastructure, and improving overall quality of life. However, sustainable development is a crucial challenge, particularly in developed nations, and the environmental load of building materials has become a more significant requirement. Among the directions for solutions are new material applications, recycling and reuse, sustainable manufacture of products, or use of green resources such as reusing various industrial wastes like industrial by-products, demolition debris, plastic waste etc., to reduce CO_2 emissions, reduce landfill waste, lower costs and more as mentioned in Table 1.

Table 1. Various waste materials repurposed in construction.

Waste Material Type	Source	Application in Construction	Benefits	Challenges
Industrial By-products	Manufacturing, processing plants	Cement replacement (fly ash, slag), aggregate in concrete, road construction.	Reduced CO2 emissions, lower costs, improved durability of concrete.	Potential heavy metal contamination, inconsistent material properties, requires proper processing.
Demolition Debris	Building demolition, renovation	Recycled concrete aggregate (RCA), reclaimed wood, bricks, and other materials for new construction.	Reduced landfill waste, conserves natural resources, lower transportation costs.	Quality control, potential contamination (e.g., asbestos), requires sorting and processing, public perception.
Plastic Waste	Municipal solid waste, industry	Use as a partial replacement for cement or aggregates in concrete, production of plastic lumber, or as a component in asphalt mixes.	Reduces plastic waste in landfills, can improve the workability and durability of concrete and asphalt, lightweight.	Concerns about the long-term stability and leaching of microplastics, potential for increased flammability, requires proper pre-processing and mixing, limited acceptance by building codes and standards.
Tyre waste	Discarded vehicle tyre	Shredded tyre can be used as an additive to asphalt mixes, as a drainage layer in landfills, or as a component in lightweight concrete.	Reduces tyre waste, improves the flexibility and crack resistance of asphalt, provides good insulation and shock absorption.	Potential for leaching of chemicals, fire hazard, requires proper shredding and processing, limited applications in building construction.

Table 2. Novelty of work – Addressing gaps in existing literature

Area of focus	Existing literature	Novelty of this work
Green Building & Waste Management	Examines green building practices and waste management separately.	Integrates green building practices with waste management strategies under the framework of the Paris Agreement.
Paris Agreement Application	Mentions the Paris Agreement as a general framework for climate action.	Investigates the specific application of the Paris Agreement as a guiding instrument for green building and waste management systems, establishing benchmarks for sustainable development.
Design Strategies & Material Reuse	Discusses design strategies for waste minimization and material reuse in green building projects.	Aims to identify the most effective design strategies and their practical implementation to meet objectives stipulated by the Paris Agreement, promoting sustainable construction industry development.

The concept of sustainable building has been studied extensively in the literature. Shen investigated the green building industry in Thailand, while Shen developed an integrated system of text mining techniques and case-based reasoning (TM-CBR) to support green building design [3]. Wang in 2022 researched the impact path of the sustainable development of green buildings in China [4]. However, there are gaps in existing literature, such as integrating green building practices with waste management strategies and identifying the most effective design strategies according to the Paris Agreement framework. This work focuses on and discusses these gaps as summarized in Table 2.

In summary, green building and sustainable development are critical areas of research and practice in the construction industry. Green buildings aim to reduce the negative impacts of buildings on the environment and promote sustainable development. Sustainable building materials, which are domestically created and sourced, can decrease transportation costs and CO_2 emissions, and their power environmental effects are thermally effective, require less energy than conventional materials, make use of renewable resources, are lower in harmful emissions, and are economically sustainable. The benefits of green buildings include environmental benefits such as enhancing and protecting biodiversity and ecosystems, improving air and water quality, reducing waste streams, and conserving and restoring natural resources. Social benefits include enhancing occupant health and comfort, improving indoor air quality, minimizing strain on local utility infrastructure, and improving the overall quality of life, as shown in Figure 1. However, sustainable development is a crucial challenge, particularly in developed nations, and the environmental load of building materials has become a more significant requirement. Among the directions for solutions are new material applications, recycling and reuse, sustainable manufacture of products, or use of green resources.

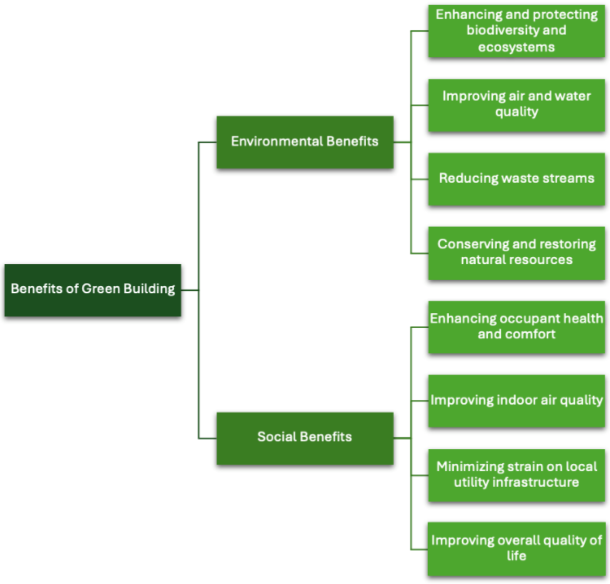

Figure 1. Benefits of green building

The Paris Agreement and its connection with sustainable buildings

The Paris Agreement is a global campaign to mitigate climate change by reducing greenhouse gas emissions. This also has huge implications for the fore construction industry, mainly in sustainable architecture and waste management. Construction is responsible for a notable amount of CO_2 produced into the atmosphere, which amounts to 39% of the total CO_2 emissions in the USA [5].

Green building is one vital element of sustainable development that seeks to reduce the effects on the environment while enhancing people's lives through resource conservation and overall improvement in quality of living [5]. Though not a new concept, green buildings have gained more prominence recently due to their contribution towards mitigating climate change effects which were found harmful indeed. To attain the worldwide reduction objective, the Intergovernmental Panel on Climate Change (IPCC) emphasizes the necessity of swift changes in the construction, energy, and transport sectors. Commercial buildings and residential facilities provide approximately 40% of global carbon emissions associated with energy consumption [6], as shown in Figures 2 and 3.

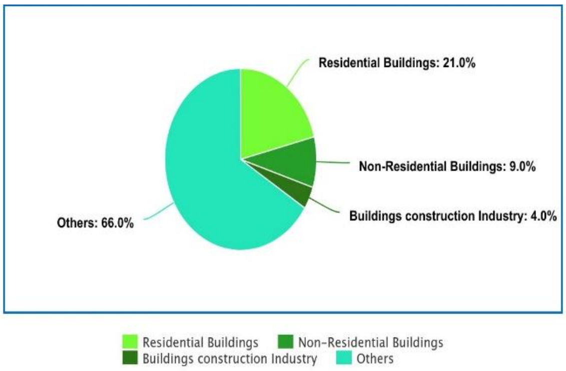

Figure 2. Energy consumption in 2022 (open access, doesn't require copyright permission).
Source: Adapted from Global Alliance for Buildings and Construction, Global Status Report for Buildings and Construction (2023)

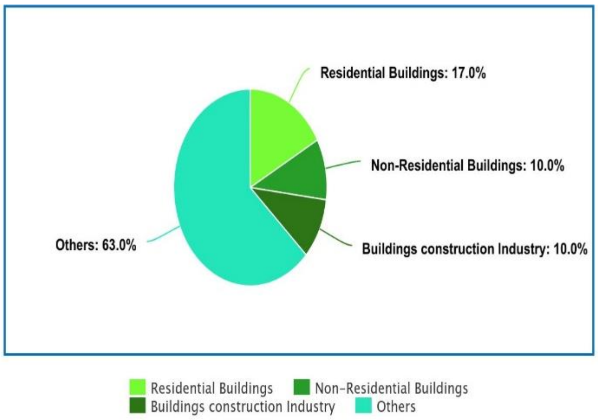

Figure 3. Global energy and process emissions in 2022 (open access, doesn't require copyright permission).
Source: Adapted from Global Alliance for Buildings and Construction, Global Status Report for Buildings and Construction (2023).

The principles underlying the design of green buildings aim to greatly reduce resource usage, thereby optimizing energy consumption, preserving and safeguarding water, optimizing space utilization and material usage, and improving indoor environmental quality, among other factors. Additionally, operations and maintenance practices are also optimized. For example, the impact of global warming can be reduced by utilizing sustainable materials like LEED recessed access doors while simultaneously ensuring the safety of workers on a global scale [6].

To achieve the ambitious targets outlined in the Paris Agreement, it is imperative to involve important stakeholders such as the construction sector. Without their participation, these goals cannot be effectively accomplished. Implementing eco-friendly construction methods and utilizing reusable resources will effectively reduce the carbon footprint of building projects and make significant contributions towards achieving sustainability objectives. Furthermore, these strategies facilitate endeavors to adjust to climate change.

In summary, the Paris Agreement possesses the capacity to influence different sectors of the economy, namely those about construction, such as environmentally conscious building and waste management. By embracing this viewpoint, individuals can establish systems that are sustainable to the environment, as they understand their obligation to reduce the effects of global warming. In essence, we must utilize all accessible resources to save planet Earth, as even the most minor efforts have a substantial effect on conserving nature for future generations to come [4].

DESIGN STRATEGIES FOR WASTE REDUCTION AND REUSE OF RESOURCES

Overview of strategies for sustainable design in buildings

Some good ways to reach the goal of getting zero waste is by following construction methods like prefabricated construction or modular construction, which will use the resources in the best way for building projects. One of these methods is using pre-made parts during the building process to cut down on waste and make the work go faster and better. The building will cost less in the long run because it can be quickly changed for different uses without doing much damage. This makes the buildings last longer [7].

Adaptive reuse is the process of finding new uses for old buildings or materials instead of making new ones. This saves energy and reduces waste by cutting down on the production process. It also makes sure that cultural and historical values connected to historic buildings are kept alive, which could be lost forever if people involved in demolition activities aren't aware of them [8]. This is very important because of the many reasons why people are still trying to protect these buildings, which are well-known around the world among experts who study how people settled in different parts of the world over time. This includes archaeologists whose job it is to study ancient civilizations from all over the world, especially those that lived along major rivers, like the Nile River Valley Civilization in Egypt, the Indus Valley Civilization in India, and the Yellow River Valley Civilization in China. By taking care of these buildings, they are being saved for future generations to use as examples of what not to do and how to avoid making the same mistakes again.

As part of a waste management strategy, waste management plans are made during the planning phase to make the processes of collecting, sorting, reusing, or recycling as efficient as possible by following the waste management hierarchy as shown in Figure 4, where prevention of wastage is the top priority followed by reducing, reusing, recycling the waste and so on. Along with it, it also includes ways that are safe to dispose of unnecessary waste. Waste Management is very important to save resources, and it also promotes eco-friendly practices in the construction industry. It reduces wastage and makes sure that everything is properly managed without its entire life cycle. Therefore, including waste management strategies like waste minimization planning, onsite sorting and recycling, and prefabrication in the construction sector as discussed in Table 3 is necessary.

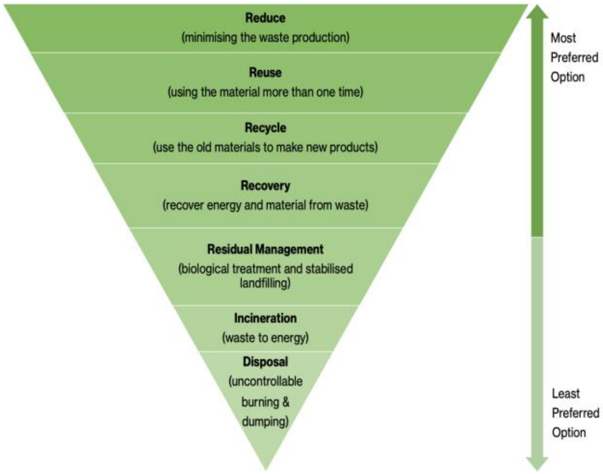

Figure 4. Waste management hierarchy

Table 3. Waste management strategies in construction

Strategy	Description	Benefits	Challenges
Design for Disassembly	Designing buildings to be easily disassembled for reuse or recycling of components.	Reduces demolition waste, facilitates material recovery, promotes circular economy.	Requires careful planning and design, may increase initial costs, requires skilled labor.
Waste Minimization Planning	Developing a plan to reduce waste generation during construction through efficient material use.	Reduces waste disposal costs, conserves resources, improves project efficiency.	Requires commitment from all stakeholders, may require changes to standard practices.
On-Site Sorting & Recycling	Sorting construction waste on-site for recycling or reuse.	Reduces landfill waste, generates revenue from recycled materials, promotes environmental awareness.	Requires space and labor, potential contamination of materials, market availability for recycled materials.
Prefabrication	Manufacturing building components off-site in a controlled environment.	Reduces waste, improves quality control, speeds up construction.	Requires careful planning and coordination, transportation costs, limited design flexibility.

Case studies/Best practices

Case studies are real-life examples that can be used to show how materials are used efficiently and methods for reducing waste are put into practice in green building projects. They give real-life cases that help make these ideas clear. Let me show you what I mean. The Edge is the name of an office building in Amsterdam that is made to be great for the environment. The building can reach a very high level of sustainability by using methods to save energy and water and programs to reuse building materials. This makes sure that the people who live there can enjoy both comfort and sustainability. In Seattle, there is a business building called the Bullitt Center [9], which is another example. Because it uses green design concepts, this building has reached net-zero energy use. Gathering rainwater, using natural ventilation methods, and using a lot of recycled materials are some of the things we do. The Renewal Workshop is in Oregon, United States of America. People bring their old clothes to this business to have them fixed up and then sell them again. This is an explanation of how the fashion business can use the circular economy idea to become more environmentally friendly.

One of the examples of sustainable waste management policy is performing audits on waste streams to establish preliminary measurements and to identify the chances of diverting them. The Energy Research Institute (TERI) in Bangalore, India, is one example of an organization that uses sustainable design concepts like passive cooling and heating to reduce energy usage. This building is situated on an axis that runs from east to west to the northern side to have glare-free light. It also has the dale cavity wall on the south side for the insulation. It has an open atrium space with skylights to increase the natural light. It also has an earth air tunnel system for efficient cooling and heating.

Another case includes an office building located in Athens, which has shown that the installation of a green roof for sunshade has resulted in a reduction of 19% of the energy that is consumed, which is used for cooling purposes, Also, there is *The Indira Paryavaran Bhawan* in New Delhi, India which is a building that has a net-zero energy building (NZEB) which shows an important leap from the usual traditional building designs. The team of this project has focused on certain initiatives to decrease the usage of energy by employing a few measures like increasing the natural light, which includes shading and garden landscaping to decrease the temperatures outside and also by using active building systems which are energy efficient. This building has achieved in reduction of 70% of the energy being consumed when compared to other traditional buildings. This has also been awarded a GRIHA 5-star rating and platinum rating from LEED [10].

PARIS AGREEMENT AS A FRAMEWORK FOR RESEARCH AND POLICY DEVELOPMENT

The Paris Agreement of 2015 is an important global treaty that aims to address climate change by reducing the emissions of greenhouse gases and promoting sustainable development. It provides certain guidelines and strategic plans for the countries to follow in mitigating climate change by encompassing various measures like promoting sustainable construction and waste management.

Understanding the Paris Agreement within the context of green building

The Paris Agreement represents a global framework for addressing climate change and its impacts with specific reference to green building and waste management among others. The construction industry accounts for large amounts of waste generation globally where significant quantities of materials are discarded during construction, renovation, or demolition worksites thereby creating environmental challenges in addition to lost opportunities for resource recovery. In this way, therefore, the Paris Agreement offers potential ways for research work as well as policy formulation on green buildings along with waste disposal methods.

The Paris Agreement acknowledges the significance of sustainable development and emphasizes the need for fully integrated actions to address global warming reduction. The articles of the agreement include measures to promote energy conservation through the use of green buildings, which involve the adoption of renewable energies and sustainable practices in the construction industry (UNFCCC Secretariat). It also emphasizes the importance of decreasing CO_2 emissions from buildings, which contribute to approximately 39% of worldwide energy-related CO_2 emissions. It calls for improving low-carbon resilient infrastructures and sustainable models.

All the countries can establish policies and measures to promote energy efficiency and the adoption of renewable energies for having sustainable building practices following a commitment to the Paris Agreement. These measures provide the requirements for using various appliances that are powered by solar panels, which help in electricity savings. In order to do such practices, they must be granted subsidies, grants, tax credits, etc., and other possible things to support them. For example, a few member states of the European Union have already implemented certain directives named the Energy Performance Building Directive (EPBD) and the Renewable Energy Directive (RED), which mandate the development of policies that improve the energy efficiency in the buildings and promote the usage of renewable energy. Another example is, that the United States has established the Green Building Council, which has certified around 50,000 environmentally friendly buildings. China has also established certain evaluation standards for constructing sustainable buildings that have appliances that use renewable energy and save energy.

The Paris Agreement establishes global guidelines for combatting climate change by raising certain initiatives like the development of sustainable buildings and waste management. Various governments can use this treaty as a foundation for making policies and implementing them to promote sustainable construction including energy saving and renewing.

Using the Paris Agreement for policy creation

The Paris Agreement acts as a global treaty that outlines certain actions that every nation must follow to generate carbon emissions. Regarded by numerous individuals as a highly significant document in the realm of environmental preservation, it is well recognized for its provision of explicit directives for action to be taken by nations worldwide.

The Paris Agreement serves as a framework for the advancement of research and the formulation of policies about change problems. One method it employs is the establishment of goals or targets that must be achieved in the context of sustainable development, among other objectives. For instance, specific regulations can be implemented under the domains of green buildings and management of waste to align with and support efforts to mitigate global warming.

The governments may refer to sustainable building certifications as an organizing principle when developing national codes for construction methods that align with the goals of low-carbon economies, as outlined in international agreements like the United Nations Framework Convention on Climate Change (UNFCCC). One method of guaranteeing that new projects adhere to the legal norms could be to integrate them into the national building laws or even make them obligatory components within those regulations.

Carbon pricing systems are essential elements that must be included in the policy-making stage. They provide incentives for investing in energy-efficient technology with low emissions in the manufacturing sectors of developing nations, as described in Articles 6 and 7. These rules are supposed to promote sustainable production methods that help reduce carbon emissions from industries that burn fossil fuels to generate energy.

The collaboration between the public and private sectors is essential to policies that are necessary to have sustainable construction practices as this helps in facilitating the relevant information and promotes transformation in various sectors that are using green building techniques as per Article 11. This collaboration creates an environment that promotes sharing knowledge and implementation in terms of sustainable building technology. Finally, to have significant progress in the construction sector globally, we must follow the Paris Agreement in terms of creating a policy for the buildings. If all the countries align their policies with the international agreement, they can speed up their efforts in creating buildings with zero carbon emissions. This also makes a significant contribution to the global objectives laid down under the UNFCCC under classes 5 and 13, which address climate change.

CASE STUDIES ON GREEN BUILDING AND WASTE MANAGEMENT

What we learned from sustainable building projects

The sustainable building projects provide a framework to incorporate green buildings to have a sustainable construction process by aligning with the goals under the Paris Agreement. One such example of a sustainable building plan is a commercial structure named Bullitt Center in Seattle [9], which has been recognized as one of the most sustainable buildings in the world. Their effort shows various things such as a rainwater-to-potable water system, composting toilets, and rooftop solar panels, resulting in overall positive energy usage. It functions as a symbol for sustainable construction methods that help enhance our comprehension of carbon neutrality and promote the efficient use of resources.

Another example of sustainable buildings is the Empire State Building, which is located in New York. It has gone through a lot of major energy efficiency during the renovation process. Though all the sustainable goals were not fully achieved, it made a significant process through this project like installing new windows, upgrading the heating ventilation air condition systems, and the addition of insulation. This has resulted in a yearly reduction of power usage by 38%. This has also helped in saving the costs annually by $4.4 million on utility bills as per the USGBC.

Innovative strategies for waste minimization

The Zero Waste Research Center in San Jose is a notable institution where novel methods for waste reduction can be explored per the Paris Agreement [10]. Within this establishment, there is a material recovery station that conducts the separation and treatment of recyclable materials, as well as a composting site where organic waste is transformed into a superior-quality soil supplement. Therefore, this working prototype can serve as a model for sustainable waste management systems. It not only demonstrates the amount of waste that could be saved through recycling but also highlights the fact that we have not yet fully utilized all potential sources of renewable energy. If these sources are effectively harnessed, they might contribute significantly to the accomplishment of carbon neutrality.

The Green Demolition Project in Toronto shows an excellent approach by which the buildings are carefully demolished to ensure that the components that can be recycled and reused are extracted and used somewhere else. Mostly, these components are sold in the open market, while others are donated to local charities or non-profit organizations. This method successfully helps in diverting thousands of tonnes of waste from landfills. Moreover, it also provides beneficial options for builders who require particular types of materials for their various projects.

Examples that show successes through reuse of waste

Materials reuse success stories demonstrate the concepts of the circular economy, which aligns with the agreements made during the COP21 Conference under the UN Framework Convention on Climate Change (UNFCCC). One of them is the *Habitat for Humanity ReStore* (Habitat for Humanity) [12], which gathers all the used or unwanted building supplies such as appliances and furnishings, processes them, and then sells them at affordable prices. This initiative has been helping in funding low-cost home projects that conserve resources and reduce the strain on the landfills by diverting these millions of tons of waste to places where they can be reused. This is a success story which has contributed to the sustainable development goals and efforts to mitigate climate change.

Sustainable development is an important concept in terms of green building through the reuse of waste. Its main objective is to achieve our present needs while protecting the quality of life of future generations. Sustainable waste management aims to minimize the waste streams and handle the resources efficiently with the use of recovery, recycling, reuse, and minimization of waste. The Leadership in Energy and Environmental Design (LEED) has a green building rating system that analyses the environmental performance of buildings in nine categories which also includes the materials and resources. The LEED includes waste management credits that mainly focus on various kinds of waste like construction waste, reusing materials, analyzing waste channels as well and successfully managing consumable and durable goods.

All these case studies and success stories regarding green buildings through waste management offer various important and valuable perspectives in terms of the ways to harmonize our practices under the goals laid down by the Paris Agreement. This can help us save a lot of resources and have proper waste management that shall help in reaching the sustainable development goals laid down in the Agreement.

ENVIRONMENTAL IMPACT ASSESSMENT OF GREEN BUILDINGS

The Paris Agreement is the most important agreement about the global climate and it aims to stop or reduce the global temperatures to less than 2°C in terms of pre-industrial levels, and it is striving to reduce the rise of the temperature to 1.5°C. The Environmental Impact Assessment (EIA) regarding Green Construction aims to analyze, control and reduce the negative impacts that the construction projects have on the ecological systems. The Life Cycle Assessment of the building materials and the measurements of carbon footprint, along with taking the biodiversity services into account, is important in terms of assessing the environmental impact of green buildings, which is in line with the goals of the Paris Agreement.

Life cycle assessment of building materials

To address the environmental impact, the Life Cycle Assessment (LCA) is used as an important tool. It analyses the product during its entire lifespan, beginning from the extraction of the raw material till the end of its disposal or recycling Assessment [13], as shown in Figure 5. So, to reduce their greenhouse gas emissions as per the principles laid down by the Paris Agreement, LCA should be encouraged, which will lead to Sustainable development [14].

The Life cycle assessment has different phases, which have a goal definition and scope setting that establishes its objectives to carry out the Assessment as shown in Figure 6. It has a system boundary setting that determines the limitations that are there and in which the Assessment of the functional unit and product system will be conducted. It has inventory analysis where the data will be collected on the inputs and outputs of the product systems, which includes their consumption of energy and the waste that is generated in the process of manufacturing. Impact assessment compares these data against predetermined values, such as global warming potential (GWP). Interpretation involves comparing all findings with relevant benchmarks while reporting and passing on this knowledge to stakeholders. For example, it displays the results obtained from determining the impacts caused by the use of certain types of building materials, along with recommendations for reducing them [15].

Carbon footprint analysis

Carbon footprint analysis assesses the efforts made by enterprises to reduce their detrimental emissions into the earth's atmosphere. The analysis encompasses all air emissions across the entire lifespan of building projects, with a particular emphasis on CO_2. This includes emissions from the extraction of raw materials, as well as the disposal or recycling of items at the end of their life cycle [16].

The construction sector has a significant impact on greenhouse gas (GHG) emissions, with concrete alone contributing to nearly 75% of the total embodied carbon in structures, while steel accounts for approximately 18%.

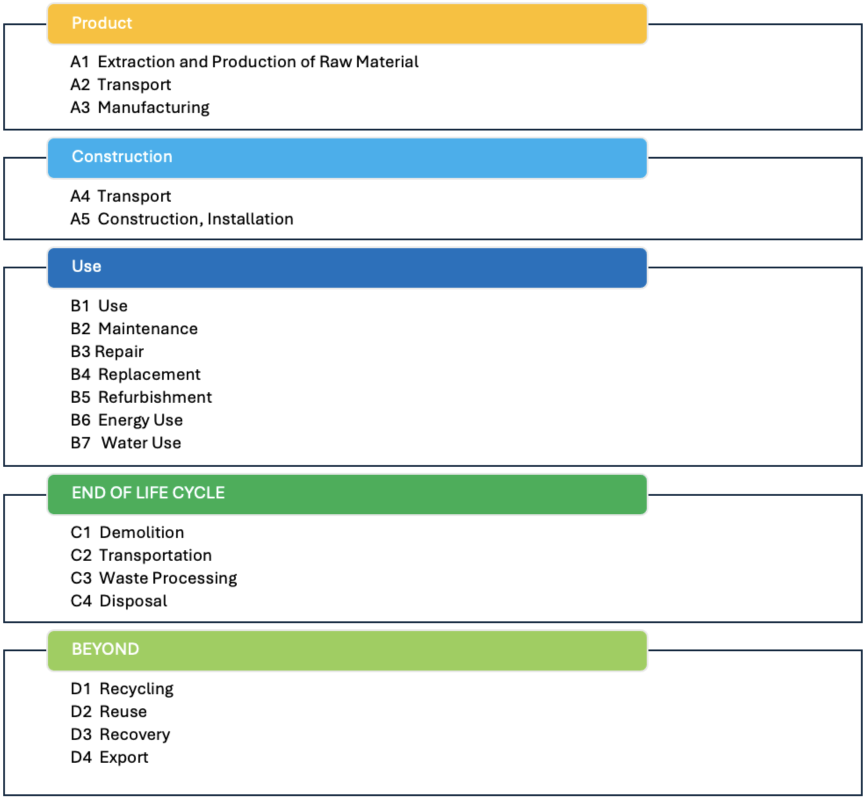

Figure 5. Life cycle stages of a building

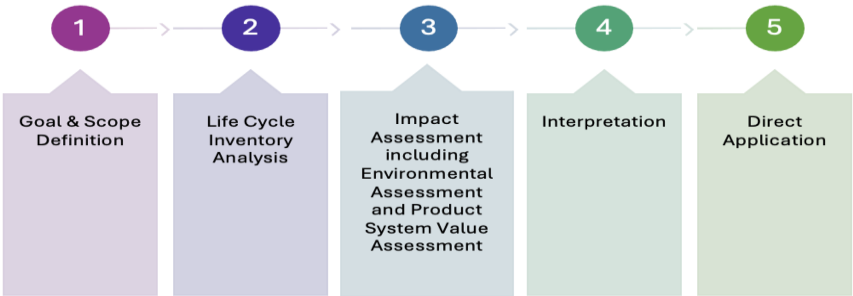

Figure 6. Phases of life cycle assessment

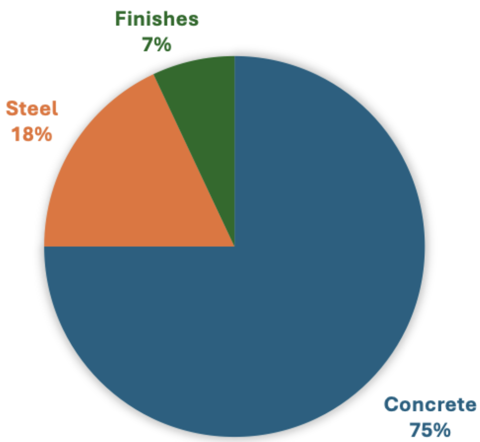

Figure 7. GHG Emissions by construction sector (prepared in this work)

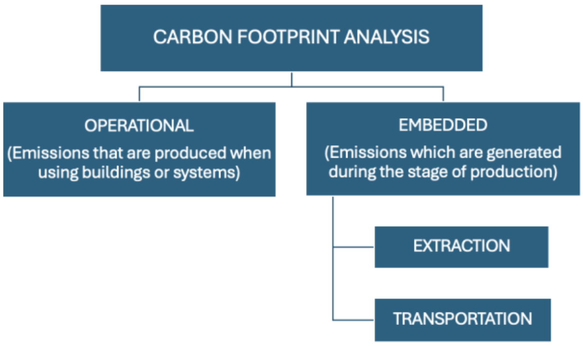

Figure 8. Carbon footprint analysis in construction industry (prepared in this work)

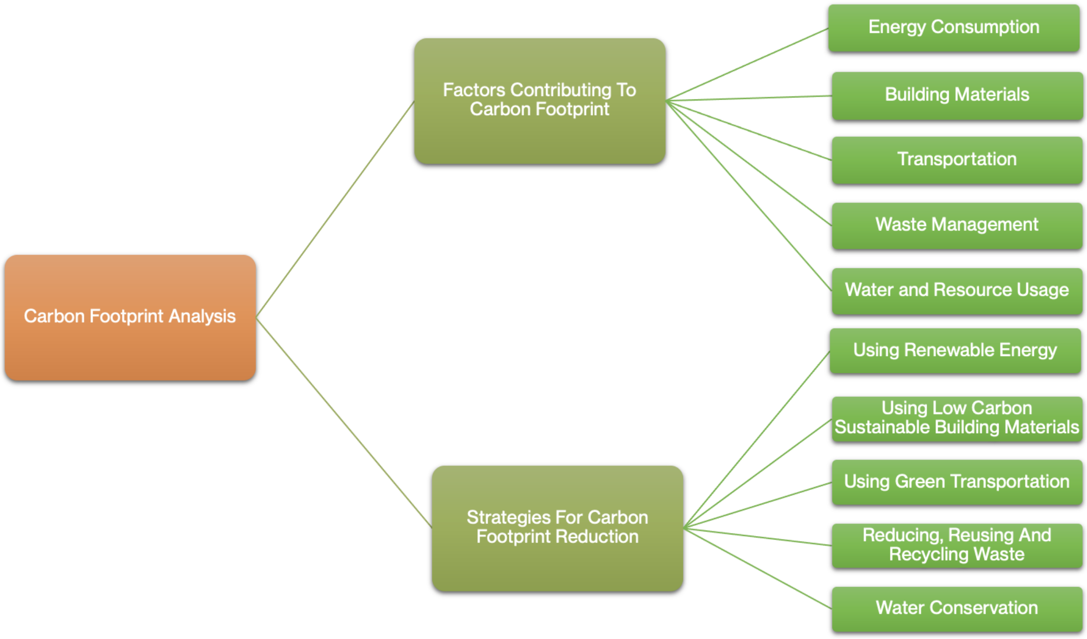

Figure 9. Carbon footprint analysis through factors contributing to carbon footprint of buildings and strategies for reducing them.

Finishes also have a substantial impact since they make up approximately 7%, as shown in Figure 7. Therefore, it is imperative to tackle these concerns as CO_2 emissions have a significant impact on climate change in the short term, making it a matter of urgency [17]. This method allows for the identification of building process stages that emit higher levels of carbon into the environment, facilitating the selection of building supplies with lower carbon content [16]. Carbon footprint analysis can be divided into two main categories: operational and embedded. The term *operational* refers to emissions that are produced when using buildings or systems, like heating systems. The other term, *embodied*, refers to those emissions that are generated during the stage of production, which includes activities like extraction and transportation [16], as shown in Figure 8. The factors that contribute to the carbon footprint of construction of buildings and the strategies to reduce carbon footprint in building operations are depicted in Figure 9.

It is important to conduct the carbon footprint analysis for green buildings to meet the lines that are outlined in the Paris Agreement, which lays down the reduction of greenhouse gas emissions and encourages sustainable development. Not only that, but this research will also help identify the areas that need enhancement. This facilitates the decision making which focuses on mitigating the adverse impacts on the environment and promotes better standards of living by reducing the levels of pollution to have a healthier planet [14].

So that it adheres to the agreement, the Inter-American Development Bank (IDB) has devised the "IDB Group Paris Alignment Implementation Approach" (PAIA). This approach assesses all new projects undertaken by the bank to ensure that they do not hinder the transition to low-carbon and climate-resilient economies, as outlined in the Paris Agreement. PAIA offers a systematic approach, a set of principles, and technical guidelines for evaluating various sectors, such as buildings. This evaluation helps in developing technological designs for operations and facilitates communication between the organization and its customers.

POLICIES AND REGULATIONS REGARDING THE GREEN BUILDINGS

Green Buildings are very important to implement construction practices and to improve the environmental impact of the buildings. So, we need policies and regulations like national and international regulations and incentives for sustainable building practices along with compliance and enforcement strategies.

The International regulations provide a basis for the implementation of sustainable construction methods. LEED, as discussed earlier, is one of the leading green building rating systems in the USA. It assesses various factors like the efficiency in energy usage, conservation of water, and indoor air quality, starting from the design face throughout the construction process. Another regulatory framework is the International Green Construction Code (IGCC), which provides the minimum standards for sustainability in many areas like site development, energy conservation, water efficiency, etc.

In India, The Indian Green Building Council (IGBC) has been an instrument in improving the implementation of green building practices within India. It has the Green Building Rating Systems, which ranks the buildings based on their energy efficiency, water usage, material selection, and usage by preventing wastage of materials and resources and other factors. It gives certification to the buildings in different categories like Platinum, Gold, and Silver depending on their compliance with these criteria. Along with the IGBC, the Green Rating for Integrated Habitat Assessment (GRIHA) also plays an important role in checking whether the buildings comply with the green building criteria to promote sustainable construction. This acts as an incentive for the developers to adhere to sustainable practices in the building, have proper usage of resources, and minimize waste.

FUTURE TRENDS AND OUTLOOKS IN GREEN BUILDINGS

Innovations about to happen

The recently developed green building technologies are highly significant for achieving the goals of the Paris Accord and promoting environmentally responsible building practices. The article titled "Market Report on Green Buildings" examines important advancements that are expected to impact the future of environmentally sustainable construction methods. Employing eco-friendly construction technology is an astute strategy to preserve energy, enhance occupant comfort, and minimize environmental harm with equivalent work. This system enables the real-time monitoring and control of activities within buildings through the utilization of automation sensors and other modern technology. The main objective of this effort is to promote energy efficiency and sustainability.

Some people perceive biophilic design concepts in green architecture as a novel trend. The objective of biophilic design is to integrate natural elements, such as plants, sunlight, and water, into the architectural design of buildings. The goal is to improve the well-being of individuals while also promoting a stronger relationship with the natural world. By integrating these elements, green buildings can improve indoor air quality, reduce stress levels, and promote efficiency. The Paris Agreement prioritizes enhancing human well-being and protecting the environment, and this initiative aligns with both objectives.

Projected changes in policy and practice

The Paris Agreement came up to put the rise intending to temperature to less than 2°C. To achieve the goal it has laid down, the government has brought up certain changes in the green buildings by bringing up the Green Buildings Standards and Certifications. These standards, like LEED or BREEAM, require buildings to follow certain environmentally friendly rules from the time they are designed until they are finished. They also require buildings to be sustainable. Carbon pricing plans, like cap-and-trade or carbon taxes, will reward behaviors that produce less carbon, while behaviors that produce more carbon will be punished.

It is believed that partnerships between the public and private sectors will be very important in advancing green building technologies and methods. These partnerships help solve money problems while also encouraging new ideas and methods that are better for the environment. More money will likely be spent on research to improve green building technology by creating new materials, putting in place energy-efficient systems, and using design methods that have less of an impact on the environment and make buildings last longer.

Sustainable urban planning ideas should be incorporated into building plans and constructions. This will allow for the growth of green spaces, public transportation systems, and renewable energy sources in city infrastructures. Climate-resilient infrastructure is becoming more and more important. This means building things that can stand up to extreme weather and change the climate. From the beginning to the end of the building process, health will be taken into account by using biophilic design principles, letting in natural light, and using materials that make the air inside better.

For green buildings to align with the Paris Agreement, stakeholders must adhere to the appropriate procedures and actively endorse these objectives and trends. This will enhance the health and resilience of habitats, benefiting both human beings and the planet.

Future goals and hopes for sustainable development in long range

The Paris Agreement is a global agreement that aims to promote the use of environmentally friendly construction methods in green buildings. Its goal is to achieve carbon neutrality by reducing the emissions of greenhouse gases and by promoting sustainability. This can be achieved by generating the same amount of renewable energy that is consumed, which will help in reducing the carbon footprint. The Agreement also highlights the importance of reducing waste and using the materials efficiently by following circular economy principles throughout the lifespan of a building.

Some of the long-term long-objectives include the integration of various energy sources like solar panels, wind turbines, etc., as efficient systems. Furthermore, this provides us with an alternative method of generating power, in addition to the utilization of fossil fuels. An alternative method for generating green energy involves utilizing geothermal heat pumps. Specialized intelligent devices, specifically created for application in residential and commercial structures, are aggressively promoted to decrease energy consumption, enhance air purity, and regulate ventilation systems. This contributes to the improvement of living and working situations that are more environmentally friendly.

Furthermore, there are also important aspirations regarding the conservation of biodiversity, the incorporation of inclusive design, and the preservation of cultural heritage within the green buildings sector for an extended period. It is crucial to prioritize the protection of nature within architectural spaces. Ensuring a healthy ecological balance between humans and their surroundings should always be of utmost importance from the planning stages to the finalization phase. Failing to do so would result in cities becoming uninhabitable, with a lack of trees, birds, and clean water, among other things. So, it's important for any design or construction process to not just meet but go beyond the minimum standards set by laws that protect biodiversity, no matter where they are in the world, especially if they are located nearby.

Another future goal of sustainable construction is the use of long-term Smart Building Technology (SBT). This concept utilizes modern data analytics and automation systems to maximize the consumption of energy in commercial buildings like hotels, malls, and supermarkets. It also enables real-time monitoring of waste production levels, providing managers with guidance on reducing wastage during normal operations, even in the absence of people. Ultimately, this leads to the creation of more pleasant environments for living that are both indoors and outdoors.

Furthermore, it is crucial to build easily reachable and cost-effective sources of sustainable energy, healthcare facilities, and educational institutions in every community. It is imperative to provide equal consideration to the conservation of various cultures while undergoing the development process. Failure to adequately plan in these areas will surely fail our systems. Hence, we urge all individuals to embrace a worldwide outlook when implementing measures at the local level. By taking action, we can increase our chances of achieving our goals (as discussed here) soon, instead of suffering imminent catastrophe if we don't make quick adjustments.

CONCLUSION

The successful implementation of green building methods requires the smooth collaboration of the contractors, engineers, architects, and clients in all stages. Green building is about safeguarding resources like water, land, energy, materials, etc., in the entire lifespan of the buildings. Its main goals are to protect the environment, reduce pollution, and provide people with a safe, pleasant, and efficient place by promoting balance in resources, reducing waste, and maintaining harmony with nature.

This study explains how waste materials can be used in the construction of green buildings to maintainable development by supporting the objectives of the Paris Agreement. It stressed the importance of using sustainable construction methods that reduce waste and promote recycling. It discussed the Paris Agreement, which states that these features are necessary and important to reduce greenhouse emissions globally.

In this study, various important points were brought up and discussed. One among them was the importance of minimizing waste in the design phase. Another one is the importance of research and adoption of sustainable methods for construction and waste management systems. It discussed that certain policies must be developed internationally like the

Paris Agreement. It also discussed the positive effects of using green building materials, which are made from recycling and reusing waste to achieve the goals that are laid down by the Paris Agreement.

The main objective of this study is to collect the existing knowledge about sustainable construction practices and their features. There are still a lot of areas that need to be looked into and researched. Apart from these, it suggests various ideas for research to be made in the future. A few of such possible future research is the investigation of circular economy models in green buildings, and another one is to analyze and assess the most efficient policies to encourage the reuse of waste materials. All these suggestions align with Sustainable Development goals made at the UN Climate Change Conference's COP 21.

These findings might help in providing valuable insights into the possibility of reusing materials and supporting sustainable building practices in the construction industry and it aligns with the goals that are set up in the Paris Agreement.

Authors' contributions: *Methodology and original draft preparation by Vyshnavi Yaddanapudi, Supervision and formal analysis by Yogesh Dharangutti and Abhijit Vasmatkar.*

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Integrating environmental justice principles into urban waste management in India through sustainable development goals

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Urban waste management in India is significantly challenging, as waste disposal lacks proper management and adequate infrastructure, leading to adverse environmental and health impacts on society. This paper examines the integration of environmental justice principles into urban waste management in India through Sustainable Development Goals (SGDs). This paper analyses the existing legal framework aimed at promoting equitable urban waste management practices, the provisions of the Indian Constitution, including Article 21 [1], Article 48A [2] and Article 51A(g) [3], and their alignment with SDGs (3, 6, & 11) [4]. Additionally, this research highlights the importance of incorporating environmental justice principles to achieve sustainable and inclusive urban waste management through a critical analysis of the "Municipal Solid Waste (Management and Handling) Rules, 2000", and its interpretation and implementation. It further identifies the loopholes in the current legal framework and aims to address them to ensure accountability among all stakeholders by adhering to the SDGs and constitutional mandates so that India can progress towards fairer and more sustainable urban waste management system.

Keywords: Environmental justice principles, urban waste management, sustainable development goals (SDG).

INTRODUCTION

Urbanization and industrial growth have greatly influenced the rapid economic progress of India, transformed its urban areas and opened up new avenues for development. These factors have presented significant challenges, especially when it comes to managing waste in urban cities. Because of the fast-growing urban population, unsustainable consumption, habits, and lack of proper waste management infrastructure the cities in India are dealing with the water crisis. It is quite challenging to manage urban waste due to various factors such as in adequate collection systems, limited treatment and disposal facilities, and a lack of public awareness and involvement. All these factors possess a threat to the well-being of both humans and environment. A lot of environmental problems are caused due to poor waste disposal practices like water, pollution, soil erosion, air contamination, and increased risk of diseases. And because of these issues, people of marginalized communities, living near waste disposal sites have been affected disproportionately.

The people of marginalized groups, informal waste collectors and sanitation workers, face, specially face higher risk of environmental and health hazards because of inadequate current waste management methods. The lack of fairness and inclusivity in waste management is a problem because it worse since social inequalities and makes it harder to achieve social justice and sustainable development goals. Therefore, there is a need for a holistic and impactful approach to achieve social and environmental justice and sustainable development goals to manage waste in urban cities. The environmental justice ensures that environmental benefits and burdens are distributed fairly among all the stakeholders, involving stakeholders in decision-making and held in institutions and policy makers, accountable for environmental governance.

The incorporation of environmental Justice principles into urban waste management aims to reduce environmental pollution, protect public health and encourage social equality, community resilience and sustainable urban development. There is a need to thoroughly assess the existing policies, methods, and systems to ensure inclusivity, promote participation and endorse environmental sustainability. This research discusses how environmental justice principles be incorporated into waste management in urban cities of India by using sustainable development goals framework. This people will thoroughly conduct a comprehensive analysis of the existing legal and policy framework, which include examining the provisions of Constitution, legislative measures and regulatory tools. It will identify the gaps contradictions or the areas that need to be addressed in order to achieve effective waste management. It further will examine how India's urban waste management strategies

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align with the sustainable development goals, specifically SDG 3 (good health, and well-being), SDG 6 (clean water and sanitation) and SDG 11 (sustainable citizen communities). This research will provide valuable insights and potential strategies to improve the efficiency inclusivity and sustainability of urban waste management in India by analyzing global business practices, case studies and innovative methods. The study involves identifying the main challenges, promising initiative and practical policy recommendations. It also aims to educate about significance of incorporating environmental justice principles into urban waste management system in order to deal with the intricate issues of urbanization, waste management and sustainable growth to the professionals, policymakers, civil society groups, and other stakeholders.

STATEMENT OF PROBLEM

Waste management in urban cities of India is a challenging issue due to lack of proper infrastructure, inadequate policies, limited involvement of stakeholders and the negative impact on the environment, society, economy and health caused by improper waste disposal, recycling and resource recovery practises. There are still major problems with how waste is managed in cities and regions across India, even though there are laws, policies and international agreements in place to encourage sustainable waste management. This leads to a major risk to environment, health, fairness, and economic losses. The current urban waste management in India is getting worse due to factors like rapid urbanization, population, growth, industrialization, consumption patterns, and lifestyle changes, causing an increase in waste generation, making it more complex and diverse issue to be dealt. As a result, waste management, systems, processes, and services are facing challenges in terms of capacity, efficiency, and effectiveness. Moreover, the lack of consideration for environmental justice principles involving stakeholders and engaging the community in waste management, decision-making, policy, creation and implementation has led to social injustice, inequality and marginalization. This leads to negative impact on the rights, dignity and well-being of waste because informal waste workers, vulnerable populations, and marginalized communities who are involved in waste collection, recycling and disposal activities. The lack of proper integration of principles of environmental justice, Sustainable Development Goals (SDGs) and constitutional provisions such as Article 51, Article 48A and Article 51A(g) into urban waste management laws along with the limited enforcement, regulations, tracking and accountability mechanisms and organizational capacities have been a barrier to progress, innovation and transformation in the urban waste management sector. This has impeded the achievement of sustainable development goals, environmental sustainability social equity and economic prosperity in the urban areas in India. Therefore, in order to transform urban waste management systems, practices and outcomes, create cleaner, healthier and more sustainable cities and communities and promote well-being, prosperity and resilience for all in India, there is an urgent need for comprehensive, integrated and inclusive approaches, strategies and interventions to address the systematic challenges, barriers and gaps in urban waste management.

LITERATURE REVIEW

The article *"Environmental Justice and Sustainable Development"* by B. Gebeyehu *et al.* [5] explores environmental justice, tracing its historical roots and focusing on racial and ethnic disparities in environmental risk exposure. It examines the evolution of the environmental justice movement to address broader issues like getting healthy food and impact of climate change on marginalized communities. The authors also underscore the interconnectedness between both, highlighting the need to meet the present needs without jeopardizing the ability of future generations to satisfy their own wants. However, this paper points outs several research gaps, including the need for a global analysis of environmental justice movements, a deeper exploration of intersectionality in the environmental impacts, more empirical studies on sustainable development and environmental justice, and concrete policy recommendations for integrating environmental justice into sustainable development initiatives.

Another article is *"Role of Indian Regulatory Authorities in Integrating Environment Justice into Industrial Siting Decisions"* by Yashaswini Mittal [6]. In this paper, the author has discussed the role of regulatory authorities in ensuring environmental justice in industrial siting decisions. It emphasizes procedural components of environmental justice, such as public participation, transparency, and accountability, and their role in promoting social justice and equality of opportunity. The article also discusses the Indian philosophy of dharma and its similarity to Rawls' theory of social justice in the context of environmental justice. However, the article lacks discussion on the impact of industrial siting decisions on marginalized communities, particularly those living in special areas like forest land and scheduled areas. The article could have also explored the role of civil society organizations and international frameworks in promoting environmental justice in industrial siting decisions and thus there is a need for further research.

Another article available is *"Waste as a Social Dilemma: Issues of Social and Environment Justice and the Role of Residents in Municipal Solid Waste Management, Delhi, India"* by Adriana Milea [7]. The author explores factors influencing waste decisions, drawing from theories on common-pool dilemma situations and environmental issues. It emphasizes the importance of understanding people's actions related to waste handling, as they are determined by historically built structures, values and knowledge. The author research aims to contribute to theories for problem-solving programs and interventions, emphasizing on the effective separation of hazardous waste from biodegradable and non-biodegradable materials. However, gaps exist, such as the lack of focus on hazardous waste and impact of social norms on trash segregation. The study employs mixed methods and is primarily deductive in its approach. The research's limitations may limit its generalizability to other contexts.

In the *paper "Innovations in Recycling for Sustainable Management of Solid Wastes"* by Nazia Parveen *et al.* [8] the authors have discussed the swift production and build-up of waste in developing is a significant issue because of urbanization, industry, inadequate government policies and population increase. The authors emphasize the need for strict laws, increased awareness, and innovative techniques to control solid waste in developing countries. They suggest waste-to-energy technologies for energy production and carbon emissions reduction. However, the review lacks comprehensive studies on waste impact, recycling and composting techniques, innovative technologies, public-private partnerships, waste management policies, and community engagement. Thus, further study can be carried out.

URBAN WASTE MANAGEMENT IN INDIA: CHALLENGES SND IMPACTS

Urban waste generation and management: an overview

India's cities are facing a growing waste management challenge due to swift urban expansion, population increase, and changing consumption habits. Current projections suggest that Indian urban areas, each year produce municipal solid waste which is more than 62 million tons, a number set to double by 2030 if the present trends persist. However, the existing waste management systems are largely insufficient to manage the rising volume and diversity of urban waste. In numerous Indian cities, the current waste management methods are largely linear and reactive, mainly concentrating on collection and disposal, rather than embracing proactive, sustainable, and circular methods that emphasize waste minimization, reuse, and recycling. The absence of holistic waste management plans, along with insufficient investment in infrastructure, technology, and manpower, has led to ineffective waste collection systems, widespread littering, open dumping, and unregulated landfill use, leading to environmental harm, health hazards, and social inequalities.

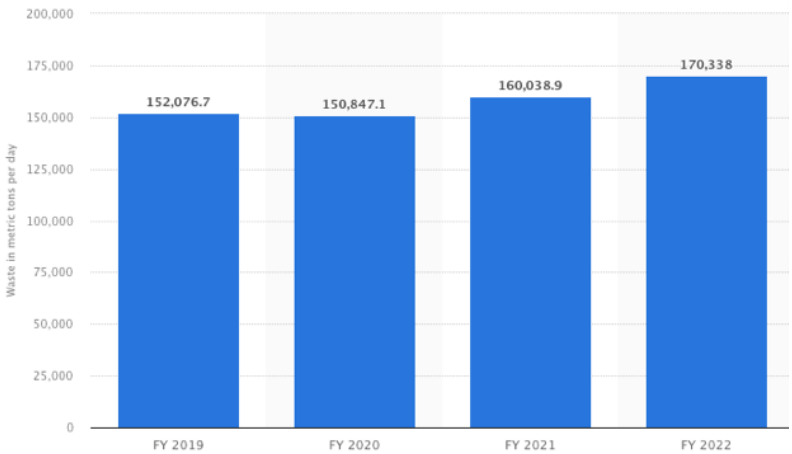

Figure 1. Total municipal solid waste generated per day in India from FY 2019 to FY 2022. [Source: India; Central Pollution Control Board; FY 2019 to FY 2022] (Open access doesn't require copyright permission)

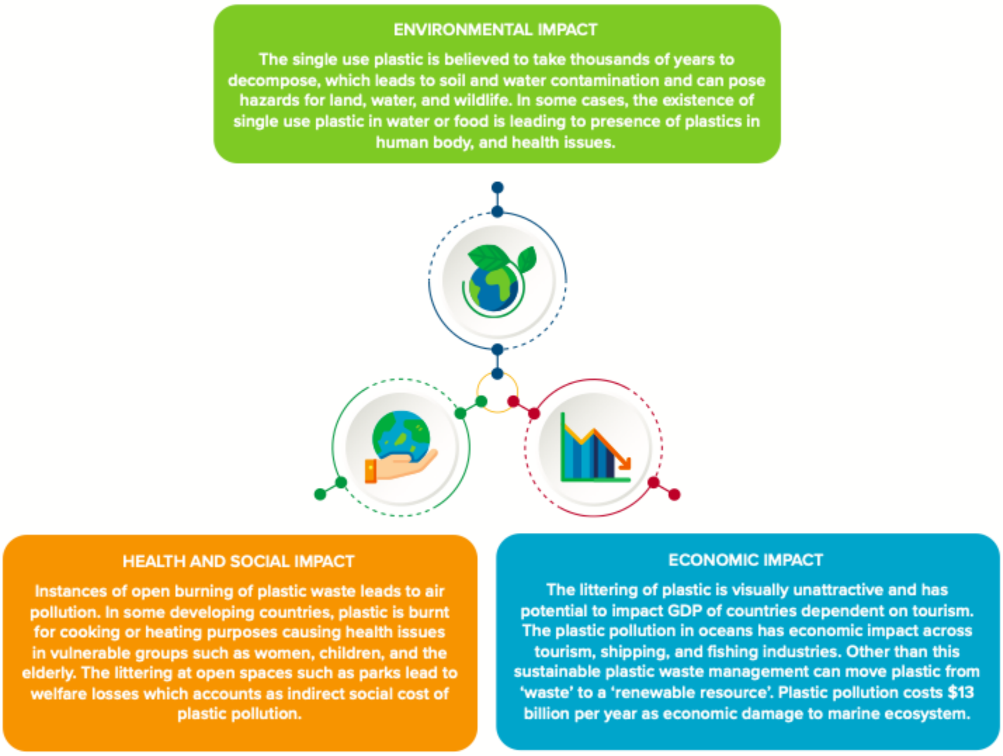

Figure 2. Environmental health and economic impact of municipal waste. [Source: https://www.unep.org/news-and-stories/story/plastic-planet-how-tiny-plastic-particles-are-polluting-our-soil] (Open access doesn't require copyright permission)

Inadequate waste management: environment and health impacts

There can be various reasons for inadequate waste management. There are a few main reasons for this, such as not having enough infrastructure, having weak legislation, and a lack of public awareness. It can be difficult for municipal authorities to implement effective waste management programs because they often have limited resources. Furthermore, in many developing countries, there is a lack of resources to set up a dependable waste management system. As a result, residents have limited choices when it comes to safely disposing of their waste. Improper waste management can cause significant harm to the environment, for example, if waste is not disposed of properly, it can result in the release of harmful chemicals and pollutants that can contaminate our environment. This contamination can lead to pollution of the soil and water. These issues lead to damaged ecosystems, loss of biodiversity, and climate change. In addition, waste disposal sites like landfills and incineration facilities release greenhouse gases that contribute to the problem of global warming. Waste management problems can have a significant impact on public health. Being exposed to hazardous waste can lead to various health problems, including respiratory issues, skin irritations, and infections. Furthermore, waste has the potential to attract and host disease-carrying insects and pests. This can result in the transmission of diseases such as dengue fever, malaria, West Nile virus, and Zika. Moreover, when waste is dumped into our waterways and oceans, it causes pollution that endangers both human and animal life.

Social inequalities in waste management

Social justice is to achieve equitable distribution of social, environmental, and economic benefits and drawbacks. Vulnerable populations worldwide still face unequal access to rights and opportunities, and bear a disproportionate weight of environmental issues, such as insufficient waste management and its consequences. The pursuit of justice for both humanity and the planet is not a separate matter, but rather intricately interconnected. The environment is constantly influencing our life, while human activity has a huge impact on it. Environmental justice is a crucial aspect of social justice that focuses on addressing inequalities related to activities such as waste disposal and resource exploitation, which lead to environmental deterioration and disproportionately affect the most vulnerable people. Most incinerators, dumps, landfills, and burn factories are situated in close proximity to low-income neighborhoods, communities of color, and marginalized populations. Residents have everyday challenges due to insufficient noise control, litter accumulation, heightened vehicular congestion, unpleasant odors, and air pollution. Incinerator emissions result in health-related problems caused by excessive exposure to particles and hazardous contaminants, hence elevating the likelihood of cardiovascular and respiratory ailments, with youngsters and the elderly being the most vulnerable. In India, waste pickers are the sole means of solid waste collection, offering numerous advantages including elevated recycling rates, improved public health and safety, and enhanced environmental sustainability. However, waste pickers persist in facing significant vulnerability, laboring under hazardous and detrimental circumstances. For many years, the environmental and social justice movement has worked to bring attention to the difficulties faced by underprivileged communities. Their goal is to address the unequal distribution of environmental benefits, such as access to nature, green spaces, clean air and water, and landscape improvements. They also aim to address the disadvantages faced by these communities, such as the risks of hazards from industrial, transport-generated, and municipal pollution. Both social and environmental justice focus on power dynamics, namely on identifying the individuals or entities responsible for pollution or waste, as well as those who are negatively impacted by it. Environmental rights are situated at the point where human rights and environmental preservation converge.

Legal framework for urban waste management system in India

During early times, the disposal of human and other garbage was not a major concern because of the limited population and ample acreage accessible for waste assimilation. However, the escalating and varied waste generated by the rapid economic expansion and overpopulation has made the management of urban waste a significant concern for many Municipal Authorities and Urban Local Bodies. This responsibility includes overseeing public health and sanitation, as improper disposal of solid waste contributes to serious health, environmental, and aesthetic issues. The situation in developing countries has become increasingly complex and challenging due to inadequate infrastructure and financing, lack of clear responsibilities and functions of the authorities, insufficient norms, legal framework, and poor enforcement. In India, the uncontrolled and rapid expansion of cities and the spread of slums, resulting from both a desired quick industrialization and an undesired population boom, have led to a significant rise in public concern regarding sanitation and environmental issues. Hence, let’s review the legal frameworks and profiles that exist for urban waste management in India.

Constitutional provisions: Articles 21, Article 48A & Article 51A(g)

The Indian Constitution serves as the supreme legal document, providing a comprehensive framework for the preservation of the environment, promotion of sustainable development, and improvement of public health and welfare. The clauses of the constitution lay the groundwork for environmental conservation, waste disposal, and sustainable development. The *Article 21 of the Constitution* ensures that every individual has the fundamental right to life and personal freedom. The Supreme Court has interpreted this right to include the right to live in a clean and healthy environment. This understanding places an obligation on the government to guarantee environmental protection and sustainable development, highlighting the crucial role of environmental quality in upholding citizens' fundamental rights and dignity. The *Article 48A of the Constitution* requires the state to conserve and enhance the environment and protect forests and wildlife. It recognizes the value of nature, biodiversity, and ecological balance, emphasizing the importance of sustainable environmental care and conservation efforts for the well-being of present and future generations. The *Article 51A(g) of the Constitution* states that every citizen has a fundamental duty to protect and improve the natural environment, which includes forests, lakes, rivers, and wildlife. This emphasizes the importance of individuals in preserving the environment, promoting awareness, education, and civic participation to foster a culture of environmental responsibility and sustainable lifestyles. These constitutional clauses provide a solid legal foundation for integrating environmental considerations, such as waste management, policy development, planning, governance, and decision-making at all levels of government and society. They enhance the legal and the ethical responsibilities for protecting the environment, promoting conservation, and fostering sustainable development.

The Municipal Solid Waste (Management and Handling) Rules, 2000

The Municipal Solid Waste (Management and Handling) Rules of 2000 are the primary legislative guidelines governing the handling, management, and disposal of municipal solid waste in India.

"These regulations aim to standardize waste management practices, promote waste reduction, segregation, collection, treatment, and disposal, while mitigating the adverse environmental impacts and health hazards associated with inadequate waste management." The main provisions of the rules include:

- *Waste segregation:* The rules require waste to be classified into biodegradable, non-biodegradable, and hazardous types at the household, institutional, and commercial levels to facilitate recycling, composting, and proper disposal. This promotes the adoption of waste segregation methods, waste reduction strategies, and sustainable consumption habits to minimize waste generation and promote resource reuse.
- *Waste collection and transportation:* The standards set for waste collection, transportation, and disposal emphasize the importance of effective and eco-friendly waste management practices, infrastructure improvement, and stakeholder engagement. The objective is to enhance waste collection efficiency, reduce littering, illegal dumping, and open waste burning, and improve the overall cleanliness and hygiene of urban areas.
- *Waste processing and treatment:* Promoting the use of waste processing technologies, composting, recycling, and converting waste to energy to reduce waste production, reclaim resources, and decrease the amount of waste sent to landfills. It advocates for the creation of sustainable waste management facilities, the adoption of cutting-edge technologies, and the incorporation of circular economy principles into waste management strategies to boost resource efficiency and environmental sustainability.
- *Landfill management:* Establishing criteria for landfill design, construction, operation, and closure to reduce environmental pollution, soil and groundwater pollution, and public health hazards linked with open dumping and unregulated landfilling. It underscores the significance of landfill gas control, leachate treatment, landfill site cleanup, and closure strategies to lessen environmental effects and guarantee the safe and sustainable handling of landfill locations.
- *Public awareness and capacity building:* Encouraging public awareness, education, and skill-building programs to stimulate community involvement, encourage behavioral shifts, and boost stakeholder participation in waste management and environmental preservation initiatives. It advocates for the active engagement of civil society, community groups, educational bodies, and the private sector in waste management projects, advocacy drives, and outreach efforts to elevate consciousness, develop capabilities, and rally backing for sustainable waste management practices.

Despite the comprehensive regulatory framework provided by the Municipal Solid Waste Rules, the successful implementation, enforcement, and oversight encounter significant obstacles due to limited resources, institutional capacity constraints, and insufficient stakeholder involvement. There is a need to strengthen regulatory compliance, enhance institutional collaboration, increase investments in waste management infrastructure, and promote collaborative efforts among various stakeholders to effectively address the complex issues of urban waste management.

Urban waste management and sustainable development goals (SDGs)

India's efforts in urban waste management are increasingly in line with the Sustainable Development Goals (SDGs), demonstrating the nation's commitment to achieving inclusive, fair, and sustainable growth. Aligning with the SDGs provides a strategic framework for integrating environmental sustainability, social inclusivity, and economic well-being into urban waste management plans and endeavors.

- *SDG 3 "Ensure healthy lives and promote well-being for people of all ages"* emphasizes the importance of providing access to secure and cost-effective healthcare services, minimizing environmental hazards, and preventing diseases associated with inadequate waste management. It advocates for integrating health perspectives into waste management policies and actions. Additionally, it stresses the need to enhance public health monitoring, surveillance, and response mechanisms to detect, counteract, and prevent health threats and disease outbreaks related to environmental contamination, water pollution, and waste-associated risks.
- **S***DG 6 "Ensure availability and sustainable management of water and sanitation for all."* highlights the significance of providing everyone with access to clean water and proper sanitation. It underscores the need for sustainable water management, wastewater treatment, and measures to prevent pollution to safeguard both water sources and public health. The goal promotes the use of comprehensive water resource management methods, water-saving techniques, and water quality checks to strengthen water safety, improve sanitation facilities, and reduce waterborne illnesses associated with poor sanitation and wastewater practices.

- *SDG 11 "Make cities and human settlements inclusive, safe, resilient, and sustainable."* underscores the necessity of building inclusive, safe, resilient, and sustainable cities and communities. It calls for thoughtful urban planning, the development of robust infrastructure, wise waste management, and effective environmental governance to enhance living standards, minimize environmental harm, and support sustainable urban growth. The goal encourages the adoption of eco-friendly building methods, sustainable transportation options, green urban areas, waste minimization efforts, and infrastructure resilient to climate challenges to advance environmental health, social equity, and economic progress in cities.

By "integrating urban waste management plans with the SDGs, India aims to address the interconnected issues of environmental harm, health hazards, and social inequalities."

Figure 3. State wise per capita solid waste generation. [Source: Annual Report on Solid Waste Management 2020-21, CPCB, Delhi] (Open access doesn't require copyright permission)

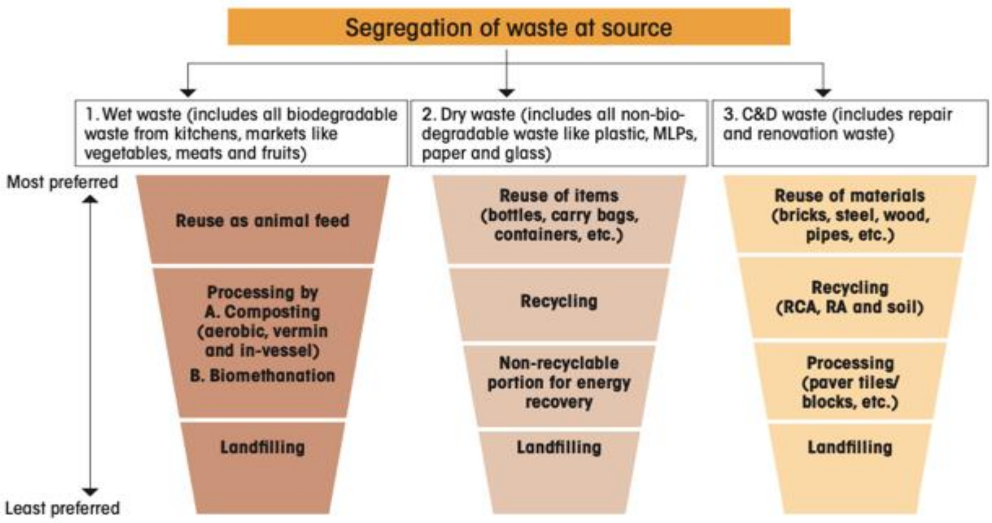

Figure 4. SDGs linkages through effective plastic waste management in a city. [Source: https://www.corpseed.com/knowledge-centre/plastic-waste-management-amendment-rules-2022] (Open access doesn't require copyright permission)

This approach establishes a connection between safeguarding the environment, enhancing public health, and striving for sustainable development goals". It calls for comprehensive, united, and community-focused approaches that consider the complex interrelations among environmental, social, economic, and institutional elements influencing waste management practices and outcomes in India

ENVIRONMENTAL JUSTICE PRINCIPLES AND SUSTAINABLE DEVELOPMENT GOALS (SDGS)

Environmental justice is the fair distribution of environmental benefits and burdens, ensuring that everyone, regardless of social status, race, gender, or location, has equal access to a clean and safe environment. "Equity ensures that everyone receives a fair share of environmental benefits and doesn't bear an unequal burden of environmental problems. It involves addressing social inequalities and systemic injustices to narrow environmental gaps and achieve the goals of environmental justice." Participation emphasizes the need for inclusive decision-making regarding the environment, involving local communities, non-profit groups, and indigenous communities. Accountability ensures that all parties involved take responsibility for their actions, following environmental laws and rules, thus preventing harm to the environment and promoting sustainable living.

- *Equity:* Environmental fairness ensures that everyone receives their fair share of environmental benefits and does not bear an unequal burden of environmental problems. It involves preventing marginalized groups and those most at risk from being unfairly exposed to pollution or denied access to clean air, water, land, and natural resources. This requires addressing social inequalities and systemic injustices that contribute to environmental damage, health problems, and economic disparities in society. "Prioritizing fairness in how we make environmental decisions, set policies, and distribute resources is crucial for promoting inclusivity, narrowing environmental gaps, and achieving the goals of environmental justice."
- *Participation:* Environmental involvement emphasizes the importance of allowing everyone to have a say in decisions that affect our environment. This includes local communities, non-profit groups, indigenous communities, and those who are often excluded from these discussions. "It's about fostering a democratic approach where decisions are made openly, with clear accountability, and where the public plays a real role in shaping environmental policies and actions." By encouraging people and communities to share their insights and concerns, we can better shape policies that truly reflect their needs and priorities, promoting both environmental care and community empowerment.*Accountability:* Environmental account-ability ensures that everyone involved takes responsibility for their actions. This means that our leaders, companies, and organizations should adhere to environmental laws and regulations, with mechanisms in place to verify compliance. It's about being transparent and honest in how we manage our environment, building trust, and ensuring that everyone abides by the same rules. By enhancing these accountability measures and encouraging businesses to fulfil their role, we can prevent harm to our environment, address any concerns people might have, and work towards a future where we all live sustainably.

INTEGRATING ENVIRONMENTAL JUSTICE PRINCIPLES INTO URBAN WASTE MANAGEMENT

- *By addressing gaps in legal framework* India is working to sync up its waste management efforts with the SDGs to tackle the intertwined issues of environmental harm, health concerns, and social disparities. "This means weaving together efforts to protect the environment, boost public health, and promote sustainable growth. It calls for a comprehensive, unified approach that considers the intricate mix of environmental, social, economic, and institutional elements that influence how waste is managed in urban areas in India."
- *Strengthening the regulatory framework:* Improving the laws and policies guiding how we manage waste in cities is vital for tackling the deep-seated issues and shortcomings in waste management practices. This involves reviewing and refreshing current laws, rules, and recommendations to embrace fairness in the environment, encourage sustainable waste management methods, and strengthen how we ensure rules are followed, complied with, and overseen.
- *Promoting policy integration and coherence*: Making sure policies work well together across various areas like city planning, protecting the environment, public health, water and sanitation, and social support is key to creating harmony, cutting down on redundant efforts, and making urban waste management projects more effective, efficient, and sustainable. This means bringing everyone together, encouraging teamwork between different agencies, and supporting a joint approach to planning, carrying out, and assessing waste management efforts.

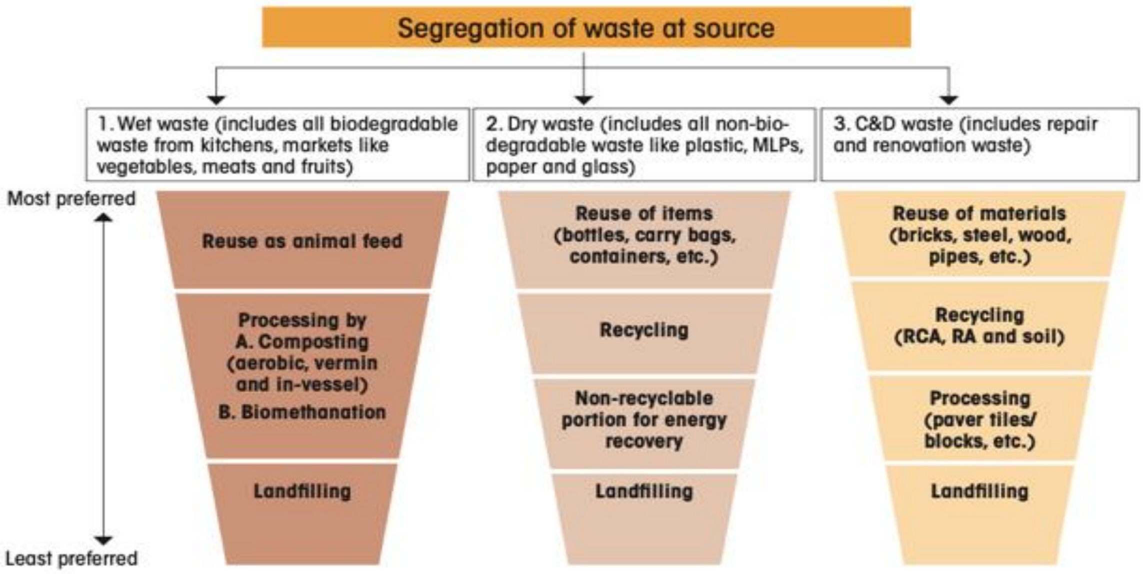

Figure 5. Hierarchy to Effective Municipal Waste Management. [Source: Guidelines for Swachh Bharat Mission (Urban) 2.0, 2021] (Open access doesn't require copyright permission)

- *Enhancing legal enforcement and compliance:* Boosting the ways we enforce the law, increasing penalties for breaking them, and stepping up oversight are crucial for making sure people follow environmental rules and standards. This means giving more power to the agencies in charge, equipping them with what they need like resources, tools, and training and working closely with the police, courts, community groups, and others to make sure environmental wrong doings are dealt with effectively and fairly.
- *Facilitating access to justice:* Making sure everyone affected by environmental issues has a fair shot at justice and access to legal solutions is key to protecting environmental rights and holding those responsible accountable. This means improving legal support for those affected, backing community efforts, supporting public interest cases, and encouraging judges to take an active role in environmental cases, making sure justice is accessible and fair for everyone.

Enhancing stakeholder participation and accountability

Getting everyone (stakeholder participation) involved and holding each other accountable in urban waste management helps make the process more transparent, inclusive, and democratic. This way, people and communities can have a say in decisions, share their insights, and make sure those in charge are doing their part responsibly and effectively.

- *Promoting public engagement and participation:* Encouraging people to get involved, share their thoughts, and work together with local authorities in planning and managing waste helps build a sense of ownership and strengthens our communities. This means spreading awareness, educating the public, organizing discussions, and setting up spaces for cooperation and partnership among government bodies, community organizations, schools, and businesses. Together, we can take collective action and find collaborative solutions to waste management challenges.
- *Promoting transparency and accountability:* Making decision-making, policy creation, and the evaluation of urban waste management more open and transparent is key to gaining trust and building credibility in these efforts. This means sharing information openly, making data accessible, and reporting on performance. It also involves giving citizens a way to oversee actions, provide feedback, and voice concerns, while also holding those responsible for waste management accountable for their actions and the effects they have on the environment, society, and economy.
- *Empowering vulnerable groups/ communities:* It's crucial to empower marginalized communities, vulnerable groups, and those often left out of the conversation, like informal waste pickers, sanitation workers, indigenous peoples, women, children, the elderly, people with disabilities, and others. This helps promote fairness, reduce disparities, and support environmental justice in managing urban waste. This means including them

in decisions, policies, and actions, addressing their unique challenges and needs, and standing up for their rights and well-being. Through focused efforts and support, we can ensure they have better access to resources, opportunities, and protection.

Developing inclusive and sustainable waste management practices

Encouraging waste management that cares for the environment, public health, fairness, and economic health is key to building sustainable cities, resilience, and ensuring everyone benefits equally from waste management decisions.

- *Adoption of circular economy approaches:* "Adopting circular economy ideas that focus on cutting waste, reusing resources, recycling, and turning waste into energy is vital. This approach helps us use resources better, cut down on pollution, and encourage more sustainable ways of making and using things." It means supporting green products, smart technologies, and new ways of doing business that help both the planet and our communities thrive.
- *Investment in technology and infrastructure:* Putting money into up-to-date, effective, and eco-friendly waste management systems and technologies is key. This means improving how we collect, recycle, compost, and manage waste, as well as how we turn it into energy. By doing this, we can boost our waste management abilities, offer better services, lessen our environmental footprint, and encourage greener waste practices. It's about getting both public and private sectors involved, using "creative ways to fund projects, and teaming up to bring about sustainable waste solutions, spur tech advancements, and make waste management more efficient."
- *Promotion of education, awareness and behavioral change:* Encouraging people, communities, businesses, and organizations to learn about the environment and change their behaviors is key to creating a mindset of caring for our planet. It's about promoting ways of living that are sustainable and getting everyone involved and excited about making waste management better. This means creating programs, campaigns, workshops, and outreach efforts that help people and communities understand and take action.

CASE STUDIES ON INCLUSIVE URBAN WASTE MANAGEMENT SYSTEM

Many cities and communities globally are tackling urban waste challenges in different ways. These range from creative local programs and community-driven efforts to technological breakthroughs and policy changes. Here are some successful case studies that prove sustainable, inclusive and robust waste management systems are possible and by drawing lessons from these effective approaches and adopting a comprehensive strategy that includes environmental justice, involving everyone and using innovative ideas, the cities can lead the path towards a sustainable future where waste is reduced, resources are used wisely and communities live in balance with their surroundings.

- *Curitiba, Brazil: Green Exchange Program*

Curitiba, Brazil's waste management system is well recognized globally for its innovative and inclusive strategy, which emphasizes on waste reduction, recycling, composting and public participation using the various methods. The Green Exchange Program in Curitiba attempts to incentivize individuals to contribute in waste sorting and recycling by providing rewards such as bus tokens, fresh produce and other things in place of recyclable materials. The campaign encourages for recycling, promotes waste segregation and cultivates stronger environmental consciousness and involvement from the community. The integrated waste management facilities have been established including composting sites, recycling centers and waste-to-energy plants. It facilitates the sorting, processing and treatment of many kinds of garbage, fostering reuse of resources and lowering the quantity of waste dumped in landfills. Curitiba emphasizes on promoting education and public awareness regarding waste management programs like extensive public awareness campaigns, initiatives like community involvement and special environmental education programs. These campaigns and programs aim to educate people, promote sustainable practices and motivating individuals to take an active part in reduction of waste and preservation of environment.

- *Fukuoka, Japan: Hydrogen from Sewage*

From its sewage, the City of Fukuoka has produced hydrogen to run fuel-cell cars. It is imperative to use cutting edge technology while striving for a low-carbon civilization. Already becoming more and more common in the city are electric vehicles; yet, Fukuoka has certain difficulties, such as charging times and relatively small driving ranges. As so, a different course of action was taken. At the specialized fueling station the city constructed, hydrogen produced by the processing of the sewage produced everyday by Fukuoka's 1.58 million residents may be injected into fuel-cell cars. In the area of hydrogen research, Fukuoka is working with several universities and businesses. Since the project's beginning, normal cars as well as motorcycles and logistical trucks in the city center have been powered by hydrogen energy produced from domestic sewage. Fukuoka plans to establish a range of energy supplies across the city in addition to using it for mobility purposes. Since the energy can be used as a reserve in case of need, the city thinks the project will facilitate resilient, disaster-resistant urban development.

- *Barcelona, Spain: IoT sensors, smart waste collection system:* Barcelona implemented a city-wide smart waste collection system using IoT sensors. Real-time monitoring allowed for optimized collection routes, leading to a significant reduction in operational costs and environmental impact.
- *Singapore: Semakau Landfill and Waste-to-Energy Plants:* Singapore, facing land scarcity, combines intelligent landfill management at Semakau Landfill with waste-to-energy plants. This comprehensive approach minimizes landfill usage while generating clean energy for the city.
- *San Francisco, USA: Zero Waste Program:* The Zero Waste Program in San Francisco focuses on getting citizens involved and using a three-bin sorting system. The city's excellent work with composting and recycling demonstrates how successfully their waste reduction plan is operating. Creating resilient, sustainable and delightful to live in cities depends critically on smart waste management.
- *Pune, India: SWaCH:* The "Solid Waste Collection and Handling (SWaCH) Cooperative is a pro-poor partnership aimed at establishing itself as a self-sustaining social enterprise of waste workers, focussed on sustainable solid waste management (SWM) and waste worker rights". The operational costs of running the initiative (equipment, vehicles) are covered by the PMC, while waste workers are paid by customers and scrap recyclers. Initially only focused on uplifting the lives of waste workers, the SWaCH Cooperative has since diversified its actions to also provide SWM services such as composting, responsible disposal of e-waste, cleaning up the city's water bodies through organized activities etc. "By late 2007, the State Government mandated the implementation of Municipal Solid Waste Laws 2000, across all cities, which acted as a catalyst for the growth of the SWaCH Cooperative"[1]. "Through SWaCH initiatives, 60 metric tons of waste is diverted away from landfills every day, with 80-85% of the waste generated in the city being recycled/processed, resulting in annual GHG emission savings of approximately 50,000 tons of CO_2"[2]. The SWaCH Cooperative's door-to-door collection model has helped PMC save INR 900M rupees (USD 12.5M) per year in labour, processing and transportation costs, which is 46 percent of the capital budget for Pune's SWM system. SWaCH Cooperative's efforts also helped with socio-economic upliftment of its 3500+ waste worker members, from formalizing their work contracts and getting them access to health and welfare protections to supporting their families and children access loans, scholarships, vocational skills training etc. "The SWaCH Cooperative has influenced policy decisions on SWM beyond Pune, and elements of the SWaCH model are being implemented across other Indian cities."[3]

Periodically, the SWaCH Cooperative organizes events that unite city dwellers, NGOs, and waste workers on a single platform in order to increase awareness and facilitate dialogue and debates on waste management problems and policies. Red dot campaign was one important effort started to raise awareness of sanitary waste disposal methods that are safe and hygienic. Waste workers initially brought up the necessity for this kind of project during one of their frequent meetings with the Board. The SWaCH staff picks up 20,000 kg of sanitary pads and soiled diapers every day. Workers who have to separate sanitary waste from other trash are at risk for health problems from exposure to it. For thirty thousand city dwellers, door-to-door initiatives were planned to spread knowledge about the need of wrapping and red-dotting sanitary trash. The SWaCh workers themselves also created paper bags with red dots on them, which they sold for a little money while they were out and about. A daily reminder of the program was provided by the red-dot-marked compartments on waste pickup vans. Public areas had posters up, and t-shirts, mugs, and other gifts with comparable messages were also widely distributed. Menstrual health and sanitary disposal are other subjects covered in the workshops offered by the SWaCH Cooperative. The "Send it back" campaign, which the SWaCH Cooperative also started in 2013, involved sending sanitary pads back to the manufacturers of these products (Kimberly-Clark and Procter & Gamble) to encourage them to consider packaging waste and disposal more carefully when creating their product strategy. Thanks to the publicity this action

[1] Ibid at 22.

[2] Waste Management Cooperative: Pune, India, https://www.centreforpublicimpact.org/case-study/waste-management-cooperative-pune-india, Accessed 25 April, 2024.

[3] SWaCH Cooperative Pune, https://swachcoop.com/ , Accessed 26 April 2024.

generated, SWaCH employees are now actively working with Procter & Gamble to identify solutions for repurposing product packaging as biodegradable red-dot trash bags. A further project is the Recycling Trail, a shadowing field exercise run by the SWaCH Cooperative in which volunteers follow SWaCH's trash workers on their door-to-door rounds to get first-hand knowledge of Pune's waste management value chain.

The procedure of community involvement focused actions at the systems, community, and individual levels. The rights of informal trash workers in the city were to be protected, and SWaCH worked closely with the PMC to handle SWM in Pune. Raising public and other communities of informal waste workers nationwide knowledge of the problems of SWM and waste worker rights was their secondary goal.

POLICY RECOMMENDATIONS

Managing urban waste is a big problem all over the world, especially in fast-growing countries like India. We need strict and efficient rules and plans to handle waste better. The suggestions below aim to make waste management better by:

- *Making stricter laws:* We need stronger rules to manage waste properly. For example, every urban housing society should be penalized in case the Solid waste is not bifurcated as per law in dry, wet, biodegradable and non-biodegradable waste.
- *Involving more people:* We need to get more people involved in managing waste by encouraging building of community centers in local areas which educate people regarding the harmful effects of irresponsible waste management.
- *Building better facilities:* In this regard, Technology companies can be involved by setting up Public-Private Partnerships to deal with urban waste and build better facilities to recycle and reuse waste.
- *Training more people:* We need to teach more people how to manage waste properly. This can be done by conducting workshops in schools, colleges, government and private office spaces, and with the help of partnership with various NGOs in all districts across the nation.
- *Developing new waste management technologies:* We need to invent new ways to manage waste. This can be done by providing Research Fellowships in the field of waste management technologies and encouraging the topic in various research institutions and technological institutions.

Strengthening legal and regulatory frameworks

- *Enforcement and Compliance*: It is important that all the individuals strictly adhere to the waste management regulations. This can be done by enhancing rule enforcement, imposing stricter fines and penalties on the individuals not complying, monitoring major waste generating industries and sectors to mitigate pollution and promote responsible waste management.
- *Harmonization and Integration:* To ensure consistency across all the regions, it is important that we have uniform waste management rules and regulations. It is also important to integrate waste management strategies with other areas like urban planning, public health and protection of environment. Coordinating with other authorities is essential for efficient implementation of waste management rules, preventing repetition of efforts and enhancing the effectiveness of waste management initiatives.

Enhancing stakeholder engagement and public participation

- *Effective Stakeholder: Engagement* In order to achieve effective decision-making with regard to waste management in cities, it is crucial to ensure active engagement and involvement of all the individuals and encourage public participation.
- *Empowerment and Involvement of Communities:* It is imperative for the communities to be engaged, given power at local level, foster collaboration with other community groups, organizations an d local businesses. This fosters increased awareness, engagement and endorsement of enhanced waste management practices among individuals.
- *Stakeholder Consultation and Collaboration:* Every individual must be involved with all the stakeholders in waste management encompassing waste pickers, informal waste workers, local businesses and corporations. Exchange of knowledge, different perspectives and varied resources can be facilitated to collaboratively address waste management challenges, through engaging individuals in policy making, implementing strategies and monitoring progress.
- *Transparency and Accountability:* It is important to adopt transparency in decision making processes, making information accessible to everyone and developing ways for individuals to obtain feedback or complains. This ensures that the individuals are responsible for making choices and delivering services in waste management and held accountable for what they do and what impact they

create. It enhances trust and ensures credibility and acceptance of waste management efforts.

Investing in infrastructure and capacity building

- *Investment in modern waste management:* To build superior, highly efficient and environmentally sustainable waste management technologies, infrastructures and abilities, there is a need of allocating funds towards it. The growth in solar panels is an example of this. Various households are now bringing in solar powered grids thereby decreasing electronic waste generation.
- *Infrastructure Development:* We should invest in waste collection systems, recycling plants, composting facilities, waste-to-energy plants, and managing landfills. These need to meet environmental and safety standards, and be efficient, to expand waste management, cover more areas with waste collection, reduce waste, and promote recycling.
- *Capacity Building and Training:* We need to improve the skills of waste management professionals, policymakers, regulators, and service providers through training programs and knowledge-sharing platforms. This will enhance their knowledge of waste management practices, technology and innovations, therefore, optimising waste management operations and advocating for the most effective approaches.
- *Public and Private Investment:* In order to speed up the implementation of sustainable waste management solutions, stimulate innovation and enhance the efficiency of waste management, it is important to secure investments from both the public and private sectors, explore new financing methods and establish partnership between two entities. This will help in addressing budgetary challenges, enhancing infrastructure and expanding sustainable waste management programs.

Promoting research and innovation in waste management technologies

- *Research and Development:* In order to investigate and evaluate novel waste management technologies, techniques and solutions it is important to allocate resources towards research and development. This will allow to address emerging difficulties and develop strategies to enhance trash collection, segregation, recycling, composting and waste-to-energy conversion. Allocating resources to research endeavors facilitates the advancement of new ideas and enables informed decision making rooted in empirical data.
- *Technology Transfer and Adoption:* It is imperative to enhance the accessibility of information and utilization of emerging technology for individuals involved in trash management. This entails offering assistance and guidance to specialists in waste management, policymakers and service providers, adding them in the adoption of the most effective technologies and methods. It is imperative to promote collaboration among many stakeholders in waste management to expedite the adoption of novel technologies and innovations.

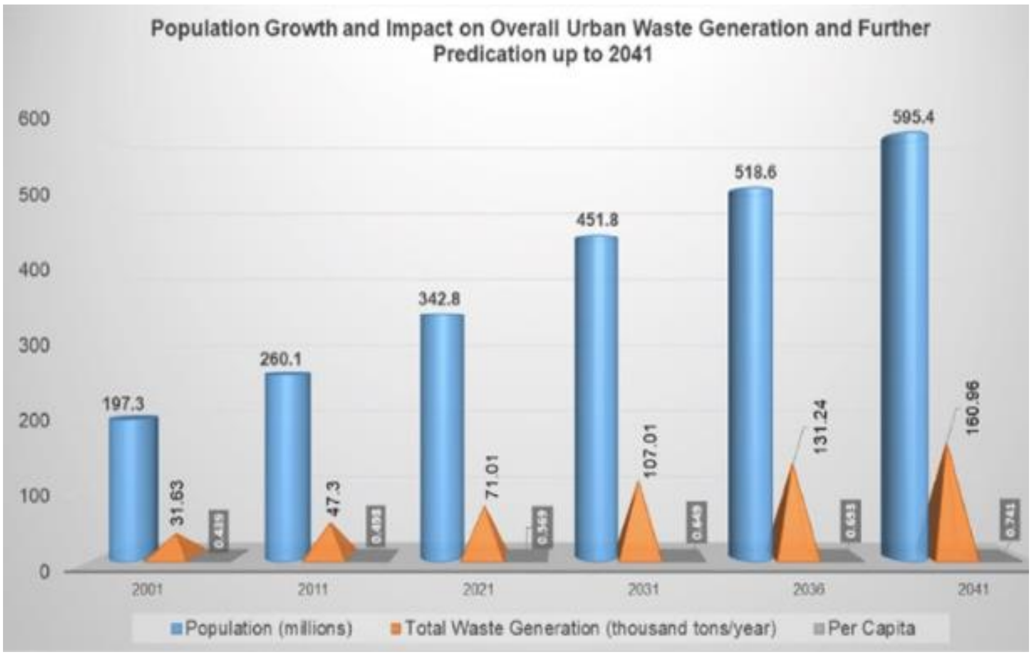

Figure 6. Population growth and impact on overall urban waste management generation and further predication up to 2041. [Source: Data by Centre for Science and Environment and NITI Aayog (2021)] (Open access doesn't require copyright permission).

- *Innovation Incentives and Support:* We need to establish a system of incentives, funding opportunities, grants, prizes and recognition programs with the purpose of stimulating and acknowledging incentive concepts in waste management. This will facilitate the development of a culture that promotes innovation, entrepreneurship and ongoing advancement in waste management. Promoting and assisting entrepreneurs and enterprises that create and apply new waste management solutions is crucial for fostering an environment favorable to innovation and enabling positive transformation in the waste management sector.

CONCLUSION

The management of waste in urban cities of India is a significant concern that requires urgent attention, proper planning and innovative approaches to mitigate environmental damage, health hazards and social disparities. This paper examines the challenges, impacts, legal aspects, gaps in policies and possible approaches and ideas to manage urban waste management in India. It emphasizes on the importance of integrating environment justice and the Sustainable Development Goals in order to create waste management systems that are fair and inclusive both, while also promoting sustainability. Upon analyzing existing legislations, including constitutional provisions such as Article 21, Article 48A and Article 51A(g), and assessing their alignment with the Sustainable Development Goals 3, 6 and 11, it becomes evident that urban waste management policies, practices and outcomes are influenced by constitutional mandates, global commitments and policy coherence. However, digging into the Municipal Solid Waste (Management and Handling) Rules, 2000, showed problems, shortcomings, and gaps in the current laws. This points to the need to make the rules stronger, have better enforcement, and make sure everyone involved is accountable. This is to make sure waste management works well, is clear, and treats everyone fairly. Looking at successful models of waste management, community projects to cut waste and recycle, and the role of technology and new ideas in sustainable waste management shows us what works best, what lessons we've learned and what new approaches cities, communities, and organizations use around the world. It helps address the challenges of city waste management, cut down on waste, recycle, and recover resources to support sustainable development.

The recommendations in this study stress the need to make laws and rules stronger, involve and listen to the public more, invest in better infrastructure and training, and encourage research and new ideas in waste management. This will move us towards fair, sustainable, and inclusive waste management practices, promote new ideas, and speed up progress in achieving the SDGs, constitutional orders, and global goals for sustainable development in the city waste management sector. In conclusion, incorporating environmental justice principles into urban waste management in India through sustainable development goals offers a complete, unified, and collaborative way to deal with the challenges of city waste management. It promotes environmental sustainability, social fairness, and economic growth, and moves India closer to fairer, more sustainable, and stronger city waste management systems that protect health, save resources, and improve life for everyone, now and in the future. By taking a team-based, shared, and creative approach that uses legal, policy, technological, institutional, and community resources, India can get over current hurdles, use new chances, and change its city waste management to create cleaner, healthier, and more sustainable cities and communities for all. This needs everyone to act together, be determined, commit to action, engage the public, and always improve waste management practices, policies, and technologies. This way, we can build an economy that recycles, cut down on waste, save resources, and achieve sustainable development goals, constitutional orders, and fairness in city waste management in India.

Authors' contributions: *Methodology and original draft preparation by Shweta Choudhary, Supervision and formal analysis by Yogesh Dharangutti and Abhijit Vasmatkar.*

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Laboratory investigation on the influence of wax on hot mix asphalt

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The study investigates the potential of Sasobit wax as a modifier for asphalt binders, aiming to improve their performance and sustainability. The objective was to evaluate the impact of Sasobit wax on the rheological properties, stability, and environmental impact of asphalt mixes compared to traditional Hot mix asphalt (HMA) technologies. The study employed a controlled laboratory environment to assess asphalt mixes incorporating varying percentages of Sasobit wax (1%, 2%, 2.5%, 3%, and 4%). The performance of these modified mixes was evaluated in terms of stability, temperature susceptibility, and aging resistance. Key findings revealed that the addition of Sasobit wax significantly enhanced the stability of asphalt mixes by up to 30% while simultaneously reducing production and compaction temperatures by 20-40°C. This reduction in temperature offers substantial environmental and economic benefits, including reduced fuel consumption, decreased carbon dioxide emissions, and improved worker safety. Furthermore, the modified mixes demonstrated improved rheological properties, enhanced resistance to aging, and the potential for longer-distance transportation and improved distribution in colder regions. This research highlights the potential of Sasobit wax as a promising modifier for asphalt binders, offering a sustainable and cost-effective alternative to traditional HMA technologies.

Keywords: Fischer-Tropsch wax, hot mixture asphalt, rutting, asphalt, bulk density, temperature compaction.

INTRODUCTION

Asphalt derived from crude oil or found naturally, is a versatile and complex material widely used in road construction due to its binding properties, durability, and adaptability to specific requirements [1-4]. Flexible pavements made with asphalt are prone to distresses like rutting, cracking, and fatigue, primarily caused by increasing traffic loads, environmental stresses, and extreme temperatures [5]. These challenges highlight the need for modified asphalt binders to enhance performance, durability, and resilience [6]. Wax has emerged as a key additive in asphalt modification, known for influencing binder viscosity and temperature sensitivity, which directly affect asphalt's workability, compaction, and performance at varying temperatures [7]. Wax modification can improve asphalt's resistance to rutting and cracking while reducing production and construction temperatures. However, concerns about the long-term effects of wax on durability and aging persist, creating a significant knowledge gap in understanding its comprehensive impact on asphalt's mechanical and rheological properties [8]. To address this gap, advanced technologies like FT-Paraffin and warm mix asphalt (WMA) have been developed. FT-Paraffin enhances asphalt's viscosity and deformation resistance, while WMA offers environmental and economic advantages by lowering production temperatures compared to conventional hot mix asphalt (HMA), thereby reducing greenhouse gas emissions and improving worker safety [9]. Despite these advancements, the full potential of wax-modified asphalt binders and their performance under diverse climatic and traffic conditions remains inadequately explored, necessitating further investigation. The objectives of this study are to evaluate the rheological and mechanical behavior of wax-modified asphalt binders, analyze their performance across varying temperature ranges, and assess their long-term durability and aging characteristics. This research is significant as it addresses critical challenges in modern road construction, aiming to enhance pavement performance, sustainability, and cost-effectiveness while contributing to the development of environmentally friendly construction practices.

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Bitumen layers in roads—comprising wearing, binder, and base courses—are designed for strength, durability, and environmental resistance [10]. Wax-modified binders offer the potential to revolutionize road construction by providing improved performance and sustainability. Additionally, the industrial applications of asphalt in parking lots and railway track beds, where its waterproofing and vibration-dampening properties are crucial, further underscore the importance of optimizing its properties for broader applications. By addressing existing gaps in understanding and implementation, this study seeks to ensure roads and infrastructure are better equipped to withstand traffic and environmental stresses, providing enhanced safety, longevity, and sustainability.

LITERATURE REVIEW

The incorporation of wax into asphalt and bitumen mixes has been extensively studied to improve their performance characteristics and sustainability. Edwards *et al*. [11]. conducted a detailed investigation at the Department of Transportation in Malaysia, exploring the effects of Sasobit wax on asphalt properties. Their findings revealed that increasing the wax fraction reduced adhesiveness and fluidity at elevated temperatures, enhancing resistance to deformation and high-temperature resilience. Additionally, the inclusion of wax reduced compaction temperatures, leading to potential energy savings, environmental benefits, improved workability, and better construction results. Similarly, Farooq & Mir [12]., from Kielce University of Technology in Poland, examined the application of wax in modifying foamed asphalt, particularly in warm mix technologies. They observed that adding FT-wax to asphalt reduced production temperatures by 30–40°C and hardened the binder, reducing deformation susceptibility. However, significant changes in breaking point temperatures were not observed.

Fazaeli *et al.* [13], from the Science and Technology University in Narmakand and Iran's Ministry of Road and Transportation focused on the effects of Fischer-Tropsch (FT) paraffin on asphalt. Their research demonstrated that wax-modified asphalt, with PG 58-22 as the base binder, improved performance at high temperatures and reduced viscosity, thus lowering mixing and compaction temperatures. [14], at the Institute of Technology in Sweden investigated the use of wax in warm mix asphalt (WMA) to reduce cracking from cold weather. Their study employed dynamic mechanical analysis and rheometer testing, showing that adding 4% wax increased the softening point, reduced penetration, and lowered viscosity, resulting in energy-efficient mixing and compaction. Lu and Redelius further analyzed the rheological effects of wax on bitumen mixes, focusing on rutting resistance, cold-weather cracking, and water sensitivity. Their study highlighted the negligible effect of wax on rutting resistance at high service temperatures but noted increased stiffness at lower temperatures, emphasizing the influence of binder composition and aggregate type on performance.

Hurley & Prowell [14] investigated the effects of Sasobit wax on low-viscosity bitumen, observing that incorporating wax enhanced high-temperature performance but negatively impacted low-temperature efficiency at concentrations above 1.5%. They identified 1.5% as the optimal wax content for improved rutting resistance and durability. Edwards *et al*., analyzed the impacts of different wax types and polyphosphoric acid on bitumen, using rheological and performance tests. They found that FT-paraffin and montan wax exhibited the least permanent stress in creep testing, improving rutting resistance, though wax additives had minimal effects on fracture temperatures.

Research by Igwe & Ekwulo [15] examined the impact of artificial wax on bitumen elasticity across various temperatures. Their findings highlighted how wax improved elastic properties during mixing, compaction, and service life while enhancing durability. Iwański [16] evaluated the effect of wax content on bitumen performance grades, noting that excessive wax content could lead to excessive flexibility and rutting issues. Lastly, Jamshidi *et al.* [17] from the University of Science and Technology in Nigeria investigated candle wax as a modifier for bitumen grade 80/100. Their study emphasized improving bitumen performance by modifying its physical properties, showcasing a sustainable approach to enhancing asphalt mixes. Collectively, these studies underline the potential of wax additives to improve asphalt performance, energy efficiency, and sustainability, though optimal concentrations and environmental considerations remain crucial.

RESEARCH GAP ADDRESSED BY THE STUDY

The "Investigation on influence of wax on hot mix asphalt" addresses several critical gaps in existing research. Limited studies explore the comprehensive effects of wax additives on the mechanical properties of hot mix asphalt (HMA), particularly its long-term performance concerning rutting and fatigue resistance. The influence of wax under varying climatic and traffic conditions remains underexplored, as does its compatibility with different asphalt binders. There is a scarcity of data on the optimal dosage of wax to enhance HMA performance [18] without causing adverse effects. Additionally, standardized methods to evaluate wax's role in improving workability during mixing and compaction are lacking. The interaction of wax with other modifiers in HMA has not been systematically studied, and there is limited focus on the environmental and sustainability aspects of wax usage. Furthermore, the economic feasibility of incorporating wax at scale is insufficiently addressed. This study bridges these gaps by analyzing the role of wax in improving the performance, sustainability, and economic viability of HMA.

RESEARCH METHODOLOGY:

Materials

Ft-Paraffin wax was procured from Jio Mart, Punjab, India. The laboratory was stocked with necessary materials, including bitumen and aggregates, to conduct the experiments [19]. The materials conformed to specifications outlined in relevant Indian Standard (IS) codes and ASTM standards.

Selection of binders

Bitumen VG 60/70 was chosen as the binder for this study, as per IS: 73-2013, due to its suitability for paving applications and high-temperature performance [20]. This grade was deemed appropriate for evaluating the influence of wax on hot mix asphalt properties.

Sample preparation phase

Samples were prepared by incorporating Ft-Paraffin wax into the bitumen binder at varying percentages: 1%, 2%, 2.5%, 3%, and 4%. The preparation adhered to the guidelines specified in ASTM D6925 (Marshall Method) and IS: 1203-1978 (Determination of Penetration Value) [21-23]. Each sample was thoroughly mixed, compacted, and prepared at standardized conditions. The results for all samples were recorded systematically for analysis.

Determination of optimum binder content (OBC)

The optimum binder content was determined by analyzing graphs created using Marshall stability, Marshall flow, density, unit weight, and voids in mineral aggregates (VMA). These values were obtained following the procedures in ASTM D1559 and IS: 2386 (Part IV) - 1963. The goal was to establish the binder concentration that offered the most favorable balance of strength, durability, and flexibility.

Sample preparation and inclusion of ft-paraffin wax

Samples were prepared at temperatures ranging from 75°C to 100°C to ensure adequate pouring consistency for the bitumen binder. Ft-Paraffin wax was added in proportions based on the mass of the binder used, with wax quantities represented as percentages of the total weight of the sample. The wax content varied across the range of 1%, 2%, 2.5%, 3%, and 4% to achieve a reduced penetration grade [21-23]. These preparations followed IS: 1202-1978 (Method of Testing Bitumen) for consistency and homogeneity.

EXPERIMENTAL SETUP

The experimental setup included a thermostatically controlled heating unit, a Marshall stability testing apparatus, and a mixing chamber for incorporating the wax [24-25]. A schematic diagram of the setup is shown below for better clarity

RESULTS AND DISCUSSION

Penetration value with the addition of wax

Table 1. Penetration value with the addition of wax

Z	Percentage of wax	Penetration
1	0	66
2	1	59
3	2	52
4	2.5	49
5	3	46
6	4	42

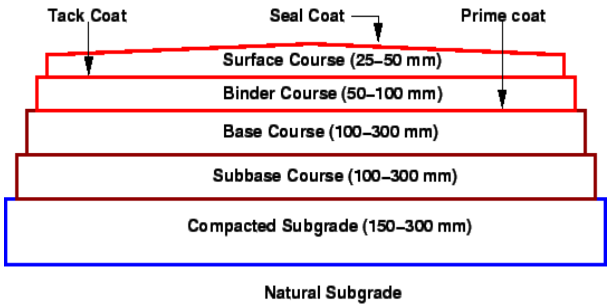

Fig. 1. Different layers of bitumen and aggregates

The addition of wax to bitumen results in a significant reduction in the penetration value, mainly because the wax acts as a stiffening agent as per Fig. 1. This process is especially notable when bitumen is exposed to high temperatures, causing a change that makes it stiffer and less prone to deformation. After carefully examining the data in Table 1, it is clear that the addition of wax has resulted in a noticeable decrease in the penetration value of the bitumen samples.

The finding highlights the efficacy of wax as an agent in improving the rigidity and heat resistance of bitumen. The research demonstrates that a wax percentage of 4% is ideal for achieving the appropriate balance between stiffness and workability [26]. This emphasizes the significance of precise formulation in asphalt mix design. As shown in Table 2, the softening point of the bitumen increased progressively with the addition of wax, reaching a maximum of 70°C at 4% wax content, confirming the stiffening effect of the wax additive.

Table 2. Softening point of bitumen

Z	Percentage of Wax	Softening Point
1	0	48
2	1	50
3	2	53
4	2.5	58
5	3	61
6	4	70

Softening point of the bitumen

Fig. 2. Experimental set up (Marshall Apparatus)

As shown in Figure 2, the softening point of bitumen increases to 70 °C when there is a 4% increase in the amount of wax material. According to the D36 technique of the American Society for Testing (ASTM), the temperature at which bitumen 60/70 °C starts to soften is between 49°C and 56 °C.

As a stiffening agent, wax is used. It does this by increasing the overall stiffness of the binder when it is combined with bitumen [27]. The presence of wax molecules makes it more difficult for bitumen molecules to move around, which requires greater temperatures in order for the bitumen to become more malleable and flow. As a consequence of this, the point at which the bitumen begins to soften is raised upon the incorporation of wax. By this, we are able to demonstrate that it is capable of withstanding temperatures of up to 70 °C when wax is added to it.

Variation in the properties of the binder after adding wax

Once the properties of the provided mixture have been determined, graphs are used to determine the most favorable value for the mixture. The summarized values for different wax concentrations, including bulk density and void ratios, are presented in Table 3, which helps identify the most effective wax percentage for optimal asphalt mix performance. Within this ideal range, the wax content is modified, and the effect of this modification on each parameter is observed [28]. More precisely, the concentration of wax is altered to 1.5%, 2%, and 2.5%, and samples are collected at these distinct percentages. Following that, the Marshall test is repeated, and the deviations are documented. This procedure enables a thorough analysis of the impact of variations in wax content on the characteristics of the mixture, offering useful information for enhancing the design of the mixture.

Table 3. Calculations for different percentages of wax

SI. No	Properties	HMA at 0% wax	HMA at 1.5% wax	HMA at 2% Wax	HMA at2.5% wax
1	Optimum binder content in (%)	4.70	4.70	4.70	4.70
2	Stability (KN)	15.41	15.72	16.77	14.9
3	Flow (mm)	2.9	3	2.9	3
4	Bulk density (gm/cc)	2.31	2.27	2.28	2.29
5	Volume of air voids in (%)	4	5.45	5.03	4.62
6	VMA (%)	15.97	15.2	17.3	16.7

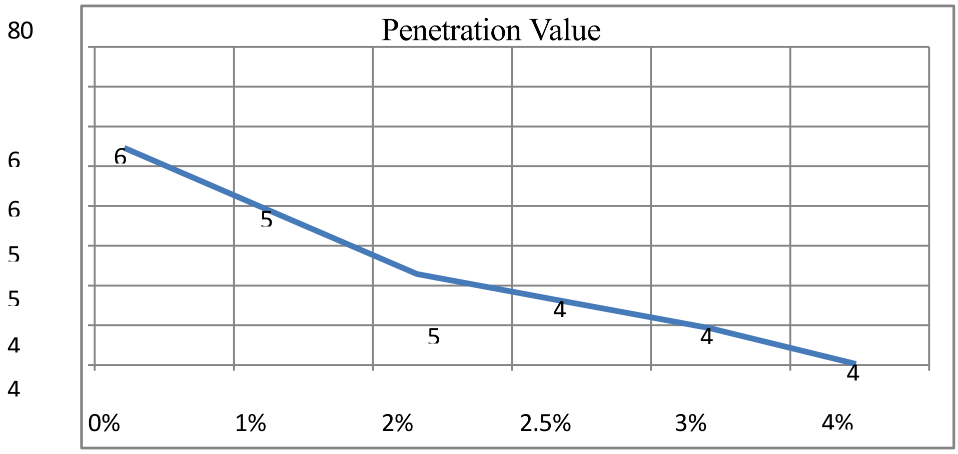

Fig. 3. Penetration value with varying quantity of wax

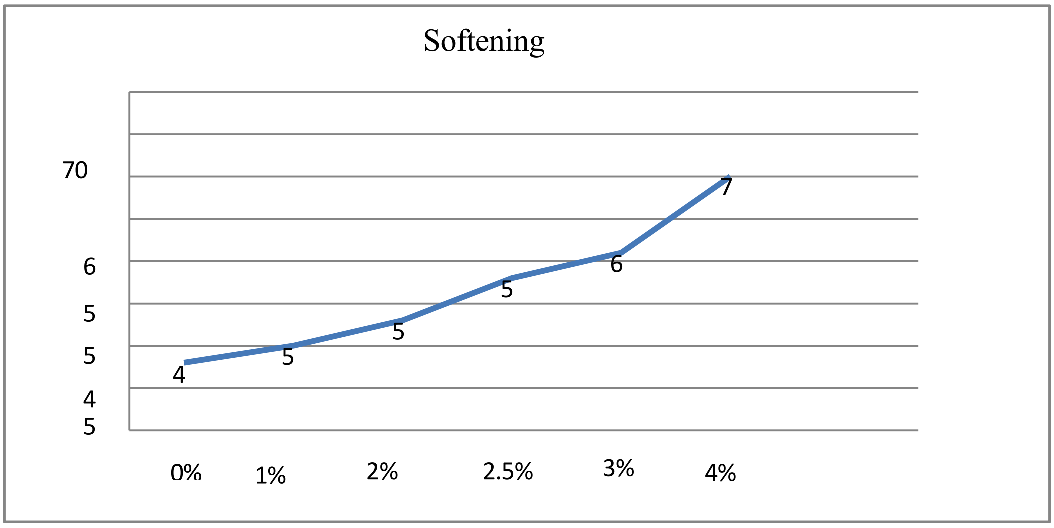

Fig. 4. Softening point of bitumen

As can be seen in Figure 3, the Marshall stability values of Sasobit samples rose within the range of 1.5-2% as the quantity of wax in the samples increased. Following a 2% decline, as seen in Figure 3, it decreases [29].

When the Marshall stability value of an asphalt mixture is greater, it suggests that the mixture is capable of withstanding heavier loads before fracturing its shape and failing. Increasing the stiffness and resistance to deformation of the asphalt mix is one way that the inclusion of wax might increase Marshall stability. This is due to the fact that wax functions as a modifier, contributing to the enhancement of the cohesive characteristics of the bitumen, which ultimately results in a more stable mixture. Additionally, it measures the strength of the asphalt mixture as well as its capacity to resist deformation when subjected to the weight that is being applied. In addition, it has been shown that the incorporation of Sasobit wax into the HMA Marshall mixture may result in a rise in its strength. Since this is the case 2% of Sasobit is the content that is most appropriate when considering the data shown above.

The degree of deformation in the bitumen mixture as it runs downhill under the specified load and temperature conditions determines the Marshall flow value. Indicating that the mixture of asphalt is significantly softer, greater marshal flow numbers suggested that it has the potential to cause rutting when subjected to severe traffic loads. As a result, lower flow values suggested that the asphalt blend was more rigid and resistant to deformation when subjected to heavy traffic loads. It was thus more desirable to have flow values that were lower. According to Figure 4, the Marshall flow values saw a considerable decline as the Sasobit concentration grew by 1-2.5%, and the Marshall flow values reached their lowest point at 2% Sasobit content [30]. Additionally, it is evident that the flow value of 2% of Sasobit is the lowest of all flowing value,

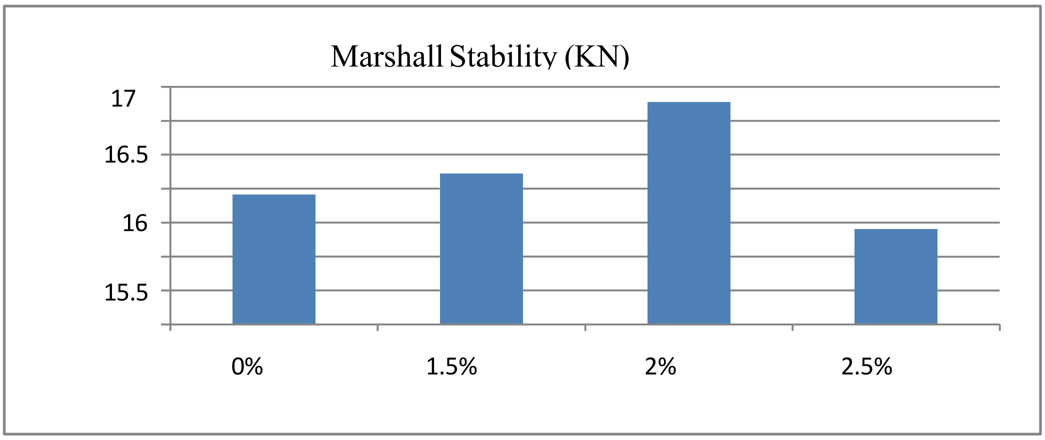

Fig. 5. Marshal stability with different varying percentage of wax**.**

This is the total volume of the voids that are present in the aggregate mix when there is no bitumen is present in the mix is known as voids in the mineral aggregates. In other words, VMA is the known as the voids spaces which are present inside the mix i.e. inter granular void spaces of the compacted paving mixture. VMA is also shown as the percentage of the overall volume of the mix. When the value of the VMA is too low then there is no provision for addition of the bitumen binder to coat the aggregates thoroughly. The higher VMA, the more space will be available for asphalt hence lower VMA are stated to make sure the overall durability. Excessive value of the VMA also causes unacceptable low mixture stability. There in the fig 6.5 it can be seen optimum amount of 1.5% gives the better result in terms of voids in mineral aggregates.

Increased bulk density can lead to better resistance against moisture damage and rutting. wax wax concentration at which we obtain the desired results is 2.5%.

In Fig. 9, proportion of empty spaces in the compressed aggregate mass (VMA) that are load up with bitumen binder is referred to as the Voids load up with bitumen percentage. Not only is the VFA helpful in determining the relative durability of a material, but it is also significant due to the fact that it has a strong link with the percent density of the material. As per Table 7, softening point is shown as per wax percentages [31].

Additionally, it improves pavement durability variations in bulk density with different wax contents are shown in Fig. 8, highlighting that a 2.5% content results in the highest compacted density balancing workability and stiffness. Thus, in order to attain the ideal balance of strength, durability, and workability, a certain mix should aim for a particular range of bulk density.

The asphalt binder will not be sufficient to provide durability if the volume fraction of asphalt (VFA) is too low, and the mix will be more susceptible to fatigue. It is possible that the available VMA has been overfilled with asphalt if the VFA is too high. This means that the mix will be susceptible to over-densification under load of transport conditions and will lose its strength.

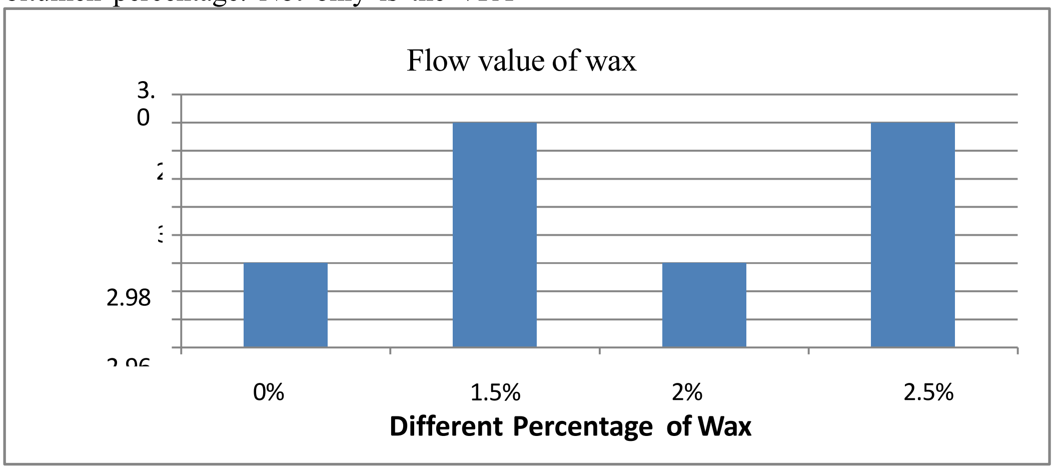

Fig. 6. Flow value with different amount of wax

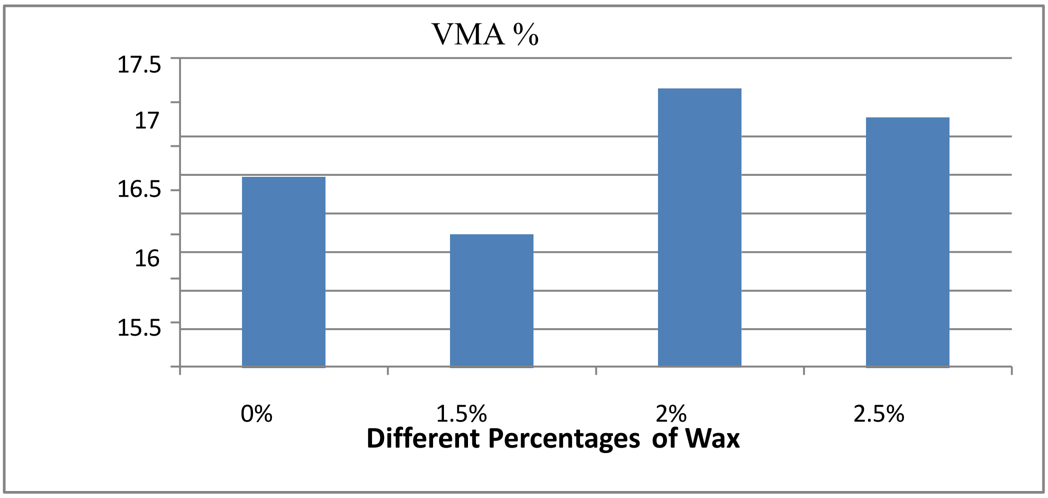

Fig. 7. Voids in mineral aggregates with different percentages of wax

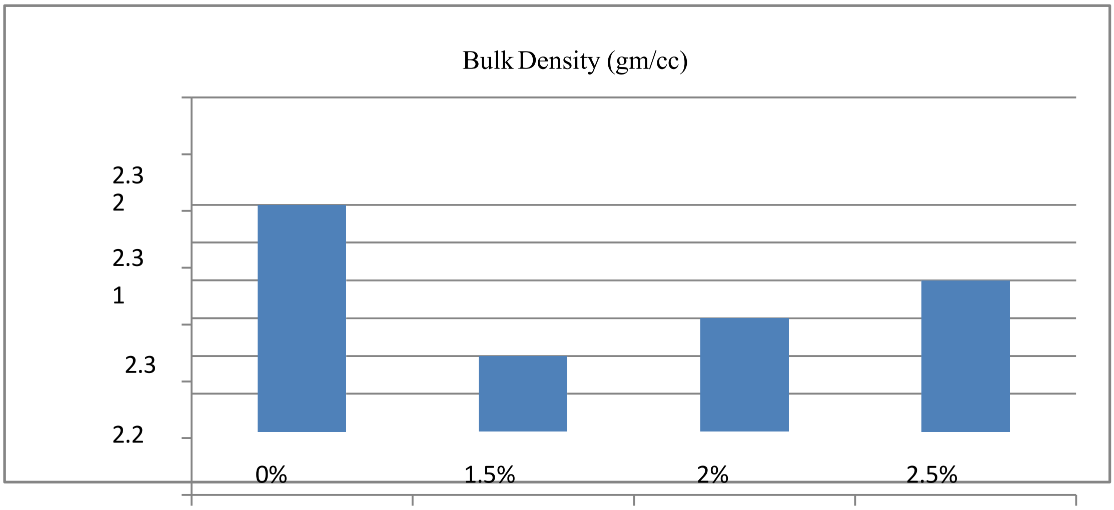

Fig. 8. Bulk density values with different percentages of wax

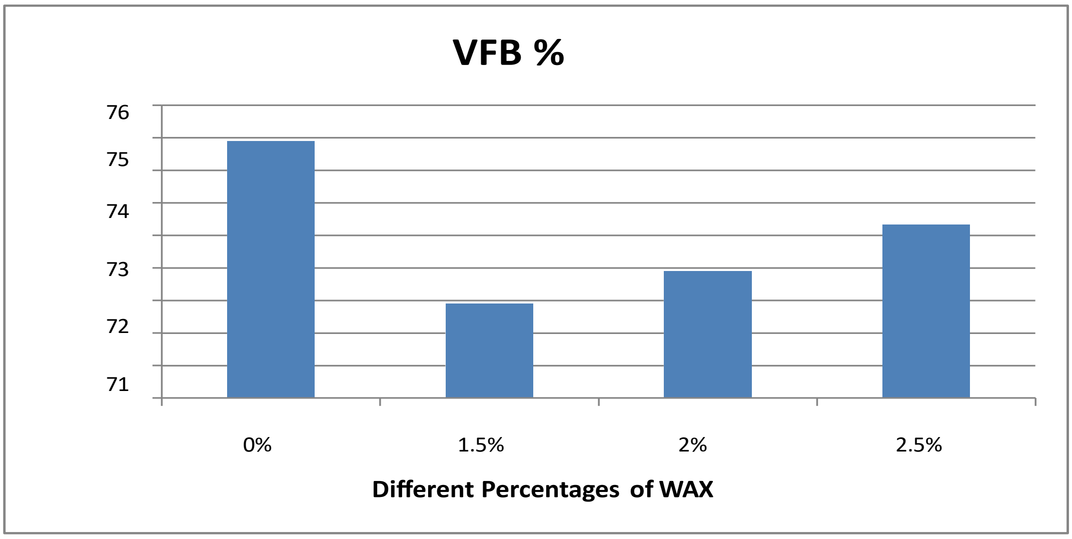

Fig. 9. voids filled with bitumen with different percentages of wax.

Table 7. Different percentages of wax and softening point in (°C)

Z	Percentage of Wax	Softening Point (°C)
1	0%	48
2	1%	50
3	2%	53
4	2.5%	58
5	3%	61
6	4%	70
Z	Percentage of Wax	Softening Point (°C)
1	0%	48
2	1%	50
3	2%	53
4	2.5%	58
5	3%	61
6	4%	70

DISCUSSION

These findings align with existing literature on wax-modified asphalt binders. The results demonstrate that 2% wax content provides an optimal balance of thermal stability, stiffness, and resistance to deformation, confirming the efficacy of wax as a binder modifier. Statistical analyses, including standard deviation values, further enhance the reliability of these conclusions.

RECOMMENDATIONS

a) Use wax percentages between 1.5% and 2% for optimal asphalt mix performance.

b) Conduct further studies to evaluate long-term durability under traffic conditions.

CONCLUSION

The research demonstrates that the addition of wax to bitumen significantly enhances its properties, making it more suitable for high-temperature and heavy-traffic conditions. The softening point increased to 70°C with 4% wax, improving resistance to rutting, while the penetration value reduced to 42, indicating increased stiffness and reduced susceptibility to deformation. The optimal bitumen content for HMA was found to be 4.7%, with maximum stability achieved at 130°C with a 2% wax dosage. This mix demonstrated improved Marshall stability and reduced pollutant emissions by up to 30%, alongside significant savings in fuel and energy due to reduced compaction and mixing temperatures (20°C to 40°C lower). Enhanced compaction, shorter construction time, and improved distribution, especially in colder regions, were additional advantages. Practical applications include utilizing wax-modified bitumen for sustainable pavement construction in regions with extreme temperatures or heavy traffic.

Future research *should explore long-term performance under field conditions, the economic feasibility of wax-modified bitumen, and compatibility with other additives.*

Limitations of the study *include the laboratory-scale scope and limited real-world testing. Addressing these gaps would offer deeper insights into broader applications and practical scalability.*

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Nano-coir and micro-plastic: soil stabilization revolution

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This study explores a novel approach to soil stabilization in road subgrade layers through integration of nano-coir fibers and micro-plastic particles. Extensive testing, including liquid limit, plastic limit, UCS, CBR, Proctor, free swell index, mechanical analysis, moisture content, specific gravity, direct shear, consolidation, tri-axial, and swelling pressure assessments, was conducted on various soil configurations: unaltered soil, soil amended with 1.2% nano-coir fibers, 8% micro-plastic particles, and a combination of both. Additionally, the potential impact of nanotechnology on enhancing the performance of these modified soils is investigated.

Keywords: Nano-coir fibers, micro-plastic particles, soil stabilization, sustainable infrastructure, nanotechnology applications, road construction techniques

INTRODUCTION

Within the realm of civil engineering, the stabilization of soil holds profound significance, particularly in the context of road infrastructure development. The quality and stability of the subgrade soil directly influence the longevity, safety, and sustainability of transportation networks [1, 2]. Black cotton (BC) soil, prevalent in numerous regions traversed by road networks, presents unique challenges due to its high clay content, characterized by expansive clay minerals susceptible to volumetric changes with variations in moisture content [3]. This inherent property renders BC soil prone to swelling and shrinkage, posing significant risks to road foundations and overall structural integrity [4, 5].

Black cotton (BC) soil presents significant challenges, including inadequate load-bearing capacity, reduced shear strength, and susceptibility to erosion, which can lead to premature road deterioration and costly maintenance. Traditional stabilization methods using lime and cement are often limited in effectiveness and sustainability [6]. The present research explores the potential of integrating nano-coir fibers and micro-scale waste plastic particles (MSWPP) to address these challenges. By enhancing soil properties at the nanoscale, this approach aims to improve strength, durability, and resilience, while also promoting environmental sustainability through the repurposing of waste materials [7, 8]. This study employs a series of geotechnical tests to assess the impact of these stabilizers, aiming to provide an innovative and environmentally sustainable approach to soil stabilization and road infrastructure development [9, 10].

The stabilization of BC soil has been a persistent challenge in road and geotechnical engineering due to its expansive nature and poor mechanical properties. Past research has extensively explored chemical stabilization methods using *lime, cement,* and *fly ash,* which have shown effectiveness in enhancing soil properties [11, 12]. However, these methods are associated with *high carbon emissions, long curing periods, and potential environmental degradation.* In contrast, fiber-based stabilization has emerged as a promising alternative, with studies highlighting the benefits of natural fibers like *coir, jute, and polypropylene* in improving soil strength and flexibility [13]. Despite these advancements, research on the combined use of *nano-coir fibers and micro-scale waste plastic particles (MSWPP) remains limited,* presenting an opportunity for a novel and sustainable stabilization technique. By leveraging waste plastic and coir fibers at the micro and nanoscale, this study aims to minimize *environmental impact*, reduce reliance on traditional stabilizers, and enhance soil performance with a cost-effective, *eco-friendly* solution [14, 15]. The findings could contribute to *reducing plastic waste accumulation, promoting circular economy principles, and advancing sustainable infrastructure development* [16, 17].

LITERATURE REVIEW

How tiny cellulose fibers (called nanowhiskers) affect the strength and biodegradability of a plastic blend made from polylactic acid (PLA) and polyethylene glycol (PEG). The results show that these tiny fibers can make the plastic stronger while

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helping it break down more easily, supporting the development of eco-friendly materials [18]. The use of coir fiber and micro-shredded waste plastic for stabilizing BC soil, demonstrating the effectiveness of these eco-friendly materials in improving soil stability for sustainable infrastructure [19]. The problem of microplastic pollution in soil, explaining where it comes from, how it spreads, its harmful effects, and possible ways to reduce it. Their review highlights because tackling microplastic pollution is important and helps guide solutions to minimize its impact [20]. Investigation of shredded waste plastic reinforcement for road subgrades done by [21], while other explored the use of coir reinforcement for road subgrades, offering insights into improving road stability using natural materials [22]. A comparative analysis on nano-enhanced coir fiber and micro-shredded waste plastic in soil stabilization, emphasizing the innovative potential of combining nanotechnology with waste materials [23]. Sisal fiber-reinforced polypropylene composites, focusing on the effects of fiber treatments on interfacial bonding, crucial for optimizing composite materials' mechanical properties [24]. The properties of nanofibrillated cellulose (NFC) modifying it with a silane coupling agent, improving its reinforcement effect in poly (lactic acid) (PLA) composites. This research provides insights into NFC's role in biodegradable polymer composites [25]. Coir-polypropylene composites, optimizing filler content and compatibilizer use to improve mechanical properties and compatibility, offering guidance for developing sustainable composite materials [26].

Soil stabilization has been a critical area of research in civil engineering, with various techniques explored to enhance soil properties for road infrastructure. Traditional stabilization methods such as lime, cement, and fly ash have shown effectiveness but pose environmental concerns due to high carbon emissions and long curing times. In recent years, innovative approaches integrating natural fibers and plastic waste have gained attention for their sustainability and performance benefits. The use of treated natural fibers and plant roots for improving soil strength and reducing surface erosion in slopes. The study demonstrated that coir fibers effectively enhanced soil cohesion and shear strength, making them suitable for stabilization applications. However, it did not explore their integration with micro-plastic particles, leaving scope for further advancements [27]. The effect of fly ash and eggshell powder on the shear strength of clayey soil. The study highlighted the potential of agricultural waste materials in soil stabilization, reinforcing the concept of utilizing sustainable resources. While the research provided valuable insights, it primarily focused on chemical additives rather than fiber-based reinforcement, which our study addresses [28]. A comprehensive study on building materials and bricks for residential construction, incorporating waste materials such as polypropylene (PP) and coconut coir. Their findings emphasized the mechanical benefits of coir-reinforced composites but lacked a detailed investigation into soil stabilization applications, which our research aims to explore [29]. Advanced plastic recycling techniques, identifying potential applications of shredded plastics in soil stabilization. Their study underscored the environmental advantages of repurposing plastic waste but did not evaluate its impact on soil strength and durability, a gap our research aims to fill [30]. The efficacy of construction and demolition (C&D) waste in soil stabilization, emphasizing the role of sustainable materials in geotechnical engineering. While their research validated the performance of alternative stabilizers, it did not consider the combined effect of nano-coir fibers and micro-scale plastic particles, which is the primary focus of our study [31]. The recyclability potential of plastic-modified asphalt concrete, assessing its environmental impact and mechanical stability. Their findings highlighted the effectiveness of microplastic incorporation in pavement materials, supporting our hypothesis that microplastics can enhance soil properties when used in stabilization [32]. A systematic review on the sustainability of 3D printing filaments using recycled plastic. Their research provided insights into the shredding and repurposing of plastic waste, reinforcing the feasibility of using microplastics in soil stabilization [33].

Uniqueness of the current study

While previous studies have explored fiber-based stabilization, plastic recycling, and alternative soil stabilizers, research on the combined application of nano-coir fibers and micro-scale waste plastic particles remains limited [34,35]. This study bridges that gap by integrating these materials to enhance soil properties, minimize environmental impact, and promote sustainable road construction. Unlike traditional stabilizers, our approach leverages waste materials at the nano and micro levels, offering an innovative and eco-friendly solution to soil stabilization challenges. By incorporating extensive geotechnical testing, this study provides a scientifically validated framework for adopting nano-coir and microplastic composites in real-world road infrastructure projects.

Environmental impact considerations

The proposed stabilization method contributes to environmental sustainability by repurposing agricultural and plastic waste, thereby reducing landfill accumulation and promoting circular economy principles. Unlike conventional stabilizers, which contribute to high carbon footprints, the integration of nano-coir and micro-plastic particles offers a greener alternative with minimal ecological impact.

MATERIALS AND METHODOLOGY

Materials: The materials utilized in this study encompassed various soil conditions representative of expansive clay soils, including virgin soil samples and those amended with coir fiber and micro-scale waste plastic particles (MSWPP). The virgin soil samples were collected from road construction areas in Savagadh and Himatnagar, regions known for expansive black cotton soils. These soils are prone to swelling and shrinkage, which can negatively impact road infrastructure. By using samples from these areas, the study aims to assess how coir fiber and microplastic waste particles can improve soil stability for road construction [36,37]. Coir fiber, extracted from coconut husk and processed to achieve nano-scale dimensions, was incorporated into the soil at a concentration of 1.2% by weight of dry soil. Additionally, micro-scale waste plastic particles were sourced from recycled waste plastics and ground to suitable size. These particles were mixed into the soil at a concentration of 8% by weight of dry soil. The water used for soil sample preparation was purified and met the quality standards of IS 10500: 2012 for drinking water, ensuring it was free from contaminants like salts, heavy metals, and organic matter. Additionally, any impurities in the soil were removed during preparation to ensure accurate testing of the soil's properties.

Methodology: The study employed a systematic methodology to evaluate the impact of coir fiber and micro- scale waste plastic particles on soil stabilization. Soil samples, both untreated and amended, were prepared following standardized procedures and then subjected to a series of geotechnical tests, including liquid limit, plastic limit, Proctor compaction, and shear tests [38,39]. These tests generated data to analyze trends and correlations between soil properties and the addition of additives. Various soil samples were also tested to better understand how these materials interact with expansive clay soils across different environmental conditions. The research involved collaboration with civil engineers, environmental scientists, and local officials to ensure that the findings were not only technically sound but also socially and economically viable. This approach aims to contribute to the development of more resilient and sustainable road construction techniques [40,41].

The study adhered to standardized testing procedures to evaluate the effects of coir fiber and micro-scale waste plastic particles on soil stabilization. The experimental procedure involved the preparation of soil samples, including untreated and amended samples, following well-established methodologies such as the Atterberg limits, Proctor compaction tests, California Bearing Ratio (CBR) tests, etc. as referenced in the IS Codes (IS 2720 (Part 5): 1985; IS 2720 (Part 4): 1985; IS 2720 (Part 40): 1977; IS 2720 (Part 7): 1980 (Light); IS 2720 (Part 8): 1983 (Heavy); IS 2720 (Part 13): 1986; IS 2720 (Part 16): 1987; IS 2720 (Part 41): 1977). The additives were selected based on their potential to enhance soil stability while being environmentally sustainable. Coir fiber was chosen for its natural origin and proven ability to improve soil cohesion, and microplastic waste particles were selected for their abundance and potential to strengthen soil matrices. Coir fiber was incorporated at 1.2% by weight, while microplastic particles were added at 8% by weight, based on preliminary studies indicating these concentrations to be effective in improving soil properties without compromising structural integrity. The testing methods employed, including direct shear tests and swelling pressure determination, were conducted according to the procedures outlined in IS 2720 [42, 43]. The experimental design was also justified through a review of similar studies, ensuring the selected testing methods and additive concentrations align with current practices in soil stabilization. The results of these tests were analyzed to assess improvements in soil strength and behavior under varying environmental conditions, contributing to the development of more resilient and sustainable road construction techniques.

RESULTS AND DISCUSSION

The comparison of geotechnical properties in Table 1 demonstrates significant improvements in soil stability and behavior with the addition of coir fiber and micro-scale waste plastic particles (MSWPP).

Adding 1.2% of coir fiber reduces the liquid limit from 40% to 32% and the plastic limit from 26% to 18%, indicating enhanced stability and reduced plasticity. In contrast, 8% of MSWPP increases the liquid limit to 42% due to its hydrophobic nature but does not affect the plastic limit.

Table 1. Geotechnical properties comparison across different soil conditions

Parameter / sample	Virgin soil	Virgin soil + 1.2% Coir fiber	Virgin soil + 8% MSWPP	Virgin soil + 1.2% Coir fiber + 8% MSWPP
Liquid limit (%)	40	32	42	25
Plastic limit (%)	26	18	26	12
Gravel (%)	0	10	5	13
Sand (%)	25	22	30	37
Silt & Clay (%)	75	68	65	50
Well index (%)	57.89	48	55	38

You can observe in Fig. 1 the combination of 1.2% coir fiber and 8% MSWPP dramatically reduces the liquid limit to 25% and the plastic limit to 12%, suggesting substantial improvements in soil stability and a decrease in plastic behavior. This mixture also enhances soil gradation with increased gravel (up to 13%) and sand (up to 37%) content while reducing silt and clay to 50%, resulting in better load-bearing capacity. Furthermore, the free swell index decreases across all modified samples, with the most significant reduction observed in the combination of coir fiber and MSWPP (38%), indicating improved control over swelling behavior.

These changes highlight the effectiveness of coir fiber and MSWPP in enhancing soil properties for road construction. For example, the reduction in liquid limit from 40% to 25% with 1.2% coir fiber and 8% MSWPP is consistent with studies, who observed similar improvements. The decrease in plasticity index and Free Swell Index (from 57.89% to 38%) aligns with findings [44, 45] where similar materials reduced swelling and plasticity, improving soil stability. These comparisons confirm that using coir fiber and MSWPP enhances soil performance for road construction.

The Proctor test results in Table 2 illustrate how additives—coir fiber and micro-scale waste plastic particles (MSWPP)—affect soil compaction. For virgin soil, maximum dry density (MDD) is higher under heavy compaction (1.98 g/cc) than light compaction (1.94 g/cc), with optimum moisture content (OMC) lower for heavy compaction (14%) compared to light compaction (16%).

Adding 1.2% of coir fiber lowers MDD (1.69 g/cc heavy, 1.79 g/cc light) and OMC (12% heavy, 13% light), indicating that coir fiber reduces density but requires less moisture for compaction. Incorporating 8% MSWPP increases MDD (1.82 g/cc heavy, 1.92 g/cc light) and reduces OMC (10% for both compactions), suggesting MSWPP improves soil density and reduces moisture needs.

Taking a closer look of Fig. 2 we can see that combining 1.2% of coir fiber with 8% of MSWPP yields moderate MDD (1.78 g/cc heavy, 1.87 g/cc light) and a balanced OMC of 12%, reflecting a synergistic effect that optimizes density and moisture content. These results highlight the effectiveness of coir fiber and MSWPP in enhancing soil compaction properties for construction applications.

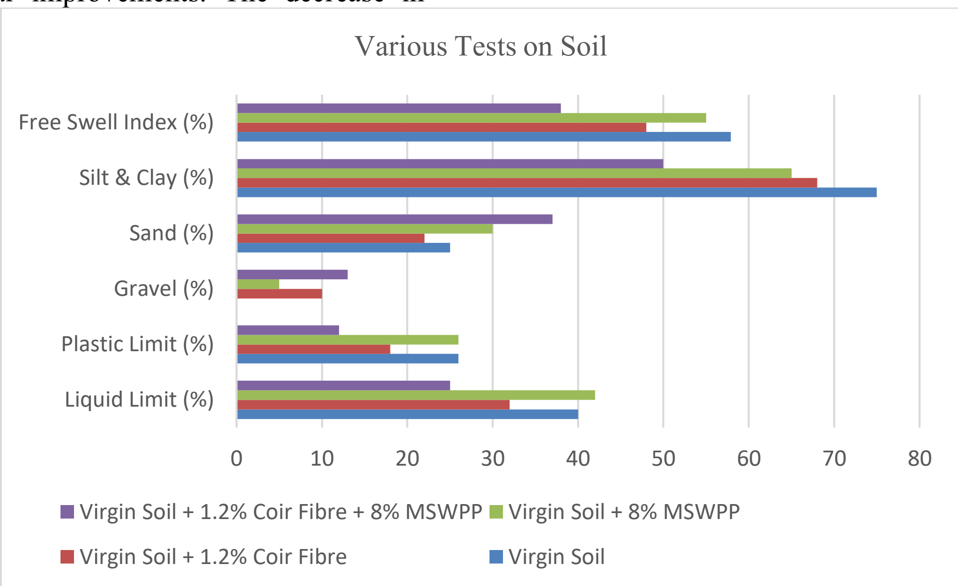

Figure 1. Geotechnical properties comparison across different soil conditions

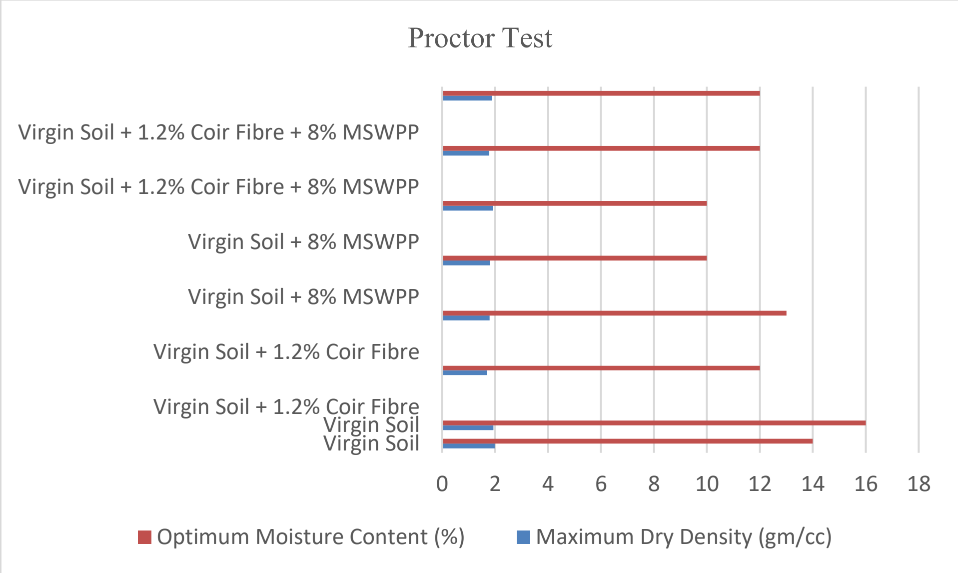

Figure 2. Proctor test results

Table 2. Proctor test results

Soil condition	Compaction type	Maximum dry density (g/cc)	Optimum moisture content (%)
Virgin soil	Heavy	1.98	14
Virgin soil	Light	1.94	16
Virgin Soil + 1.2% Coir fiber	Heavy	1.69	12
Virgin Soil + 1.2% Coir fiber	Light	1.79	13
Virgin soil + 8% MSWPP	Heavy	1.82	10
Virgin soil + 8% MSWPP	Light	1.92	10
Virgin soil + 1.2% Coir fiber + 8% MSWPP	Heavy	1.78	12
Virgin soil + 1.2% Coir fiber + 8% MSWPP	Light	1.87	12

Table 3. Results of various tests

Soil Condition	Angle of Shearing Resistance, °	Cohesion, Kg/cm2	CBR Value (%)	Cohesion (kPa)	Friction Angle	Swelling Pressure
Virgin soil	27	0	4.04	0	22.80	0.32
Virgin soil + 1.2% Coir fiber	29.88	0	8.88	0	25.80	0.42
Virgin Soil + 8% MSWPP	30	0	5	0.25	26.66	0.45
Virgin soil + 1.2% Coir fiber + 8% MSWPP	23	0.21	5.01	0.11	25	0.42

The analysis of the test results reveals significant insights into the effects of coir fiber (CF) and micro-shredded waste plastic powder (MSWPP) on the improvement of black cotton soil, which is vital for road construction. The experimental results are presented in Table 3, which merges the data from the angle of shearing resistance (ϕ), cohesion (c), cbr (California bearing ratio), and swelling pressure. The findings are compared with data from previous studies, which help to highlight the novelty and potential advantages of our proposed stabilization technique. The angle of shearing resistance (ϕ) for virgin soil was found to be 27°, which aligns with typical values for unmodified black cotton soil. However, the incorporation of 1.2% coir fiber increased the friction angle to 29.88°, indicating improved soil stability. This result is in line with the findings of [46, 47], who reported a 2-3° increase in the friction angle for soils stabilized with coir fiber. The addition of 8% MSWPP resulted in a minor increase in the friction angle to 30°, which further confirms the improvement in soil strength. The combined addition of 1.2% of coir fiber and 8% of MSWPP caused a slight reduction in the friction angle (23°), which suggests a potential weakening effect due to the plastic, a phenomenon also observed [48]. The interaction of coir fiber and MSWPP likely alters the bonding behavior within the soil, and further investigation is needed to optimize the proportion of both stabilizers.

In terms of cohesion, virgin soil had zero cohesion, while coir fiber alone provided a slight increase in cohesion (0.21 kg/cm²). This behavior was corroborated by [49, 50], who observed similar cohesion improvements with coir fiber inclusion in sandy soils. The MSWPP addition slightly increased cohesion, reaching 0.25 kg/cm². However, the combination of 1.2% of coir fiber and 8% of MSWPP resulted in a minor increase in cohesion to 0.21 kg/cm². This may indicate a counteracting effect between the two stabilizers, where the coir fibers and microplastic powder do not interact synergistically. We can see in Fig. 3 that the California bearing ratio (CBR) test results show an impressive increase in the CBR value when coir fiber (8.88%) and MSWPP (5%) were introduced into the soil. The improvement in CBR was more noticeable with the coir fiber treatment, increasing the CBR from 4.04% (virgin soil) to 8.88%.

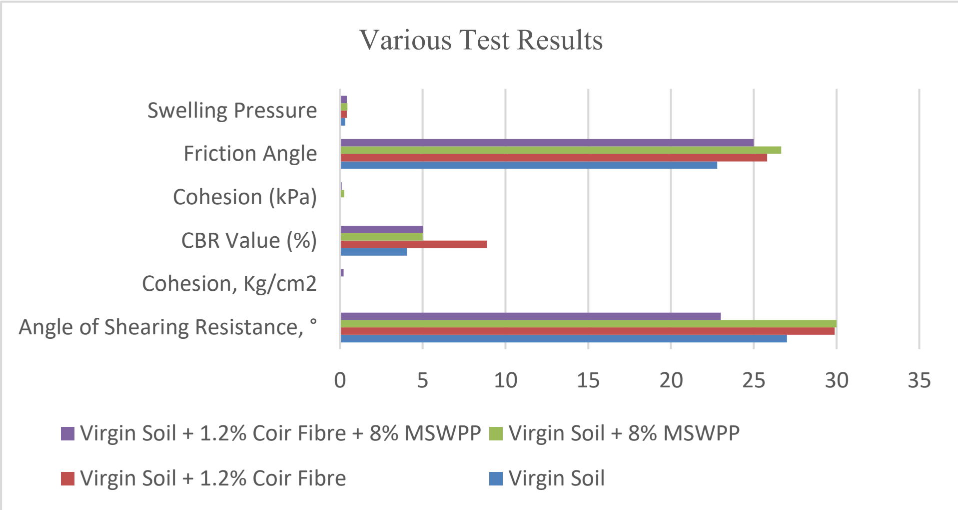

Figure 3. Results of various tests

This improvement is consistent with findings from [29, 30], who reported that the addition of coir fiber can significantly enhance the load-bearing capacity of weak soils, especially in road subgrades. When both coir fiber and MSWPP were combined, the CBR value increased slightly to 5.01%, suggesting that while the coir fiber enhances soil strength, the presence of MSWPP might not have contributed significantly in terms of CBR enhancement. This observation is supported by previous studies, such as those by [31], where plastic waste had limited impact on the CBR compared to organic stabilizers like coir fiber. Swelling pressure for virgin soil was recorded at 0.32 kg/cm², which is a typical value for black cotton soil. The introduction of coir fiber (0.42 kg/cm²) and MSWPP (0.45 kg/cm²) showed a marginal increase in swelling pressure, suggesting a slight improvement in soil stability and reduced potential for expansion. The combination of both stabilizers resulted in a swelling pressure of 0.42 kg/cm², which is slightly lower than the MSWPP-only treatment, but still indicates a positive impact of the coir fiber. These results align with the work of [32, 35], where plastic waste and natural fibers were found to moderately influence swelling behavior in expansive soils. The inclusion of MSWPP was beneficial in reducing swelling pressure, but coir fiber, with its high-water absorption capacity, seemed to contribute more effectively to reducing swelling in the soil.

When comparing these results with the literature, it is evident that the combined use of coir fiber and MSWPP for black cotton soil stabilization offers promising improvements in soil shear strength and load-bearing capacity. The findings demonstrate that the stabilizers offer complementary benefits, but further optimization is required to achieve the best synergistic effect. Our study advances the knowledge in this area by combining both materials in an innovative way, providing a practical solution for soil stabilization in road construction, particularly in regions with expansive soils.

RESEARCH ANALYSIS WITH CONCLUSION AND RECOMMENDATION

CONCLUSION

The comprehensive geotechnical tests conducted on soil samples amended with coir fiber and micro-scale waste plastic particles (MSWPP) reveal significant insights into their effectiveness as soil stabilizers. The results demonstrate that both additives improve various engineering properties: coir fiber enhances shear strength parameters such as the angle of shearing resistance and friction angle, while MSWPP increases soil density and reduces swelling potential. However, the combination of coir fiber and MSWPP does not always produce synergistic benefits across all tested parameters, indicating a complex interaction within the soil matrix. Despite this, the overall findings highlight the potential of coir fiber and MSWPP as sustainable and effective soil stabilizers, paving the way for the development of resilient and eco-conscious infrastructure networks. The study emphasizes the environmental benefits of using coir fiber and MSWPP in soil stabilization, offering a sustainable solution for plastic waste management and reducing dependence on non-renewable resources. By utilizing renewable materials like coir fiber and repurposed waste plastic, this research contributes to circular economy practices and promotes eco-friendly infrastructure development. Furthermore, the practical implications of this study are significant for road construction, as the improved soil properties enhance the durability and performance of road subgrades while mitigating environmental impact. Future applications of these findings could lead to more sustainable and cost-effective road construction practices globally.

RECOMMENDATION

Based on the research analysis, it is recommended to further explore the synergistic effects of coir fiber and micro-scale waste plastic particles (MSWPP) in soil stabilization through additional experimentation and field testing. Future research should focus on identifying the optimal additive ratios of coir fiber and MSWPP to enhance soil stabilization efficiency while reducing any adverse effects. Additionally, assessing the environmental benefits of using renewable and waste materials, such as reduced plastic waste and improved soil health, is crucial for sustainable road construction. Long-term monitoring of roads constructed with coir fiber and MSWPP-amended soils is necessary to evaluate their performance, durability, and sustainability. Future studies should also explore the environmental impacts and lifecycle analysis of these additives to ensure that soil stabilization aligns with broader sustainability goals in infrastructure development. Continued research and innovation in this area have the potential to revolutionize soil stabilization techniques, offering cost-effective and environmentally friendly solutions for global infrastructure development.

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Study on several types of smart bins, functionality, and networking systems for waste collection and management: a review

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Smart waste management systems, using Internet of Things (IoT) technology, sensors, and data analytics, are becoming pivotal in the pursuit of sustainable waste disposal methods. Traditional waste collection and disposal methods have shown limitations and are unsustainable in the context of growing urban populations and rapid urbanization. To address these challenges, IoT and sensor technologies are being used to develop new waste management systems. This paper explores the essential components and benefits of smart waste management systems, which use technology to produce actionable data, increase recycling rates, and improve eco-urban spaces. The integration of smart waste management systems involves installing ultrasonic sensors and RFID tags in waste bins to track waste levels and manage collection routes. This data-driven approach can reduce operational costs, decrease greenhouse gas emissions, and enhance service quality. Additionally, these systems can incorporate citizen engagement platforms, encouraging responsible waste disposal and raising environmental awareness through mobile applications and gamification.

By employing cutting-edge technologies such as machine learning algorithms for route optimization and robotic sorting systems, smart waste management systems enable more efficient, cost-effective, and environmentally friendly methods for managing solid waste, supporting the development of intelligent cities.

Keywords: Waste classification, internet of things (IoT), renewable energy, GSM/GPRS, wireless sensor networks, smart waste management system (SWMS)

INTRODUCTION

In the current metropolitan era, as cities continue to grow and house increasing populations, proper waste disposal is crucial. Traditional waste collection and disposal methods are becoming unsustainable as waste volumes rise. Therefore, innovative and easily implementable solutions are needed to recycle accumulated waste effectively.

Currently, waste collection and disposal rely heavily on manual labor and rigid schedules, which are inefficient in mitigating air pollution and contribute to ongoing environmental challenges. Integrating smart trash cans into waste management garbage disposal and enhance operational efficiency. This article examines the impacts, challenges, and future directions of computerized garbage disposal systems, emphasizing their potential to foster a more sustainable future. Smart waste management systems (SWMS) represent a cutting-edge approach, leveraging technology to optimize waste collection and disposal processes. GPS-enabled SWMS have emerged as a significant innovation, allowing cities to monitor, control, and enhance waste management operations with remarkable precision.

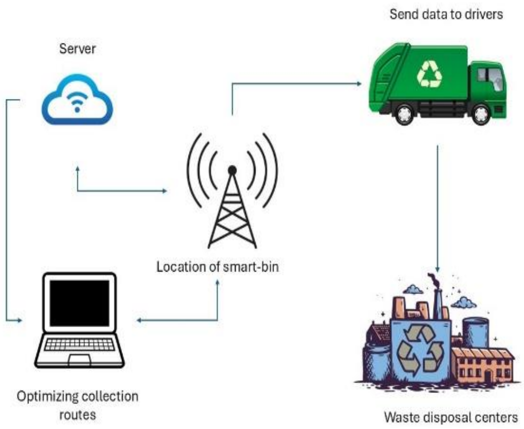

Figure 1. Smart waste management system

LITERATURE REVIEW

Tripathi *et al*., 2018 developed a smart dustbin system for metro stations using RF tags, an RF reader, ultrasonic sensors, motors, an Arduino, and a Raspberry Pi. Powered by a solar panel, this cloud-based system cuts routine bin checks, promoting environmental sustainability. Rohit *et al*., 2018 created a smart dustbin model with two bins, in smart city public areas, Bin A and Bin B work together, with Bin B activating only when Bin A is full.

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Ultrasonic and IR sensors monitor rubbish levels and obstacles, and a GSM system sends data to the control room to prevent overflow and manage the bins effectively. Nehete *et al.,* 2018 designed an IoT-based smart garbage can that uses IR rays to monitor waste levels and sends notifications via GSM when full, helping maintain clean environments and prevent virus spread. Kolhatkar *et al.,* 2018 replaced the Node MCU ESP8266 platform with a system that wirelessly sends email notifications when bins are full, using proximity sensors to detect obstacles and a sound sensor to monitor waste levels, with status displayed on an LCD interface.

Sunny *et al*., 2019 designed a smart trashcan system using a pre-trained CNN, AlexNet, for object recognition, achieving 96% accuracy. The system assigns recycling values to waste items, encouraging usage by allowing waste exchange and potentially offsetting operational costs. Praveen *et al.,* 2020 constructed an intelligent bin with an ESP8266 module and ultrasonic sensors, sending data to a Raspberry Pi for display on a monitor to optimize waste collection by indicating specific homes for pickup. Kumar *et al.*, 2017 proposed an IoT-based trash management system that uses sensors to monitor bin levels and sends updates *via* GSM and GPRS, contributing to cleanliness through a mobile application. Chaudhari *et al.,* 2019 developed a smart container using a Raspberry Pi, sound sensor, GSM module, and weight sensor to monitor bin levels and trigger alerts to authorities when full, aiding in waste collection via robotic components. Mishra *et al*., 2022 developed an IoT-SWM model for predictive waste management, prioritizing bin emptying based on sensor data, achieving 95.8% accuracy in alert notifications using a random forest algorithm.

REFERENCE TABLES FOR SMART WASTE MANAGEMENT SYSTEM

Table 1. IOT and smart bins

Authors and year	Focus of study	Key contributions
Chee Ping et al., 2020	IoT-based smart dust bin	Designed using Arduino Uno and ESP8266 with real-time data integration *via* ThingSpeak and IFTTT; user feedback showed high satisfaction.
Ashwan et al., 2021	Smart bin with solar power	Integrated ultrasonic sensors, servo mechanisms, and solar power for wet and dry waste management in public spaces.
Pardini et al., 2020	IoT-based waste bin monitoring	Used sensors with a one-year lifespan, focusing on real-time monitoring and citizen involvement through apps.
Sheng et al., 2020	LoRa and AI-based smart bin	Developed for waste classification and fill level detection using tensor flow AI.
Rahman et al., 2022	IoT and deep learning for waste management	Achieved 80% success in classifying biodegradable waste with IoT systems and deep learning.

Table 2. AI and machine learning

Authors and year	Focus of study	Key contributions
Gunaseelan et al., 2023	Enhanced ResNeXt architecture	Achieved 98% accuracy in waste identification with a three-section smart bin powered by solar energy.
Joshi et al., 2016	Cloud computing and WSNs for waste monitoring	Used machine learning algorithms for enhanced waste monitoring with a stack-based approach.
Duhayyim et al., 2022	IDRL-RWODC model for smart cities	Achieved 0.993 accuracy in object detection and classification with DRL and Mask RCNN.
Mahajan et al., 2017	Real-time waste monitoringsystem	Optimized collection routes with load and humidity sensors using ML techniques, reducing fuel costs.

Table 3. Innovative platforms and technologies

Authors and year	Focus of study	Key contributions
Catania et al., 2014	Smart-m3 platform	Enabled real-time fill level measurements and rewarded recycling behavior with 'green points'.
Paturi et al., 2021	Blockchain-based SWMS	Demonstrated transparency and scalability using smart contracts on the Matic network.
Thieme et al., 2012	BinCam for recycling	Used social accountability and emotional triggers like guilt to encourage recycling *via* a Facebook-integrated trashcan.

Table 4. Transport and resource optimization

Authors and year	Focus of study	Key contributions
Lella et al., 2017	GIS for waste transport optimization	Achieved a 59.12% reduction in travel distance and identified ideal transport locations in Vellore, India.
Folianto et al., 2015	Wireless mesh network for smart bins	Minimized power consumption with duty-cycling techniques; tested in outdoor environments.
Mamun et al., 2016	Real-time monitoring for waste bins	Optimized collection routes using wirelessly transmitted data.

RESULTS AND DISCUSSION

Table 5.

Section	Aspect	Details
Merits of Implementing SWMS	Enhanced efficiency	GPS-enabled SWMS improve waste collection by using real-time tracking and optimized routing, significantly reducing collection time.
	Cost reduction	Integrating GPS into waste management systems lowers operational costs by creating efficient routes, reducing fuel consumption, and cutting labor expenses.
	Waste bin monitoring	Enables real-time monitoring of garbage bins, preventing overfilling and minimizing litter and environmental pollution.
	Sustainability	Supports sustainability by cutting greenhouse gas emissions and fuel consumption through optimized routing, leading to a smaller carbon footprint.
	Resource allocation	Enhances efficient use of fleets and personnel by optimizing vehicle deployment, reducing costs and improving service.
	Real-time insights	Continuous monitoring provides insights into waste generation patterns, improving resource planning and sustainable waste management practices.
Future scope of smart waste management implementation	Intelligent waste management	Future systems will incorporate sophisticated sensors for real-time monitoring of fill levels, waste composition, and hazards like strong odors, improving collection schedules and cost savings.
	Data analytics & machine learning	Advanced analytics and machine learning will optimize route mapping, predict waste patterns, and assist in city planning for waste reduction strategies.
	Robotics & AI in sorting	Automated systems with image recognition and tactile sensors will enhance the efficiency and accuracy of sorting recyclables, increasing recycling rates and reducing contamination.
	Renewable energy integration	Innovations like kinetic energy harvesters and biogas generators will improve the energy self-sufficiency and environmental sustainability
	Advanced waste-to-energy technologies	New methods, including plasma gasification and engineered bacteria, will create cleaner and more efficient ways to convert waste into high-value products like biofuels or biodegradable plastics, advancing environmental goals.

Analysis of smart waste management systems highlights predictive maintenance as a critical driver of operational and environmental efficiency. IoT sensor data enables predictive algorithms to detect equipment anomalies from compactor malfunctions to lid failures before breakdowns occur, reducing downtime, maintenance costs, and service disruptions while extending infrastructure lifespan. This proactive approach also supports sustainability, optimized resource allocation, fewer emergency repairs, and reduced emissions from maintenance activities collectively lower the ecological footprint of waste operations. By aligning operational reliability with environmental stewardship, predictive maintenance emerges as a dual-purpose innovation for modernizing urban waste systems.

CONCLUSION

Looking ahead, the implications of these advancements are far-reaching:

1) *Environmental impact:* Smart waste management systems have the potential to significantly reduce carbon emissions associated with waste collection and processing. By optimizing routes and improving recycling rates, these systems could play a crucial role in cities' efforts to combat climate change.

2) *Public health:* Real-time monitoring and rapid response capabilities of smart systems could prevent the build-up of waste in public areas, reducing the risk of disease transmission and improving overall urban hygiene.

3) *Resource efficiency:* As waste-to-energy technologies advance, smart systems could turn our waste streams into valuable resources, contributing to the circular economy and reducing dependence on virgin materials.

4) *Urban planning:* The data gathered from smart waste management systems will provide invaluable insights for urban planners, potentially influencing future city designs to better accommodate efficient waste handling.

5) *Behavioral change:* Through increased public engagement and awareness, these systems have the potential to drive long-term changes in consumer behavior, promoting more responsible consumption and disposal practices.

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Recent advances in the development of edible coatings and films to extend the shelf life of fruits and vegetables: a review

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The vegetables and fruits can be packed with films or coated with a substance that is edible which forms thin layers to protect them from damage during handling from chemical changes and microbial invasion. Rapid respiration, high moisture content, and transpiration rate in fruits and vegetables make them perishable. Combining edible coatings/films with storage at controlled temperature and relative humidity is one way to make agricultural produce last longer after it is harvested. It can modify the internal atmosphere thereby minimizing the physicochemical changes in the agricultural produce. Nutrients, flavors, and antimicrobial substances are some of the important components that are found in edible coatings/films. The main parameters usually affected under storage are firmness, sensory attributes, weight loss, and nutrients. In this article, we review films and edible coatings, their different types, and the scope of their most recent developments, as well as the ways films and edible coatings affect the physicochemical properties, sensory qualities, and microbial inactivation of fruits and vegetables.

Keywords: Edible coating, edible films, types of edible coating, and physical barriers

INTRODUCTION

A transparent covering of edible material less than 0.3 mm thick is called an edible film or coating. In contrast, edible films are preformed edible layers molded into sheets that will be applied as wrapping over the products. They are made by combining various biopolymers in an aqueous dispersion medium with additives [1]. A thin coating that covers the surface of food is called edible coating. It could help reduce the permeability of water vapor, carbon dioxide, and oxygen [2, 3]. This should not result in the complete depletion of oxygen because it can facilitate anaerobic respiration leading to ethanol formation and development of off-flavor. It can also deliver a barrier against oxygen, microbial load, moisture, and solute transfer in food products. The efficiency of edible coatings depends on the type of fruit and the materials used for the coating. Commercially, these coatings play a crucial role in maintaining product quality, meeting market standards, and reducing production and packaging expenses. They control the movement of substances such as oxygen, carbon dioxide, flavors, lipids, moisture, and dissolved compounds, thereby lowering respiration rates and minimizing weight loss [4]. Lipids, proteins, and polysaccharides are contained in three main categories of edible coatings. Edible coatings or films upon application to the food surface can serve as physical barriers that prevent ripening by altering the internal conditions of the fruit. Use the following healthy substitutes to increase the longevity of fresh, lightly processed fruits and vegetables after they have been harvested [5]. When edible films or food coatings are used, they cause no problem for release since they are eaten along with the film or the coating [6]. Producing semi-permeable barriers, these coatings help prolong the shelf life of various fruits e.g. papaya, kiwi, and strawberry by retaining gases and water vapor. These coatings keep the fruit's shiny looks and quality during part of the storage period, causing a fall in the respiration rate that tends to be minimal [7-10]. This can also be used as a vehicle for the delivery of flavor, color, and anti-browning agents shown in Figure 1 [11]. Many fruits such as papayas, kiwis, and strawberries benefit from using edible coatings which prolong their shelf lives. Additionally, they help maintain the glossy aspects of the fruit's appealing taste and provide nutritional value for health benefits [12-14].

An essential element of food preservation involves packaging the food because it protects it from various environmental factors like microbes. Additionally, it offers comprehensive product information, significantly influencing the commercialization and distribution of food items [15]. The choice of suitable packing material depends upon the physicochemical characteristics of food products.

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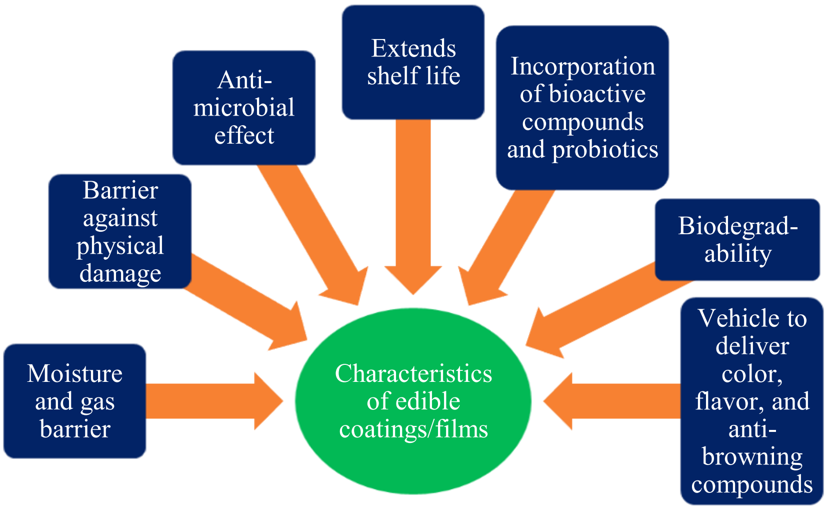

Figure 1. Characteristics of edible coatings/films.

The application of the different traditional kinds of wrapping materials such as paper, glass, cardboard, and plastic has caused massive junk [16]. Recycling packaging materials is also becoming difficult because they are made up of various types of materials with different characteristics [17]. Recently, experts have started checking on how edible films can be used against the deficiencies seen in normal package materials as alternative biodegradable packages [18, 19]. Different parameters that are generally affected during storage are firmness, sensory attributes, weight loss, ascorbic acid, dietary fiber, and antioxidant activity. The edible coatings/films are also beneficial for the environment and consumers [20, 21]. Nanotechnology presents a novel technique for synthesizing new material layers for fresh food preservation and coating through the diminution of the material to the nanometric scale. Due to the combination of larger specific surface area and higher mass transfer rates, nanoparticles are more penetrative, chemically and biochemically reactive, enzymatically active, catalytically active, and quantum active than larger particles of the same material [22]. This review aims to outline various edible coatings and film types, their current advancement, and their microbiological activity, taste characteristics, and physicochemical properties of fruits and vegetables.

DISPERSION SYSTEMS EMPLOYED IN THE PREPARATION OF EDIBLE COATINGS/FILMS

By effectively mixing oil and water with emulsifiers, emulsions are created to form a consistent mixture. There are several types of emulsions depending on their properties, such are water-in-oil and oil-in-water emulsions [8]. The structure of these emulsions can interact with polar and nonpolar compounds due to their dual nature containing hydrophilic and hydrophobic components in their structure [23]. The first type is based on the properties of oil and water. The preferred form of emulsion in preparation of edible coatings or films is oil in water due to the easy solubility of various lipophilic compounds like bioactive and plant-based essential oils [24, 25]. Emulsions are described as oils and aqueous phases that are being homogenized by emulsifiers. They have unique properties that enable them to be classified into water in oil (w/o) emulsions and oil in water (o/w) emulsions based on these properties [26]. Therefore, emulsions are A typical system for the generation of edible coatings or films due to the unique nature of the substances involved which are capable of effectively preserving and retaining additives [27, 28]. The gelling of the coating solution can be induced by the addition of calcium ions through the oxidation of compounds present in the pectin and by the synergistic effect in gelatin. The alginate chains can be held together by calcium ions to form junction zones followed by the gelling of the solution [29]. The starch-based coating suspension can be prepared by heating the solution by which starch can be dissolved until gelatinization followed by cooling to room temperature and mixing with other components [30].

Spreading, dipping, spraying, and wrapping are some of the techniques used to apply edible coatings or films as illustrated in Figure 2 [31].

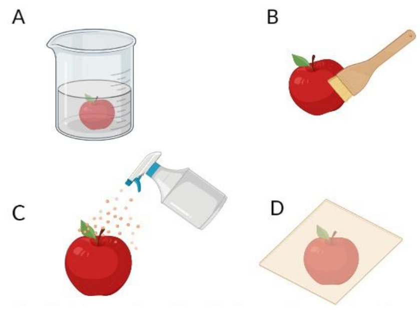

Figure 2. Techniques used for applying edible films or coatings on food products: (A) Dipping (B) Spreading (C) Spraying (D) Wrapping.

Dipping is a simple method used for edible coatings which comprises three different steps such as immersion and dwelling, deposition of coatings over the surface, and evaporation of solvents remaining on the surface at ambient temperature or using dryers. The thickness and morphological characteristics of edible coatings are dependent on various factors like immersion time, withdrawal speed, drying conditions, and characteristics of coating solution (density and viscosity). The disadvantages of this method are the requirement of the high amount of coating solution per unit area of the product and the chances of the formation of layers with a higher thickness which in turn affects respiration and surface damage. The other drawbacks include contamination of the coating solution by the dirt and microorganisms present on the surface of agricultural produce posing problems in scale-up. The spreading technique is more suitable for highly viscous coating solutions. The spreading rate and wettability are the important factors affecting the coating process. Parameters like surface geometry, drying conditions, and composition of coating solution also affect the efficiency of the coating process. The specialized technicians generally perform brushing because human factor influences the quality and homogeneity of coatings on the products. Spraying is a way of applying a layer of coating fluid uniformly over an object's surface by using many nozzles clustered together which release tiny droplets. Since the coating fluid has less thickness, Its result is usually thicker compared to dipping methods., the formed coating ends up being thicker than what the 'dipping' method produces [32].

Usually, the food products are wrapped in a solid sheet of edible film, which acts as the primary packing material. This can be prepared using molding, steel belt conveyors, extrusion, electrospinning, and thermoplastic methods. In casting, the liquid will be poured over the mold followed by solidification whereas, in steel belt conveyors, the coating solution is allowed to spread uniformly on steel followed by drying. Extrusion is preferred over the casting method due to the less energy and processing duration requirements. The specific mechanical and processing barrel temperature is required to synthesize edible film using an extruder. Electrospinning is an economical method where the droplets of the solution are electrified to create a jet that is strengthened and elongated for the synthesis of fibers. The thermoplastic method is better suited for chitosan and gelatin-based films. It involves the continuous synthesis of edible films under high pressure and temperature, with reduced water usage [33].

PARAMETERS AFFECTED DURING THE STORAGE OF FRUITS AND VEGETABLES

Firmness, ascorbic acid retention, sensory attributes, weight loss, and antioxidant activity are among the several factors commonly impacted during the storage of vegetables and fruits.

Firmness

Fruit and vegetable firmness is an essential aspect when assessing their overall quality. The important properties that determine firmness are maturity, shelf life, and optimum harvest date. Typically, force and deformation are generally used to describe firmness. The acoustic resonance test, destructive Magness-Taylor compression test, and non-destructive compression test are the three comparatively easy methods for determining hardness. Therefore, it is feasible to establish connections between the described firmness characteristics, and it's essential to determine which trait is suitable for defining the maturity and/or ripeness or firmness of a particular type of fruit [34].

Sensorial analysis

As depicted by ISO 9000:2015, the quality of food is defined as the extent to which an object's intrinsic properties meet requirements. The assessment of the kinesthetic qualities of food has long gone hand in hand with the analysis of sensorial attributes. With the application of advanced texture analyzers, the desired product can be developed. Food quality is also estimated in terms of textural properties by consumers. Recent studies demonstrate that a food's crispness and crunchiness are mostly related to its texture analysis profile. Hence, instrumental analysis and sensory analysis are two independent approaches for evaluating the right sharpness or food palatability and other kinesthetic properties, including crunchiness. The instrument used for textural analysis was the TA.XT PlusC™ texture analyzer (Stable Micro Systems Ltd., Godalming, UK) and the method was compression/acoustic type [35]. Examined by sensory analysis are the attributes of appearance, flavor, brightness, texture, and color [5]. Pigments like anthocyanin and carotenoids often undergo chemical degradation leading to color fading and also bioactivity loss [36].

Weight loss

Vegetables and fruits lose weight after they are harvested. Several factors contribute to the weight of these products, such as the loss of water from inside and outside the cells, the breakdown of sugars, cellular respiration, and the collapse of the cell walls due to cell death [37]. Loss of weight is another crucial quantitative approach to understanding the shelf life of non-coated and coated vegetables and fruits [38].

Ascorbic acid and dietary fiber

Ascorbic acid is a vital phytonutrient with potent antioxidant activities that can neutralize the body's generated reactive oxygen species, defending against a variety of severe diseases [39]. Edible coating treatments can retain the maximum ascorbic acid content by limiting the oxygen availability required for the oxidative breakdown of ascorbic acid [40]. Although ascorbic acid content starts increasing during the different stages of ripening, it tends to decrease after reaching the fully ripe stage [41]. The degradation rates of ascorbic acid in horticultural products will vary depending on genotype, stage of development, and storage conditions [37]. The continuous respiration and cell wall thickening of the agricultural produce may lead to a small increase in fiber content when being stored [42]. Vegetables and fruits contain trace amounts of soluble dietary fiber [43].

Antioxidant activity

Fruits are very important for human survival because they carry many essential elements that can prevent cancer and heart diseases by cutting down on the body's toxic load as a result of their micronutrient and antioxidant properties; hence they are the best sources of polyphenols which are antioxidants found in natural foods. Numerous diseases are prevented by antioxidants, including endothelial dysfunction, which has been linked to illnesses associated with aging, including hypertension, hypercholesterolemia, and atherosclerosis [44]. Many antioxidative enzymes that help the body eliminate the effects of free radicals, like glutathione peroxidase and thioredoxin reductase, depend on it as a cofactor [45].

DIFFERENT TYPES OF EDIBLE COATINGS FOR VEGETABLES AND FRUITS

The three common types of edible coatings used to preserve important quality characteristics such as firmness, sensory properties, pigmentation level, nutrient retention quality, and reduction in weight loss, are proteins, lipids, and polysaccharide-based coatings (Figure 3).

Polysaccharide-based edible coatings/films

The key polysaccharides utilized in polysaccharide-based edible coatings include plant gums, pectin, starch, cellulose, dextrin, alginates, and chitosan. Polysaccharide coatings that can be ingested are used with antioxidants or antimicrobials to enhance food quality as well as shelf life during storage [46]. For instance, a variety of polysaccharides including alginate, cellulose, cellulose, carrageenan, gum arabic, starch, and guar are widely classified as safe by the US Food and Drug Administration [47].

- *Alginate.* The food industry uses alginate as a gelling agent that is naturally obtained mainly from bacteria and brown algae. Colloidal properties such as solid gels are characterized by the interaction with multivalent metal cations, such as calcium which leads to insoluble polymers [48, 49]. Alginate-based edible coatings and films are noteworthy for preserving fruit quality, they also make sure that the shelf life is extended by decreasing dehydration, controlling respiration, improving product appearance, stifling microbial growth, and boosting mechanical properties [50]. In [49] Menezes *et al.*'s study, they used a dipping method to investigate how fruit pectin and sodium alginate-based coatings, containing 2%, affected sapota fruits after being kept in them for two or four min. Consequently, the sample was kept under refrigeration conditions at about four °C over a period of thirty days. Between the control group and coated sapota fruits, there was a noticeable change in terms of physicochemical properties. The polysaccharide coating with a 2 min dipping time proved successful in retaining the fruit's organoleptic characteristics (sensorial attributes). During storage at 4°C for 12-15 days, the outer layer of a newly sliced watermelon was made of three concentrations of sodium alginate (0.5%, 1%, and 2 %), with an antimicrobial ingredient trans-cinnamaldehyde, calcium lactate and pectin for each concentration used [51]. The antimicrobial edible coating has not affected the pH (5.2) and water activity (0.99) of fruits.

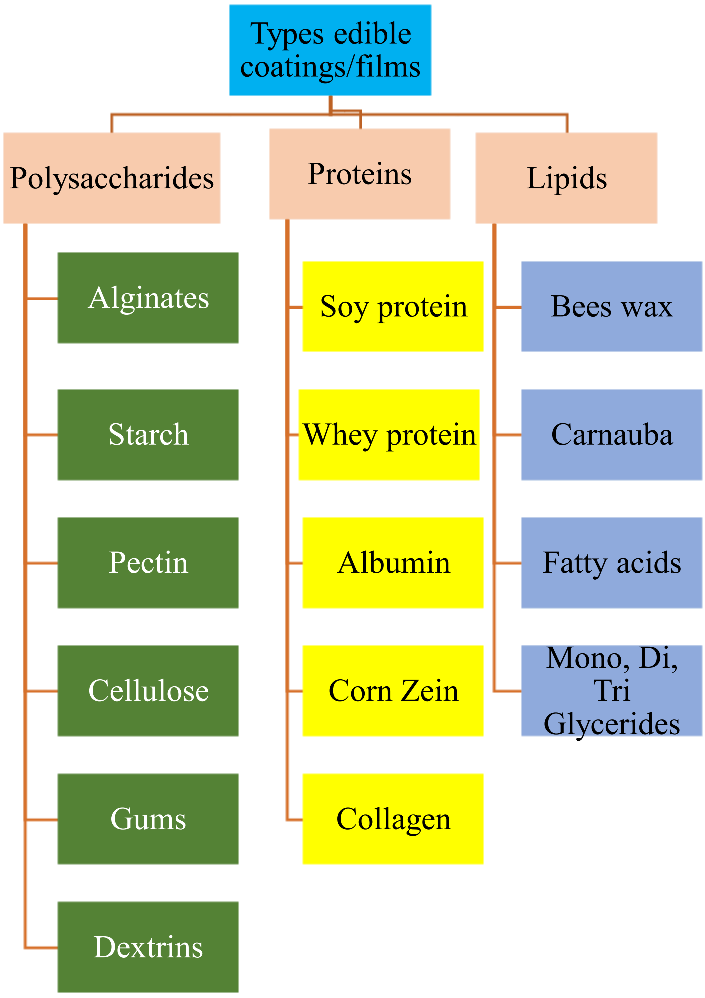

Figure 3. Different types of edible coatings.

Microscopic analysis showed that the coating with 2% pectin, 1% sodium alginate, and 2% natural antibacterial agent was consistent and had high adherence across the entire fruit surface. Sensory analysis indicated flavor, color, or odor of coated fruits was not affected during storage.

Ghavidel *et al.* [52] used edible coating of fresh-cut apple wedges by different solutions like carrageenan (0.5%), alginate (2%), whey protein (5%), and soy protein (5%). Storing for 15 days at 4°C alginate-based coating retained higher water content and better texture compared to other coated fruits. However, the sensory analysis showed that whey protein-based coated fruits were preferred over other coated fruits regarding color, appearance, and odor. Bal *et al.* [50] stated that edible coating of cherry tomatoes with alginate (2%) with or without UV-C treatment was stored at 10°C for a maximum of 20 days. UV-C treatment alone retained the nutrients when being stored during at early storage period but declined during the final stages of storage. The retention of ascorbic acid, phenol, and lycopene content was enhanced by the combination of UV-C and alginate coating, which also helped to reduce respiration rate and weight loss.

- *Gums and mucilage.* Dietary fiber with mucilage had the ability to take in huge amounts of water., dissolve, and spread out to form a viscous or gelatinous mass known as a colloidal mass [53]. Almost all plants and specific microorganisms produce mucilage, which is a thick, glue-like substance Hence, it is a metabolic by-product generated within the cell and is not easily dissolved in water. Mucilage can operate as a water-transfer barrier despite being hydrophilic, which could decrease water loss and increase fruit flesh hardness. Several plants, such as fenugreek, aloe vera, cactus, okra, and taro, contain mucilage [54]. Mucilage has been utilized in numerous fruit preservation strategies which include cellulose, amino acids, and water-soluble polysaccharides [13]. The gum can be created from naturally existing polysaccharides having the capacity to hydrate in water, stabilize emulsion systems, or form a gel [55]. The traditional source of psyllium gum is the psyllium seed husk which is a mucilaginous material that is rich in both soluble and insoluble fibers. Yousuf *et al*. [56] studied how adding psyllium gum (0.5-1.5%) to edible coatings containing sunflower oil could be used in preserving fresh-cut papaya fruit at 4°C for 2 weeks. Results showed that the coating applied at a 1% concentration of psyllium gum reduced mass loss, promoted better ascorbic acid retention, and contributed to a stable level of titratable acidity, soluble solids, and color quality. The sensorial attributes of coated papaya fruits 12 days after being stored were similar to those of fresh papaya fruits. After nine days of storage at 5°C, researchers studied the mucilage-based fruit coating extracted from the cladodes of Opuntia ficus-indica [40]. Throughout the storage, mucilage maintains the weight, total soluble solids, firmness, sensorial attributes, visual appearance, and content of ascorbic acid and betalain, because it's a glycol protein-based edible coating. Coated fruits exhibited a lower increase in microorganisms while in storage than did uncoated fruits. The effect of probiotic mucilage (quince, flax, and basil) based edible coating on strawberries, cucumber, tomato, and banana was studied by Davachi *et al.* [57] Coated agricultural produce retained freshness for a longer duration than uncoated products. Quince-based probiotic films kept more bacteria alive and were more stable mechanically, physically, and morphologically.

The reddish-brown peel of almonds protects the kernel from oxidation because the peel is rich in antioxidants while the peeled almonds suffer from shorter shelf life. Hence, studies are being conducted on edible coatings to improve shelf life. Farooq et al [58] reported mastic gum edible coatings (0.5-2%) of peeled almonds during storage at 25-27°C for 4 months. The mastic gum-based coatings at different concentrations prevented moisture absorption and reduced the thiobarbituric acid, peroxide, mold growth, and total yeast throughout the storage duration. Ghosh et al [59] studied guar gum (4-10%) based edible coating of tomatoes for a storage period of 32 days. The 6% guar gum concentration was effective in terms of overall acceptability during sensory analysis and also lesser weight loss during the storage period. The lycopene, carotenoid, phenol, and TSS content of tomatoes was also maintained. People can preserve tomatoes within a maximum time of thirty-two days by using a coating of edible guar-gum which slows down ripening. This decrease in the rate at which tomatoes lose weight can be attributed to the ability of the coating to act as a partially permeable barrier through which air and other gases, as well as water vapor and solutes, cannot pass thereby slowing down respiration, desiccation, and oxidation.

According to Saberi *et al.* [60], edible films were used in Valencia oranges stored at 5°C for 4 weeks and then transferred to 20°C for an extra 7 days. By employing the layer-upon-layer technique, coatings like guar gum, pea starch, shellac, and oleic acid were developed. Lipid compounds also allowed decreasing a rate of respiration, an ethylene formation, loss of weight, and a decay presence and ensured orange texture preservation. Oranges covered with a layer of guar gum and pea starch alone, as well as shellac, guar gum, and pea starch, kept their consistency and color characteristics fresh throughout storage. Even though the layer-by-layer approach improved the firmness, and reduced respiration rate and weight loss, this has resulted in the formation of ethanol causing off-flavor. When compared to commercial wax-based coatings, guar gum combined with citrus fruit shelf life can be effectively increased with edible coatings based on pea starch.

- *Starch.* Starch contains amylose and amylopectin; it is the most widely utilized biopolymer [61]. It is mainly derived from maize and a huge number of smaller amylose molecules coexist with amylopectin molecules [62]. The presence of amylose in starch is responsible for its film-forming ability. The starch-based coatings are biodegradable, affordable, and eco-friendly when compared to traditional packaging materials. Starch is hydrophilic which in turn makes them a poor water barrier [63]. According to Hernández-Guerrero *et al.* [30] having a starch-based coating, the shelf-life of stenospermocarpy mangoes can be increased by putting the fruit in those two conditions; stenospermocarpy mangoes that had a starch-based coating when they were kept in that manner [10 days at 10°C and then 5 more days at 22°C for ten days]. Tropical fruits were used to extract the starch like banana pear, soursop, and mango. The coated fruit storage temperature at 10°C for 10 days has not affected the fruit color, firmness, total soluble solids, and organoleptic properties. However, further storage at 22°C resulted in increased weight loss in treated fruits in 5 (3.32%) and 10 (3.36%) days of storage. The storage of mangoes treated with mango starch resulted in reduced weight loss, soluble content, and higher firmness compared to uncoated fruits. Mango starch-based coatings also increase the shelf life to fifteen days or five days at 22°C and ten days at 10°C.

Strawberry fruits are perishable with a very short post-harvest life due to mold decay caused by quick metabolic reactions. Garcia *et al.* [61] assessed storage at a temperature of 5°C for 15 days and an edible coating made of a 3% concentration of cassava starch and potassium sorbate. Apple-based coating increased weight loss, and firmness and decreased the respiration rate, while the uncoated fruit has consumed 9 days; the concentration of potassium sorbate does not influence bacterial spoilage. The cassava starch-based coatings have better sensorial characteristics and extend strawberries' shelf life to twelve days. Adjouman *et al.* [64] reported cassava starch edible coating of tomatoes with and without microcrystalline cellulose (30%) followed by a storage temperature at 20°C for 4 weeks. Both edible coatings improved physicochemical parameters. Titratable acidity, noticeable firmness, total soluble solids, sugar/acid ratio, and color corresponded with the storage period. Aly *et al.* [65] alleged that fresh-cut taro shelf life was prolonged by 100 % chitosan-starch edible coating at 4 °C to 20 days. This has also led to adorable product quality as far as moisture content, firmness, soluble solids, and sensory characteristics are concerned, as well as halting the development of microbes including yeast and mold. Moreira *et al.* [63] reported modified starch and gelatin-based edible coatings enriched with peppermint oil (0.5-1.5%) for preserving the guava fruits for storage temperature at 25°C for up to 15 days. The physicochemical properties like acidity, firmness, soluble solids, and pH, weight loss were better maintained with the modified starch and gelatin-based coating without essential oil. The filamentous fungal and bacterial growth was reduced in fruits that were coated with modified starch and gelatin-based coatings containing 1.5% peppermint oil.

- *Cellulose.* One of the most common polysaccharides is cellulose which can form films and have a wide range of permeabilities to gases and water vapor [66]. Various biopolymers and biometrials can be used to increase the biocompatibility and processability of carboxy methylcellulose [67]. Commercially available cellulose derivatives are hydroxypropyl methylcellulose, carboxymethyl cellulose, and methylcellulose. Transparency, flexibility, absence of flavor or odor, water solubility, and resistance to O_2 and CO_2 permeability are the common characteristics of coatings and films created from these cellulose ethers [68]. Carboxymethyl cellulose is an essential derivative of cellulose that is commercially in use. It is not soluble in water and has a good ability to combine into a coating. Most carboxymethylcellulose-based coatings are flexible, translucent, odorless, and tasteless [69]. Vegetables and fruits are kept firm and fresh because of the barrier qualities of cellulose to the movement of moisture and oil [70]. Tumbarski *et al.* [71] studied the enrichment of bacteriocin obtained from *Bacillus methylotrophic* BM47 in a carboxymethylcellulose (0.5%) based edible coatings on the enhancement of the shelf life of strawberries. The bacteriocin and carboxymethylcellulose-based edible coatings maintained antioxidant activity values similar to that of fresh fruits. The absence of fungal growth on the surface of fruits has been observed after the 8th day of storage under refrigerated conditions. Ballesteros *et al.* [69] reported edible coatings based on carboxy methyl cellulose enriched with polysaccharides and phenolics extracted from spent coffee grounds of goldenberries kept between 20 and 4°C. The carboxymethylcellulose-based edible coating containing 0.2% polysaccharides or 0.2% phenolics effectively controlled the fungal growth. This coating has reduced the gas diffusion rate by pore blockage over the fruit surface which in turn altered the internal gas composition (high carbon dioxide and low oxygen). Both the coated and uncoated fruits suffered weight loss while it was higher in higher-temperature storage compared to low-temperature storage. Coated fruits retained more ascorbic acid and phenolic substances while retaining the same sensory qualities.

Panahirad *et al.* [72] reported carboxymethylcellulose (0.5-1.5%)-based coatings of plum fruits. The higher titratable acidity, firmness, ascorbic acid, and minimal weight loss were observed in plums coated with 1% carboxymethylcellulose. All the coated fruits retained higher antioxidant activity, anthocyanin, and flavonoid content than uncoated samples. In all the coated fruits, peroxidase activity was found to be increased while a decrease in polyphenol oxidase and polygalacturonase was observed. Vishwasrao *et al.* [66] reported the hydroxypropyl methylcellulose and palm oil-based edible coating being stored at 24°C to maintain the quality of pink guava fruits. The fruits coated with 1% palm oil plus 0.3% Hydroxypropyl methylcellulose HPMC retained ascorbic acid, chlorophyll, and soluble solids, reducing sugar and titratable acidity to a greater extent. It also reduced peroxidase and polyphenol oxidase peroxidases. The enhanced shelf life of fruits coated victorious over uncoated fruits by staying for twelve days compared to nine days is due to their delays and increase in enzyme activities for PPO and POD enzymes. An edible coating made up of carboxymethylcellulose derived from banana rachis on strawberry fruits was examined by Abdullah *et al.* [12] The coatings can effectively enhance the shelf life of strawberry fruits to six days at the temperature of 22°C and 16 days at 4°C. Anthocyanin, weight, soluble solids, retardment of senescence, pH, ascorbic acid, and sensory attributes and firmness of coated fruits when being stored at the temperature of storage samples at a temperature of 4°C gave better results compared to those stored at 22°C. Njoku *et al.* [73] examined the application of commercial carboxymethylcellulose in comparison with carboxymethylcellulose extracted from coconut husks in the edible coating of tomato fruits for 40 days at ambient conditions. Edible coatings based on commercial carboxymethyl cellulose help control weight loss more successfully than CMC extracted from coconut husks and uncoated samples, and increases both sugar-acid ratio and lycopene content well.

- *Pectin.* Plant cell walls contain pectin which is a soluble component of plant fiber. According to [74], pectin could help in making environmentally friendly films and coatings that are used in the packaging of food. Also, in the development of a multi-layered coating for vegetables and fruits pectin is combined with other functional components. Panahirad and other authors determined that when plum fruits were kept at 19°C, an edible coating made from pectin (0.5–1.5%) helped to preserve their antioxidant activity [75]. The pectin concentration of 1 and 1.5% was better in retaining the higher concentration of antioxidant activity, ascorbic acid, flavonoid, anthocyanin, total phenolics, and peroxidase activity compared to 0.5% pectin-coated and uncoated fruits. There was a decrease in polyphenol oxidase activity in treated fruits when compared to the uncoated samples. Maftoonazad *et al.* [76] focused on the effect of a consumption-based coating, composed of monoglycerides, sorbitol, beeswax, and 3% pectin, on the post-harvest shelf life span of lime fruits at ambient temperatures of 10 to 25°C. At an equal temperature with uncoated lime fruits, the rate of respiration for these in coated conditions had exceedingly reduced significantly. The loss of mass from fruits was minimal compared to control samples. Pectin forms a barrier to gas aiding in averting oxidation and thus enhances retention of ascorbic acid thereby leading to an increased shelf life of up to 40 days at the above temperatures compared to 13 days where the fruit was uncoated. The ripening of fruits during storage decreases the firmness while this change was reduced during low-temperature storage and coated fruits.

According to Heristika *et al.* [77], edible coatings for red chilies were made using pectin and gelatin in different ratios (50:50, 75:25, and 25:75) with garlic essential oil being stored at 29°C for 14 days. A blend of pectin, gelatin, and essential oils altered the acidity, ascorbic acid, weight loss, texture firmness retention, and antioxidant activity; 2% to 3% garlic essential oil was contained in the above products (50:50 w/w). Using pectin and a gelatin-based coating containing garlic essential oil can enhance the shelf life of red chilies for the temperature at 29°C up to 14 days. According to Gragasin *et al.* [78], they extracted pectin from mango peels and used it to cover mangoes between 8–10°C storage and 25–27°C storage. At 25-27°C and covered, the mangoes were well kept for 12 days thereby preventing ripening, and disease attacks and at the same time maintaining firmness and soluble solid constant unlike in those left uncovered which lasted only 6 days. The coated fruits at chilled storage reduced the metabolic reactions and preserved the quality in terms of visible disease resistance for up to 24 days. The uncoated mangoes were affected by 50% damage and disease development in 12 days. The pectin coating (2-4%) can be effectively used for coating mango fruits to extend the post-harvest life.

The higher moisture content of tomatoes facilitates higher respiration and transpiration rates that in turn affect the shelf life and quality. These physiological processes can be minimized by harvesting at the specific stages of maturity and by suitable coatings. Completely mature tomatoes, turning green, and light red were harvested, stored at 22°C and coated with chitosan and pectin [79]. The turning stage tomatoes showed better results compared to other stages of maturity. Compared to uncoated tomatoes, fruit that was coated significantly decreased weight loss, ripening index, and disease severity. The pectin and chitosan-coated tomatoes retained higher lycopene, phenolics, ascorbic acid, and total soluble solids compared to uncoated tomatoes. Table 1 prrsents several edible coatings for food products that are based on polysaccharides, whereas untreated fruits had a shelf life of 10 days which is 16 and 17 more days than pectin-coated and control fruits, respectively.

Table 1. Reports on polysaccharide-based edible coatings on various food products.

S. no	Edible coatings	Fruits and vegetables	Remarks	Ref.
1	Sodium Alginate	Sapota	weight loss reduced, its pH levels went down, it also became less firm, had a color change, and lost some of its total soluble solids content (TSS). Consequently, acidity was lowered in it during the storage at 4 degrees Celsius. Maintained organoleptic qualities for up to 30 days.	[49]
2	Alginate-based multi-layered antimicrobial coating	Watermelon	Reduced weight loss, no change in pH, a slight difference in color, and extended shelf life with original quality storage for 12 and 15 days at a temperature of 4°C.	[51]
3	Alginate (sunflower oil)	Fresh cut apples	Improved texture quality and water retention, maintained sensorial attributes and visual appearance. When kept in storage at 4°C, fresh-cut apples had a 15-day shelf life.	[52]
4	Alginate coating with UV-C	Cherry tomato	low ascorbic acid and total phenolic content; low respiration rate; and less weight loss.Extended the postharvest life at 10°C for up to 20 days.	[50]
5	Mastic gum	Peeled fresh almond	Prevented moisture absorption and increased shelf life of the coated almonds for 4 months at room temperature.	[58]
6	Psyllium gum	Fresh cut papaya	Maintained color, textual and visual appearance, and taste. Increased quality and shelf life up to 2 weeks.	[56]
7	Guar gum	Tomato	Decreased ascorbic acid, weight loss, and respiration rate. Increased lycopene content, carotenoid content, and TSS. The color of the treated tomatoes transitioned from green to a yellowish-orange hue throughout storage. Preserved quality of tomato during storage for up to 32 days	[59]
8	Guar gum	'Valencia' oranges	Absence of color change, together with decreases in respiratory rate, weight loss, ethylene production, and firmness.	[60]
9	Starch	Mango	Reduced weight loss, and titratable acidity. Firmness, color, and TSS are not affected. The shelf life was prolonged for a duration of up to 15 days.	[30]
10	Starch	Strawberries	There was no significant impact on the color, pH, soluble solids, or titratable acidity of strawberries. Strawberries' shelf life was increased, though, and could last up to 12 days while stored.	[61]
11	Cassava starch	Tomato	Enhanced physicochemical parameters including titratable acidity, total soluble solids, and firmness were observed. Tomatoes saved at 20°C were longer preserved at least for four weeks.	[64]
12	Chitosan/starch	Fresh cut taro	The moisture content decreased while firmness increased. By using chitosan starch, the shelf life of fresh-cut taro samples can last up to twenty days.	[65]
13	Starch/gelatine	Guava	We kept the weight, pH, and soluble solids the same, but made sure that the food stayed fresh for up to 15 days without refrigeration.	[63]
14	Carboxymethylcellulose	Fresh golden berries	Maintained all physicochemical parameters without changing sensory characteristics. Extended shelf life of golden berries fruit after 12 and 28 days when being stored.	[69]
15	Carboxymethylcellulose	Plums	The overall phenolic content did not significantly change with slight variations observed in flavonoid content and total anthocyanin. Extended post-harvest storage for up to 8 days at 19°C.	[72]

16	Hydroxymethyl cellulose	Pink Guavas	TSS content was maintained, TA decreased, and instead of 9 days, its overall quality shelf life was 12 days.	[66]
17	Carboxymethylcellulose	Strawberries	Maintained the TSS content, decreased TA, and maintained an overall quality twelve-day shelf life as opposed to nine days.	[12]
18	Carboxymethylcellulose	Tomatoes	Increased weight loss. Reduced TSS, ascorbic acid, and firmness. Postharvest treatment slowed the aging process of coated fruits at 4°C.	[73]
19	Pectin	Plum	Increased levels of phenolic, anthocyanin, flavonoids, and ascorbic acid. Retained their capacity to absorb antioxidants. PPO activity decreased while POD activity increased. The postharvest life of plum fruits treated with a pectin-based edible coating was extended to an eight-day shelf life at 19°C.	[75]
20	Pectin	Lime fruit	Diminution of firmness, respiration rate, ascorbic acid content, and reduction in weight loss. While at 25 °C, the system quality stayed within acceptable levels for only seven days, it was higher than at 15 °C but less than 22 days in duration.	[76]
21	Gelatine-pectin	Red chilies	Weight loss was reduced while maintaining levels of vitamin C, antioxidants, total dissolved solids (TDS), and acidity. When placed at ambient temperature (29°C, 69% relative humidity), its shelf life became longer by fourteen days.	[77]
22	Pectin	Tomato	Reduced weight loss, firmness, ascorbic acid, and respiration rate, while increasing titratable acidity (TA) and pH. Under ambient conditions, the shelf life was extended to 17 days.	[79]
23	Pectin from mango peel	Mango	A decrease was seen in weight decrease, respiration rate, ascorbic acid content, total soluble solids (TSS), and firmness as well. Water–soluble mango pectin at various concentrations ranging from 2 to 4% may prevent rapid spoilage of undried mangoes.	[78]

TSS- Total soluble solids; TA- Titratable acidity; TDS- Total dissolved solids; PPO-Polyphenol oxidase; POD-Peroxidase; AA- Ascorbic acid

Proteins

Proteins have exceptional mechanical strength and gaseous (O_2/CO_2) permeability due to the intimate interactions among the chains during the coating's deposition involving covalent, non-ionic interactions and hydrogen bonding, essential in preserving the freshness of fresh fruit for longer periods [80]. Various edible coatings are made of milk, gelatine, soybeans, peanuts, wheat, or corn are reported. The majority of hydrophilic surfaces, protein-based films, and coatings work effectively, although they often exhibit minimal resistance to water vapor transport. Edible coatings made of proteins have weak mechanical properties but better water and carbon dioxide barrier properties [81].

- *Soy protein.* Protein materials of soybeans are more suitable for application in edible coatings because of their permeability which has been low to carbon dioxide along with oxygen as well as their reasonable price. Soybeans are plant protein. Most plant protein sources have few amounts of essential amino acids like histidine, methionine, lysine, and cysteine and many anti-nutritional substances and unbalanced composition of non-essential amino acids [82]. The shelf life of walnut kernels and freshly cut eggplants has been extended by the application of substances derived from soybeans. Zhang *et al*. [83] suggested that a soybean-chitosan coating improves the retention of fruit chelator and water-soluble pectin as well as increases weight loss, titratable acidity, soluble solid content, and hardness. The untreated apricot fruit demonstrated a firmness of 2.69 N after 42 days of storage as against 4.15 and samples of 4.26 N coated with soybean protein isolate and soybean protein isolate -chitosan, respectively. Apricots covered with chitosan-coated with soybean protein isolates showed a weight decrease that was visible and significantly less than observed in the controlled group. On the other hand, the soybean protein isolate and chitosan-coated apricots had weight reduction that was less than that in the control group, but it was still observable. On the 35th day weight loss of 19.93% for the fruits coated with soybean protein isolate and 18.10% for the non-treated fruit, respectively, was observed.

When compared with the control fruit, TA declined during storage in the coated fruit a little bit more slowly. Maintained quality and extended post-harvest of coated apricot fruits when being in storage periods and also maintained better firmness of the fruits. The apricot's physicochemical properties were maintained by soybean protein isolate-chitosan coating after 42 days due to inhibition of water loss mainly linked to weight loss similar to the group that was covered with soybean protein isolate.

- *Whey proteins.* The milk protein-based coatings and films that are edible serve as a barrier between food ingredients or as a protective layer on foods. Their crucial features include mechanical defense, mass transfer control, and sensory attributes [84]. As a by-product of producing cheese, whey is a good source of amino acids that contain sulfur, methionine, and cysteine. The whey-based films made from whey protein isolates and concentrates contain 90% and 50-80% of protein, respectively. The ability of whey-based film formation is determined by the heat denaturation of whey protein in an aqueous solution [85]. Galus *et al.* [86] reported whey protein edible coating containing lemongrass and lemon essential oil on fresh-cut pears in comparison to the uncoated fruits upon storage temperature at 4°C. Incorporating essential oil in whey protein-based coatings enhances their ability to block gases. All edible coatings inhibited the browning of pears, except lemongrass oil whose yellow color contributes to its non-effectiveness in controlling browning. The fruit's texture was maintained throughout the storage for 28 days except for the lemon oil-based coating. The use of edible coatings made from whey proteins did not affect the color, taste, and smell of fruits. Essential oils led to a reduction in the general acceptability of fruits during sensory analysis.

Elsayed *et al.* [87] reported that they can use a 1-3% concentration of mango peel extract to extend its shelf life while also preserving the post-harvest quality of fresh-cut broccoli with an edible coating made from whey protein for 28 days if stored at 5°C. Whey protein-based coatings in combination with mango peel extract resulted in better retention of green color and reduced weight loss in broccoli which has been compared with uncoated broccoli. The ascorbic acid, sulforaphane, and phenolic content retention were also better in coated fruits. An edible coating derived from whey protein with mango peel extract (3%) coated broccoli received higher sensory scores and a reduction in bacterial and fungal counts. In their findings, Rossi-Márquez *et al.* [88] devised a method that involved applying an edible whey protein coating consisting of pectin along with transglutaminase onto roasted peanuts to extend their shelf life. As a result of the presence of these mixtures, the peanuts could maintain balanced moisture levels as well as peroxide while at the same time preventing them from getting spoiled within a short period thus promoting long ordinarity. This situation arose due to improved moisture barrier capacities that come with such envelopes. The enzyme within those combinations lowers the surface charge of the whey-protein pectin compound hence the peanut's surface coating solution is seen with better wettability and adhesive properties [88]. During sensory analysis, >50% of the consumers preferred coated peanuts compared to uncoated samples over storage for 50 days. The peroxide value was in the acceptable range for the coated peanuts (20 to 30 $mEqO_2$/Kg). The uncoated peanuts attained a higher moisture level (>8%) after 2 weeks of storage whereas coated peanuts maintained a moisture content of 2.5-3% throughout the 50 days of storage. The coated samples appeared lighter in color while uncoated samples were darker in color.

- *Cereal protein.* In both the glutelin and prolamin fractions of wheat proteins, wheat gluten, and the prolamin portion of maize zein and maize proteins, their ability to form films has been the focus of extensive study. Films formed of gluten have high mechanical properties, a good capacity to isolate oxygen, and a resistance to water vapor. Comparing the without-treated group to the presence of a substance like mineral oil which has no polarity and is hydrophobic, there is a difference in vapor permeability reduction levels of about 25 % [85]. Corn-zein protein is a renewable and biodegradable substance that can be used in coating and packaging film applications [89]. The incorporation of ethanolic extract of propolis into gelatin-based edible films was studied by direct incorporation and by encapsulation into the zein nanocapsules to control the release of extract [90]. The inclusion of extract in the films resulted in increased elasticity and stretchiness but left their water barrier properties and microstructure unaffected. The incorporation of nanocapsules containing the extract promoted better preservation by improving the antifungal activity compared to the direct incorporation. The reports on protein-based edible coatings on various food products are compiled in Table 2.

Table 2. Reports on protein-based edible coatings on various food products.

S. no	Edible coating	Fruits and Vegetables	Remarks	Ref.
1	Whey protein	Fresh cut pears	Maintained firmness. Reduced flavonoids and polyphenols. Did not affect sensory attributes. Maintained quality attributes of the treated sample during storage for 28 days except lemon oil-based coating at 4°C.	[86]
2	Whey protein	Broccoli	The weight loss, rate of respiration, and levels of bioactive compounds or antioxidant activity were at the lowest level. Maintained post-harvest quality and shelf life at 5°C for 28 days.	[87]
3	Whey protein	Roasted peanuts	Surface charge and water uptake decreased, while wettability and surface adhesivity increased. These improvements helped keep roasted peanuts at top quality even after 50 days of storage.	[88]
4	Soy protein	apricot	There was a decrease in dietary consumption, respiration rate, titratable acidity as well as soluble solids. The quality was maintained and the post-harvest life of coated apricot fruits was extended the temperature up to 42 days of storage.	[83]

TA- Titratable acidity; SSC- Soluble solid content

Lipids

Wax and oils like beeswax, vegetable oil, sucrose, mineral oil, carnauba wax, acetylated monoglycerides, and beeswax esters of fatty acids are used in the production of lipid-based coatings, which are frequently employed as a good water barrier for preserving moisture in the fatty acids based on food materials [91]. Lipid-based coatings are the maintenance of the moisture content in food products of the main advantage. By creating the hydrophobic barrier in products, they can halt moisture loss as well as microbial invasion. It can maintain product quality while improving its aesthetic appeal. The rice processing industry's secondary byproduct that has beneficial nutritional qualities is rice bran wax which is proven to have good film-forming characteristics, making it a useful edible coating ingredient [92].

- *Beeswax.* Beeswax can be used as an effective moisture barrier for perishable commodities. Food preservatives along with beeswax can increase the functional characteristics of edible coatings whereas it can also limit the growth of mold, bacteria, and yeast when being stored and distributed [93]. Due to the hydrophobic nature of beeswax, it enhances air passage but reduces water vapor passage. The freshness and quality of food products can be preserved by reducing transpiration rates and minimizing flavor and weight loss. It has been shown that by using hydroxy propyl methylcellulose-based coatings and the application of beeswax hardness can be maintained over longer periods by several kinds of fruits among which are tomatoes, mandarins, mangoes, plums or guavas [94]. The effects of HPMC and beeswax coating on 'Angeleno' plums were elucidated by Navarro-Tarazaga *et al.* [95] with 0-60% of beeswax lipid content and 4 weeks storage temperature of 1°C, then it was stored for another three weeks at a temperature of 20°C. Beeswax with lower lipid content has been effective in decreasing the softening and bleeding of plums because the surface of the fruit develops a changed atmosphere. The beeswax coating with 20% lipid content is further recommended to enhance the shelf-life of plums with higher quality products.

Formiga *et al.* [96] reported the effect of edible coatings of 'Pedro Sato' red guavas using HPMC and beeswax (10-40%) during 8 days of 21°C storage. The coated fruits appeared greener, firm, and turgid compared to uncoated fruits. The increase in the wax concentration decreased the chlorophyll content when being stored. The guava fruit's shelf life without coating is six days. However, the fruit's quality and its shelf life extension by six days were preserved by HPMC and 20% beeswax. Fagundes *et al.* [93] studied the anti-fungal properties (*Botrytis cinerea)* of HPMC and beeswax coating along with different food preservatives (potassium carbonate, ammonium carbonate, sodium propionate, and ammonium phosphate) on cherry tomatoes stored at 5°C. All the coated fruits showed antifungal activity while sodium propionate-based HPMC and beeswax coating exhibited higher antifungal activities. Ammonium carbonate-based HPMC and beeswax coating maintained firmness and decreased weight loss significantly compared to other combinations. Sousa *et al.* [94] have shown that the storage life of palmer mangoes treated with beeswax and ammonium carbonate HPMC can be prolonged. The study investigated the effects of a hydroxypropyl methylcellulose-beeswax edible coating (10-40%) on mangoes stored for fifteen days at a temperature of 21 ºC. The coating controlled the fruit ripening and maintained pigments, antioxidant activity, soluble solids, phenol, sugar, ascorbic acid, firmness, titratable acidity, and β-carotene content. It has also minimized weight loss, and oxidative stress and does not cause fermentation of fruits during storage. The application of 20% beeswax combination with HPMC enhanced the shelf life for an additional 6 days.

- *Carnauba wax.* Many fruits and vegetables have been treated with carnauba wax, which is an edible coating that is lipid-based so that they last longer after they are harvested. Its main use is to reduce evaporation and keep its shine. This wax comes out of Brazilian palm tree leaves. Commercial carnauba-shellac coatings can prolong the ripening of pears because of the production of more carbon dioxide compared to uncoated fruits, thereby maintaining firmness and delaying color changes [97]. In 2018, the US Food Drug and Administration provided GRAS status to carnauba wax. It also prevents pigment degradation, maintains texture, and enhances the mechanical integrity and aesthetic properties of fruits [98]. Carnauba wax contributes to the product's aesthetic improvement by increasing its shine [14]. Bhattacharjee *et al.* [99] reported edible coating of pointed gourd using chitosan and carnauba wax at 27-32°C. The carnauba wax-coated fruits showed a higher disease reduction index and chlorophyll content, minimal weight loss, and spoilage compared to chitosan-coated fruits. Therefore, Instead of being coated with chitosan-based coatings, products can be coated with carnauba wax to enhance quality and increase longevity. Nazoori *et al.* [100] led the investigation on prolonging the shelf-life of pomegranate fruits by storing them under cold conditions while applying edible coatings of 0.5% carnauba wax and 5 mM or 10 mm GABA for 45 or 90 days. The edible coating maintained freshness decreased the loss of taste, and malondialdehyde formation, improved antioxidant activity, and reduced cold injury. The weight loss was not controlled by the GABA and carnauba-based coatings. Carnauba wax (0.5%) with GABA (5 mM) can be used for storage for 45 days while carnauba wax (0.5%) with GABA (10 mM) storage for 90 days.

Oliveira Filho *et al*. [14] found that *Cymbopogon martini* EO and carnauba wax nanoemulsion (CWN) could be used to coat papaya fruit for storage after harvest. The coated fruits retained higher firmness, pH, decreased weight loss, and lower soluble solids and TA. The edible coating containing 1.5% of CWN+CEO reduced the disease incidence during the 9 days at 16°C of storage. Miranda *et al*. [98] inquired about the utilization of high-pressure-produced carnauba wax nanoemulsion base and the usual 9% and 18% carnauba wax emulsion in enhancing tomato quality and shelf life, which were held at 23°C during 15 days, in their research. The nanoemulsion coating made of carnauba wax fruits had higher gloss and sensory scores compared to carnauba wax emulsion and uncoated fruits. Both the coatings decreased the weight loss but the color and sugar content of tomatoes was significantly affected when being stored. In the study, Singh *et al.* [97] investigated how carnauba wax-based edible coatings influenced eggplant characteristics when it was stored in polypropylene pouches at (20°C). The coated and packaged eggplant retained higher antioxidant activity and firmness compared to the uncoated eggplant. As for shelf life duration extension, one observed that coated packaged eggplants lasted for 12 days more than the untreated ones.

- *Fatty acids.* Lauric acid, a dodecanoic acid that is abundantly present in coconut oil contains a huge amount of lauric acid and it undergoes endogenous conversion to monolaurin, a substance with antiviral, antifungal, and antibacterial activities. The coating-based coconut oil can inhibit the lenticle's opening and stomata, slow respiration and transpiration, and reduce microbial deterioration rates [101]. In the example given by Memete *et al.* [102], some sunflower oil, coconut oil, beeswax, or gelatin-type edible coatings were applied to them and stored at four degrees celcius for eight days. Non-coated fruits presented significantly higher anthocyanin and phenolic content as well as better firmness and sensory scores compared to the other coated fruits. Therefore, the oil-based edible coatings have demonstrated that the mulberries' shelf life could be increased at the storage temperature of 4°C for 8 days while preserving the product important in terms of texture, antioxidant activity, and sensorial score. Nasrin *et al*. [101] have investigated the impact of beeswax and the quality of post-harvest in the edible coatings that have been developed using coconut oil of lemons in ambient conditions (21°C), with and without modified atmosphere packaging (MAP). Using MAP, it was found that beeswax coatings containing 80% coconut oil and 10% lemons were able to prolong their shelf life by 15 days and more. However, uncoated lemon could be acceptable in terms of color, flavor, and texture for only up to 6 days. The coated fruits moderately reduced the shrinkage of lemon while MAP plays an important role in preventing the shrinkage. Manju Danu *et al.* [103] determined that coconut oil edible coating (3%) under refrigerated conditions (T8) has been the most efficient treatment for Malta fruits in terms of TSS: Acid ratio, total soluble solids, fruit juice volume (ml), juice percentage, fruit color, taste, texture, flavor, and overall acceptability. In comparison, mustard oil (T2) and almond oil (T10) coatings were particularly beneficial for maintaining pH and preserving titratable acidity (%). It was concluded that the edible coconut oil coating effectively preserves the chemical and sensory characteristics of Malta.

- *Resins*. Trees and shrubs with specific plant cells respond to wounds by producing and secreting a class of acidic substances known as resins. Petroleum is a component of synthetic resin production. Chauhan *et al.* regarded the tomato as a product to determine the use of shellac resin produced by Laccifer lacca wasps and found in India, as well as aloe vera gel, which was used as an edible coating. Aloe vera gels promote the penetration of water vapor, carbon dioxide, and oxygen into the membrane. The development of the aging process, changes in ethylene synthesis, and the respiration rate occurred more slowly. The fruits' texture and color characteristics were more preserved than the fruits without the coating when labels were stored at 28°C, uncoated. Shelf life increased by 12, 10, and 8 days with the use of shellac, aloe vera, and aloe vera and shellac-based consumable films [104].
- *Rice bran wax*. In the study done by Abhirami *et al.* [90], where rice bran wax was used on edible tomatoes as a coating to prolong their shelf life, the products' weight loss, lycopene content, texture, soluble solids, and respiration rate of the products were kept intact at 27 days of storage by applying a 10% wax coating. This implies that the uncoated samples are maintained for a maximum of 18 days. The tomato wax coating, which blocked the lenticels and stomata, may also be causing the slower rate of weight reduction. Moreover, the reduced tomatoes' respiration rate with coatings might be due to the reduced metabolic processes in tomatoes. Rice bran wax is utilized and prepared as an edible oil source [105]. Reports on lipid-based edible coatings on various food products are discussed in Table 3.

CURRENT CHALLENGES AND FUTURE PERSPECTIVES

Different edible coatings and films that integrate useful components have substantially extended the period within which fruits and vegetables can last. Moreover, the use of edible coatings and films successfully preserved the nutritional value and sensory qualities of the produce while maintaining its post-harvest quality. The main area of research in the use of edible films and coatings has been laboratory work. Therefore, it is essential to conduct scale-up studies to ease the commercialization of the process. Further work can be carried out by incorporating nano-encapsulated compounds to facilitate the controlled release of functional ingredients to provide stability against adverse storage conditions. The layer-by-layer edible coating successfully retained physicochemical characteristics, sustained quality and nutraceutical benefits, and improved the antioxidant enzyme system, aiding in oxidative stress regulation and the functioning of the ascorbate–glutathione cycle (Figure 4) [106]. The layer-by-layer coating treatment effectively reduced decay percentage and Physiological weight loss while preserving total chlorophyll pigments. This, in turn, likely inhibited the accumulation of total carotenoids by suppressing the activities of chlorophyllase (CPS), pheophytinase (Phe), Mg-dechalatase (MGD) and chlorophyll degrading peroxidase (Chl-POD) enzymes in harvested mangoes [107]. The layer-by-layer approach resulted in better retention of product quality but limited research work is available in this area. Therefore, future studies can focus on developing a layer-by-layer approach and/or coatings and films incorporated with nano-encapsulated functional ingredients. The types of edible coatings and their functional benefits are presented in Table 4.

CONCLUSION

Edible coatings and films can replace conventional packaging materials, which are not biodegradable. Most fruits and vegetables can be preserved with edible coatings and films to reduce wastage. These coatings and films consist of proteins, carbohydrates, and lipids - naturally occurring polymers to maintain freshness, microbial spoilage, and moisture loss in agricultural produce. The deterioration rate is slowed down by them acting as barriers to gas, moisture, and solutes. The novel polymers and advancement in formulation techniques can define the new trend in edible coatings and films. Further research can be focused more on improving the stability, barrier ability, anti-microbial nature, and mechanical properties to widen their scope, usefulness, and acceptability. Nanotechnology in the use of edible coatings and films stands out as a possible aid in enhancing their mechanical properties and increasing preservation time for different food products.

Table 3. Reports on lipid-based edible coatings on various food products.

S. No	Edible coating	Fruits and vegetables	Remarks	Ref.
1	Rice bran wax	Tomatoes	Maintained lycopene content, respiration rate, texture, and soluble solids. Increasing the shelf life to 27 days.	[92]
2	HPMC Beeswax	Cherry tomato	Weight loss and respiration rate were reduced, with improved control over water loss and enhanced visual appearance. Tomatoes now last 15 days at 5°C instead of 5 days at 20°C.	[93]
3	Beeswax	Mango	There was a decline in weight loss as well as an increase in firmness and the antioxidant activity remained unchanged. The mangoes stayed at 21°C for 15 days before being extended by another 6 days.	[94]
4	HPMC Beeswax	Guava	The weight loss was reduced and, in the process, color and firmness were preserved. By doing this, it added up to six more days of staying on the shelf.	[97]
5	Coconut oil beeswax	Lemon	Quality, Ph, sensory analysis, ascorbic acid (AA), and total soluble solids were maintained. With the addition of modified atmosphere packaging, the extended shelf life reached 15 days and exceeded 18 days.	[101]
6	Beeswax content on HPMC	Plums	Weight loss decreased, sensorial attributes remained unaffected, and lipid content increased. Extended shelf life of store plums at 1°C for up to 4 weeks, then at 20°C for 1-2 weeks.	[95]
7	Beeswax	Mulberry	Maintained firmness and antioxidant activity. Improved shelf life of mulberry to 8 days at 4°C	[102]
8	Carnauba wax	Eggplant (*solanum melongena*)	Extended eggplants for 12 days at 20°C as a way of reducing weight loss, and increasing firmness and moisture content.	[97]
9	Carnauba wax	Tomato	Weight loss decreased, while ascorbic acid (AA), total soluble solids, and pH remained unaffected. Storage of tomatoes at 23°C increased their shelf life to 15 days.	[98]
10	Carnauba wax Nanoemulsion	Papaya	Decrease in weight loss and maintain its firmness. Temper down on both TSS and TA. Papaya fruits ripen during the 12-day storage period.	[14]
11	Gamma-Aminobutyric acid & carnauba wax	Pomegranate	Weight loss and firmness were reduced, while sensory analysis and nutritional quality were maintained. Extended shelf life of carnauba wax (0.5%) with GABA (10 mM) for 90 days of storage.	[100]
12	Carnauba wax	Gourd	Weight loss was reduced and ripening was delayed. This led to a prolonged shelf life of gourd under ambient storage conditions (27.4-32.3°C and 70-81% RH).	[99]

TSS- Total soluble solid; TA- Titratable acidity; AA- Ascorbic acid; GABA- Gamma-Aminobutyric acid; HPMC- Hydroxy propyl methylcellulose

Table 4. Types of edible coatings and their functional benefits

Type of edible coating	Integrated components	Benefits	Challenges	Future scope	Ref.
Polysaccharide-based	Antioxidants, antimicrobials	Moisture control, barrier properties	Limited moisture resistance	Nano-encapsulation for enhanced functionality	[108]
Protein-based	Sodium alginate, cedar mucilage, calcium chloride Components	Sustainable food production Reduce food waste	Increase Effectiveness and commercial viability	Layer-by-layer approach for better retention	[106]
Lipid-based	Essential oils, hydrophobic agents	Improved water resistance	Poor mechanical strength	Combining with polysaccharides for balanced properties	[109]
Composite coatings/films	Nanoparticles, functional ingredients	Synergistic barrier properties	High-cost, complex production	Scale-up studies for commercialization	[110]

Fig. 4. Advantages of layer-by-layer edible coatings.

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Transforming waste to wealth: biochar production from MSW for pollution mitigation and resource recovery

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The rapid surge in waste generation worldwide is primarily fueled by population expansion. Open dumping of municipal solid waste (MSW) leads to significant environmental issues due to gaseous emissions and discharge of harmful substances from landfills. Biochar, a carbon-rich material derived from various biomasses, presents an opportunity to recover valuable resources and mitigate pollutants, thereby converting municipal solid waste into a valuable product. This article delves into producing biochar from waste materials, emphasizing that the techniques used for creating biochar from municipal solid waste can yield materials with a broad spectrum of characteristics. The article explores the potential uses of biochar, such as application as a permeable reactive obstacle to decrease pollution and as an eco-friendly absorbent for treating leachate. Likewise, biochar can serve as a covering material to diminish unpleasant odors. The generation process of biochar from waste materials is thoroughly discussed, highlighting the diverse material properties that can result from various methods employed for its creation. Additionally, the article examines the multiple functionalities of biochar, ranging from mitigating pollution as a permeable reactive barrier (PRB) and eco-friendly adsorbent for leachate treatment to its role as an effective covering material for odor reduction.

Keywords: Biomass, waste, biochar, municipal, material
Abbreviations: MSW-Municipal solid waste; AC-Activated carbon; IC-Inorganic contaminant; OC-Organic contaminant

INTRODUCTION

The increasing urbanization and industrialization rates heavily demand substantial energy consumption, often at the cost of environmental well-being. The global population of 8 billion is expected to soar to 8.5 billion in the upcoming years. The world was expected to make 2.3 billion tons of solid waste in 2020, which is about 0.79 kg of waste generated per person per day [1]. As cities and populations grow quickly, the amount of trash made each year is expected to increase by more than 70% from 2020 to 2050, reaching 3.88 billion tons. MSW demands urgent attention for proper management. Fig. 1 demonstrates the percentages of different materials found in MSW. In many regions, open dumping remains the predominant method for managing MSW despite the growing interest in more sustainable alternatives like composting and vermicomposting, primarily due to their relatively lower costs [2]. Moreover, highly toxic sulfide gas is generated in the composting method. Nonbiodegradable wastes with low moisture content, referred to as low-moisture urban garbage, are ideal for incineration. However, waste's high costs and moisture content restrict the widespread application of incineration, particularly in developing nations, especially those within the tropical belt with high yearly rainfall. However, incineration offers many benefits over landfill disposal, including a substantial volume reduction under relatively limited space, its implementation is constrained. The fly ash generated from the incineration of MSW serves as a significant contributor to pollution. Incineration can also lead to the formation of hazardous dioxins [3]. Solid waste management in underdeveloped nations accounts for a significant portion (20–50%) of local governing bodies' budgets [4, 5]. Astonishingly, this waste is generated by less than 50% of the city's population. In economically developed nations, MSW is considered an asset utilized for the production of the source of energy, which includes the generation of heat, primarily through pyrolysis and gasification processes [6]. Open dumping, prevalent in lower- and middle-income countries, releases a spectrum of environmental toxins into the environment, includ-

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ing CO_2, CH_4, N_2O, and acetic acid, classified as greenhouse gases, volatile organic compounds (VOC), potentially hazardous elements, and persistent organic contaminants [7].

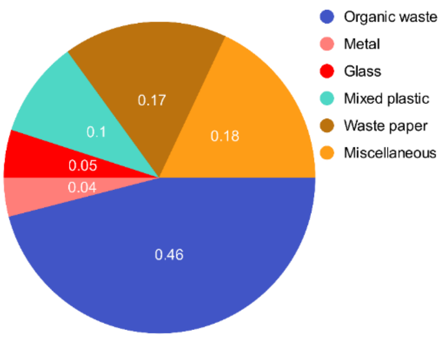

Fig. 1. Percentages of different materials found in MSW

Methane gas emission from open landfills significantly contributes to climate change, while these dumps frequently contain noxious substances like benzene, ethylbenzene, xylene, and toluene. The leachate from these dumps contains highly toxic substances, impacting various organisms and demonstrating increased transport capacity of trace metals like Cd, Ni, Hg, Cu, Mn, Pb, and Zn. Treatment of landfilled leachates poses a significant challenge due to their complexity [8]. A major global challenge remains in finding practical solutions to address the pollution from MSW. The development of efficient waste management systems must align with the reliability, quantity, and content of collected waste in specific areas. Anthropogenic factors, for instance, an absence of favorable attitudes regarding waste management, pose hurdles in establishing sustainable waste management systems due to the intricate nature of the problem, variability in waste sources, technological limitations, and scarcity of information flow. One potential solution involves the transformation of municipal waste into biochar and biogas through pyrolysis, representing a direct waste-to-energy process. The emerging trend of material recovery from debris involves utilizing biochar to achieve sustainable economic objectives. Biochar, distinguished for its exceptional adsorption properties, has found relevance in material science, leading to cleaner water and healthier soil [9]. Both pre-treatment of biomass feedstock and modification of biochar influence the characteristics of biochar. The presence of functional groups such as carboxylic acid, ketone, and hydroxyl along with the aromaticity in biochar derived from MSW facilitates the adsorption of contaminants *via* various mechanisms including surface coordination, electrostatic interaction, pi bonding, ion exchange, and hydrogen interaction. By converting raw waste into biochar, there is a significant reduction in waste production, rendering the process more environmentally friendly due to reduced energy consumption. The transformation of municipal waste into biochar, as shown in Fig. 2, usable as an adsorbent or soil amendment, holds promise in alleviating the mounting global waste burden. Utilizing biochar derived from municipal waste for wastewater purification, leachate treatment, and soil enhancement through nitrogen recovery [10] forms the focal point of this concise overview.

BIOCHAR FROM MUNICIPAL SOLID TRASH

Technologies

Resource recovery processes for MSW can primarily be categorized into biological and thermochemical methods (Fig. 3). The thermochemical accumulation of biomass is a pivotal process technology employed for the production of biochar within the temperature range of 200–900°C. This process encompasses three primary thermochemical techniques, namely pyrolysis, carbonization, and gasification, as illustrated in Fig. 4. The selection of specific process conditions is contingent upon various factors, including the biomass sources, their pre-carbonization treatment, and the intended main

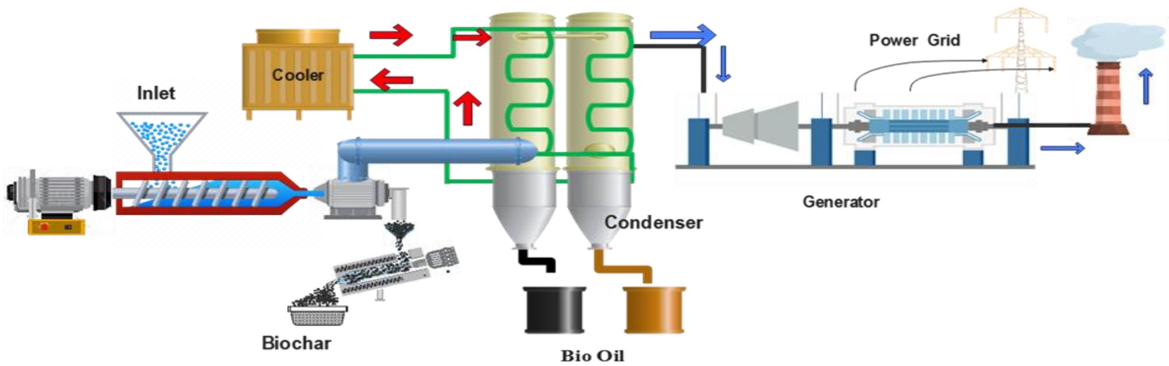

Fig. 2. Layout of the process of biomass conversion into various useful products

product, be it bio-oil, biochar, or energy. Pyrolytic transformation has emerged as a proven and effective method for converting biomass to mitigate contaminants [11]. Biochar's ability to remove organic and inorganic contaminants from soil and water environments is susceptible to the feedstock and pyrolysis conditions under which it was produced. These factors profoundly affect the physicochemical processes that determine the bioavailability of infection in certain ecological settings. Among the various pyrolysis techniques, gentle pyrolysis with low speed is among the most commonly utilized methods for biochar production. Slow pyrolysis features a slow rate of heating (typically less than 10 °C/min) and extends for a duration ranging from minutes to several hours [12]. This method yields a substantial amount of biochar, often reaching up to 35% of the original biomass. Conversely, fast pyrolysis, characterized by a high heating cycle (~1000°C/s), results in a lower biochar production (around 10%) while primarily generating bio-oil as its principal product (approximately 70%) [13]. Torrefaction, another pyrolysis process, operates at lower temperatures (190–281 °C) and leads to the partial accumulation of biomass [14, 15]. In MSW, numerous research studies have concentrated on low to moderate mode of pyrolysis methods for its management. On the other hand, fast pyrolysis of MSW is also gaining attention. Notably, the reported biochar generated from numerous researches exhibits a broad range, from 15% to 65%, reflecting the diversity and complexity of factors influencing the biochar production process. The principal method for generating biochar from MSW involves pyrolysis of biomass, as shown in Fig. 5. Within this domain, slow pyrolysis is conducted at temperatures between 390–600°C to maximize biochar yield; bio-oil, C1–C2 hydrocarbons, and syngas are generated by-products. Results are susceptible to reaction parameters and the specifics of the used agricultural waste. In contrast, hydrothermal carbonization is a viable method for biochar production in regions characterized by wet, humid atmospheres or surroundings, where MSWs possess substantial moisture content [16]. This method reduces the energy required for drying, decreasing the overall price and power required for biochar production compared to conventional pyrolysis techniques. However, it is important to note that the surface area obtained by hydrothermal carbonization tends to be less than by other pyrolysis techniques [17]. Existing MSW biochar manufacture studies have mostly been conducted at small or laboratory scales. Scaling up the production to a larger, industrial scale, targeting a given quality is challenging due to MSW feedstocks' dense and amalgamated nature. The diverse nature of these feedstocks poses a challenge in designing an effective large-scale production process that meets specific criteria.

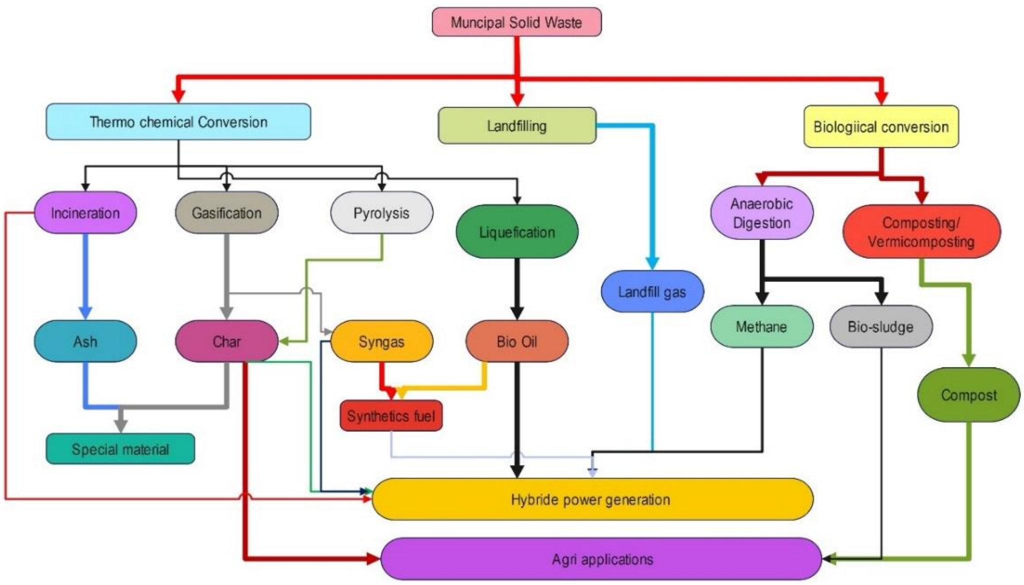

Fig. 3. Different techniques for MSW conversion

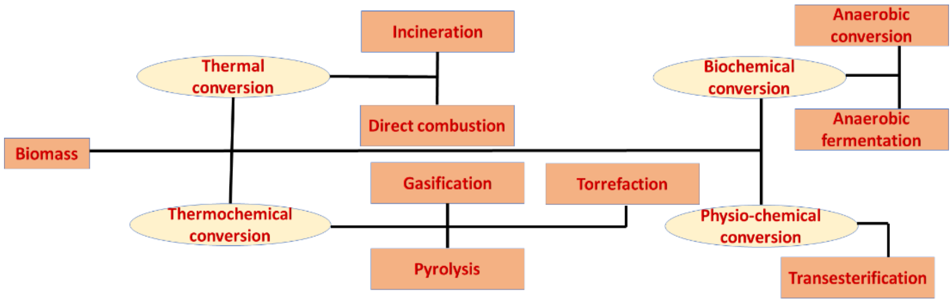

Fig. 4. Conversion of urban biowaste into biofuels, gaseous products, and carbon-rich solids. Torrefaction and gasification are mostly used to pretreat biomasses before combustion, not to make MSW biochar.

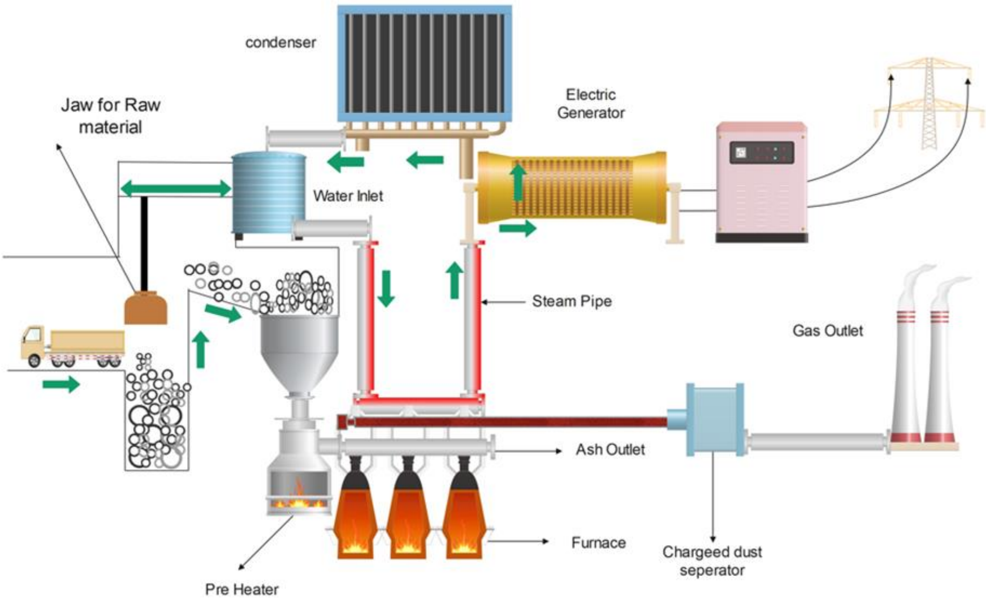

Fig. 5. Pyrolysis of biomass

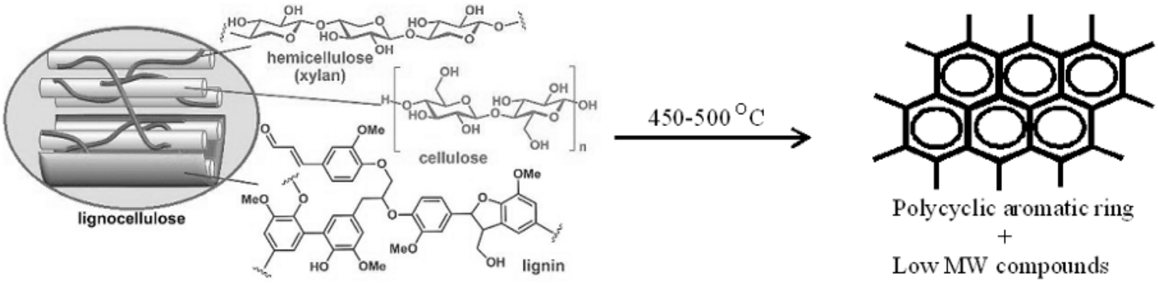

Fig. 6. Biochar formation [18] (open access, no copyright permission required)

Biomass pyrolysis occurs through 3 fundamental steps:

(1) *Evaporation:* At 100°C, the biomass releases moisture content and forms amorphous carbon, which is used for biochar production.

(2) *Biochar production:* Biochar is an aromatic polycyclic molecule formed during the pyrolysis process of biomass. Since primary biochar easily breaks down into secondary biochar, water, and gas, it acts as a catalyst for secondary reactions. So, it must be quickly removed. As a result, the yield of bio-oil declines. The synthesis of benzene rings and their coupling with polycyclic compounds constitute the primary route of this reaction. The formation of biochar from biomass is shown in Fig. 6.

(3) *Depolymerization:* The depolymerization procedure breaks down the lignocellulosic polymer bonds yielding smaller monomers and saturated substances of low molecular mass at temperatures ranging from 300 to 450 °C. This causes chain formation and produces volatile compounds that condense to liquids at room temperature.

(4) *Disintegration:* This process involves the covalent bonding between the monomeric units,

which produces small straight-chain chain molecules and noncondensable gases. Cellulosic biomass undergoes decomposition into alcohols, carbonyl acids, and other compounds at a temperature of about 600 °C. This process is depicted in Fig. 7.

(5) *Secondary processes*: At the operating temperature of the furnace, volatile substances are not persistent when produced during the depolymerization and disintegration process; instead, they further undergo secondary processes which include cracking and repolymerization. The process of cracking involves the breakdown of bonds of volatile substances and the creation of molecules with high weight. Large polycyclic hydrocarbons, which are occasionally stable at the operating temperature of the furnace, are created when volatile substances recombine in repolymerization reactions. The reaction processes for biomass pyrolysis are shown in Fig. 8.

Properties of MSW-derived biochar

The summary from Table 1 underscores the considerable variability in the properties of MSW biochar, emphasizing the impact of different processing conditions, feedstock composition, and methodologies used in the production process. The correlation between pyrolysis temperature and the resulting surface area indicates a trend that could provide insights into optimizing biochar production for specific applications or desired properties.

APPLICATIONS OF BIOCHAR

Biochar as a green adsorbent

Due to its promising results in reducing the concentrations of numerous pollutants, including heavy metals, contaminants, and other nutrients, biochar has been the subject of extensive research and widespread interest. Among the diverse ranges of feedstocks used for biochar production, MSW has recently emerged as a focal point in waste management strategies. Several studies have highlighted the application of biochar synthesis from MSW as a dual-purpose solution [19].

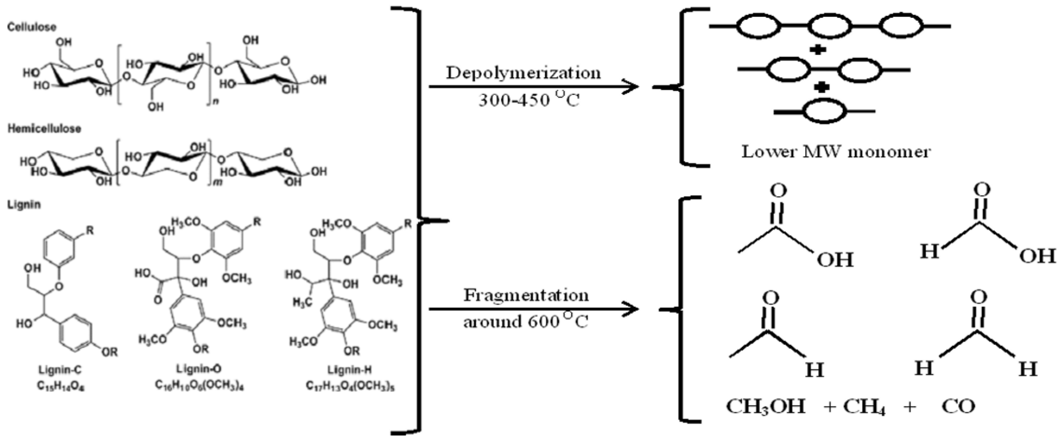

Fig. 7. Depolymerization and disintegration process in pyrolysis [18] (open access)

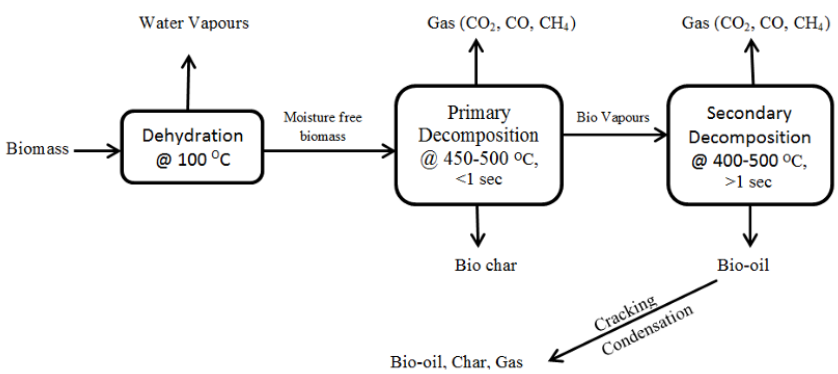

Fig. 8. Reaction processes for biomass pyrolysis [18] (open access)

Table 1. Main properties of the biochar pyrolyzed at different temperatures

Country	Process	Temp Zone (°C)	Volatile matter (%)	Ash (%)	Fixed material (%)	% (of N, C, O, H)				Surface area m^2/g	Pore volume cm^3/g	Ref.
China	SP	D	67.9	74.2	--	1.54	17.4	10.4	0.7	--	--	[20]
		E	73.7	77.9	--	1.38	18.4	7.3	0.34	--	--	
		F	78.6	81.5	--	0.95	16.92	6.8	0.21	--	--	
India *(Agri-culture)*	SP	D1	64.2	18.1	--	3.39	74.37	--	2.21	--	--	[21]
Sri Lanka	SP	C	30.1	15.6	46.5	1.33	60.8	14.6	2.79	212.9	0.013	[22]
Australia	SP	C	11.9	72.7	13	6.09	68.2	20.1	4.33	--	--	[23]
		D	8.5	76.5	12.6	5.79	76.7	13.6	2.84	--	--	
			6.3	76.8	14.3	6	80.7	10	2.64	--	--	
USA *(Mixed material)*	SP	C	--	6.1	65.2	1.3	48.6	31.4	12.2	20.7	--	[24]
		D	--	9.2	63.8	1.4	59.5	20.8	9.1	29.1	--	
		E	--	6.2	78.2	1.3	70.1	13.7	8.4	29.8	--	
	SP	C	21.9	6.4	71.7	1	76.8	12.5	3.3	359.8	0.14	[25]
		E	9.4	7.9	83.6	1	83.8	6	1.2	380.9	0.15	
South-Korea	Hydro-thermal carboni-zation	A	74.2	12.5	13.3	0.4	41.7	40.1	5.3	--	--	[26]
Qatar *(Hard, Soft, Paper, Mixed material) (P2, P4, P6 at 2, 4, 6 h time span)*	P1	B	--	10.1	--	0.3	40.7	53.6	5.2	--	--	[27]
		D	--	20.5	--	0.7	51.7	45.8	1.7	--	--	
		F1	--	20.6	--	0.5	61.2	38.3	0.01	--	--	
	P2	B	--	10.3	--	0.6	45.6	49.7	4.6	--	--	
		D	--	20.5	--	0.6	56.3	41.3	1.9	10	--	
		F1	--	30.2	--	0.5	62.5	37	0	5	--	
	P3	B	--	10.5	--	0.6	48.2	46.6	4.5	140	--	
		D	--	20.5	--	0.8	55.2	42.5	1	155	--	
		F1		30.1	--	0.5	60.5	38.9	0.1	160	--	
Canada	SP	C	--	--	--	2.7	19.2	12.7	1.3	--	--	[28]
		C1	--	--	--	2.6	18.6	11.9	1	--	--	
		D	--	--	--	2.4	17.2	10.9	0.8	--	--	
		D1	--	--	--	2.1	15.2	9.2	0.6	--	--	
	SP	D	18.45	18.6	61.13	5.97	60.7	31.24	2.01	--	--	[29]
		D1	17.51	21.35	60.2	6.57	66.1	23.8	2.84	--	--	
Spain	SP	C	--	--	--	1.3	30.1	6.8	1.6	--	--	[30]
		D	--	--	--	1.3	28.8	5.5	1.2	--	--	
		F	--	--	--	1	28	1.9	0.7	--	--	
UK	SP	C	--	--	--	1	47.2	5.7	0.8	--	--	[31]
Brazil	SP	B	--	--	--	3.17	24.3	75.23	1.73	--	--	[32]
		D	--	--	--	2.9	20.99	70.7	0.88	--	--	

Note: Slow pyrolysis-SP, Pyrolysis- P, Not Available-NA, Nitrogen-N, Oxygen-O, Hydrogen-H, Carbon-C
Temperature range °*C (A-200-299, B-300-399, C-400-449, C1-450-499, D-500-549, D1- 550-599, E-600-699, F-700-749,F1-750-799*

Table 2. Potential application of biochar for mitigation of inorganic and organic contaminants

Biomass source	Temperature (°C)	Medium	Pollutant	Type of contaminant	Ref.
Green biomass	450	Water	Atrazine	OC	[33]
Hard wood	400	Soil	Arsenic	IC	[34]
Cotton straw	850	Water	Chlorpyrifos and fipronil	OC	[35]
Rice straw	700	Soil	Pentachlorophenol	OC	[36]
Soybean	700	Water	Mercury	IC	[37]

Note: OC-Organic contaminant; IC-Inorganic contaminant

Table 3. Average yields of biochar at various pyrolysis temperatures and residence times [40]

Pyro temperature (°C)	Duration (min)	Yield (%)				
		BC	BC-K (1)	BC-K (0.5)	BC-P (1)	BC-P (0.5)
300	30	62.5	47.7	60.5	62.9	53.9
400	30	28.5	37.4	35.1	48.9	48.4
500	30	27.3	27.2	31.7	36.9	39.3
300	60	58.1	47.2	51.1	55.1	65.7
400	60	25.5	30	28.2	45.6	42.2
500	60	27	21.5	28.9	34.5	35.4
300	90	64.2	42.6	32.9	57.1	59.8
400	90	27.5	33.6	28.7	40.8	41
500	90	31	25.9	25.5	34.4	37

The multifaceted applications of MSW-derived biochar have shown promising outcomes, particularly in treating leachate, constructing permeable reactive membranes, and capping landfills. These applications have displayed effective results in addressing environmental pollution challenges. Table 2 presents an overview of various biochar feedstocks and their potential for mitigating organic and inorganic contaminants. Studies have also delved into the efficacy of biochar in soil applications, demonstrating its ability to supply and retain nutrients beneficial for plant uptake. Notably, biochar exhibits the potential to retain bioavailable nutrients in the soil over prolonged periods, thereby contributing to enhanced soil fertility and plant growth.

In Table 3, the amount of biochar that can be synthesized at various pyrolysis temperatures and residence times, is indicated by the information that has been provided. Interestingly, the increase in residence duration did not influence the biochar yield. No substantial variations were observed among samples subjected to pyrolysis temperatures for 30, 60, and 90 min. This suggests that pyrolysis reactions reached completion within the initial 30-min period, indicating no significant benefit in extending the pyrolysis duration beyond this timeframe. Therefore, conducting pyrolysis for a longer duration is unnecessary, as the reactions seem to be fully realized within 30 min of the process. Since the majority of the biomass's active sites have already been occupied, increasing the residence time does not increase the breakdown of biomass [38]. Secondary processes like gradual carbonization of tars or thermal cracking of volatile substances may take place during prolonged residence times. The quality and composition of the biochar are mostly impacted by these processes and not the total yield [39].

An increase in the temperature of the pyrolysis process resulted in a significant reduction in the amount of biochar produced. For instance, when the pyrolysis temperature was raised, there was a significant reduction in the amount of biochar (BC) that was produced. The yield was measured as 62.5 % of the dry feed mass when the temperature was 300°C, but when the temperature was 400°C , the yield dropped to 28.5 %. The amount of biochar produced by BC, BC-K(0.5), BC-K(1), BC-P(0.5), and BC-P(1) decreased by 34.9 %, 27.9 %, 21.1 %, 13.9 %, and 19.8 %, respectively, as the temperature increased from 300 to 500°C. This decline in amount of biochar produced is probably related to additional pyrolytic transformation, which suggests that the original feedstock underwent a more thorough primary breakdown or that secondary reactions of the solid residue took place [41]. The reduction in biochar yield with increasing pyrolysis temperature signifies a shift towards a more complete conversion of the original biomass material, resulting in a lower proportion of biochar in the final product. The trend of decreasing biochar yield with an increase in pyrolysis temperature has been noted by numerous researchers. For instance, Kim & Parker observed a 34% reduction in the amount of biochar when the thermal decomposition temperature of digested sludge was escalated from 250 to 500°C. This pattern aligns with the broader trend observed in various studies, where higher pyrolysis temperatures often result in a diminished yield of biochar [42], while Shen & Zhang found comparable results [43]. Hossain observed the biochar generation through pyrolysis of sewage sludge in a fixed-bed reactor. He noted that at a temperature of 300°C, the biochar accounted for 72.3% of the initial mass [44]. However, as the pyrolysis temperature was increased to 700°C, the biochar yield decreased significantly to 52.4%. This observation reaffirms the common trend in pyrolysis processes, where a rise in pyrolytic temperature correlates with a reduction in the amount of biochar.

The chemical impregnation of sewage sludge exhibited a minimal impact on biochar yield produced at 300°C. Interestingly, the presence of H_3PO_4 resulted in a decrease in the weight reduction rate from 300-500°C. Specifically, at the temperature of 500°C, the biochar amount of BC-P(0.5) was measured as 39.3%, which was notably higher than other biochar samples averaging approximately 30% at the same temperature. Furthermore, the increase in the impregnation ratio from 0.5 to 1 did not affect the biochar yield [42].

Similarly, Lim *et al*. examined activated carbon (AC) production from palm shells and noted that the chemical impregnation ratio did not influence the yield of the solid product [45]. This suggests that in certain cases, variations in impregnation ratios or the presence of specific chemicals during the pyrolysis process may not significantly impact the biochar output but this primarily controlled the sorption capacity and specific surface area of AC [46].

Leachate treatment

Leachate, which is a water-based solution that comes from open dump sites, is full of different kinds of contaminants that are formed when waste degrades in landfills [47]. The organic constituents of leachate change based on factors such as type of waste present, duration of landfill operation, and prevailing weather patterns. Leachate from landfills typically contains significant quantities of pollutants, with around 80 to 95 % being inorganic and 52% as organic. Thus, any treatment method employed should possess the capability to extract highly toxic elements, such as zinc, mercury, nickel, Cd, Mn, Cu, and Pb, that have significant concerns associated with these leachates. Biochar, in general, has showcased remarkable efficiency in the removal of possibly hazardous elements from both soil and aqueous sources. The distinct blackish coloration of landfill leachate is attributed to the abundance of organic matter (OM), particularly rich in humic and fulvic acids [48]. Additionally, leachate stemming from MSW dumps contains persistent organic pollutants and volatile organic compounds. Biochar exhibits a favorable ability as a material for eliminating these highly noxious compounds. In the domain of leachate treatment, biochar serves as an effective adsorptive for the removal of harmful components like NH_3–N, colorants, hazardous metals, and chemical oxygen demand (COD) [49]. Traditional leachate method often falls short in meeting discharge requirements, where biochar emerges as a supplement due to its small, low-volume pores and high surface area, facilitating adsorption and chemical reactions within the treatment process. The superior functionality of biochar to eliminate a diverse array of biodegradable and non-biodegradable pollutants dissolved in a water medium is attributed to its microporous structure, thermal stability, and expansive surface area. However, despite its efficacy, the high production cost and expensive nature of carbonaceous substances stand as restricting different aspects in the widespread utilization of biochar for leachate treatment. Addressing the challenges associated with the production cost of biochar for leachate treatment can be achieved by utilizing in the vicinity accessible, economical resources such as industrial by-products and agri and food residue [50]. This approach holds the potential for reducing production expenses and enhancing the feasibility of implementing biochar for effective leachate treatment. Further analysis of biochar derived from MSW revealed minimal traces of metals. However, these trace amounts were not significant enough to hinder its efficacy or use as an adsorbent. This finding underscores the promise of biochar as an effective adsorbent for removing hazardous gases from landfill sites without posing significant constraints on the environment [51]. This demonstrates the potential of biochar derived from MSW as a viable and environmentally friendly solution for addressing leachate-related issues. Due to their cost efficiency, biological methods are employed for the removal of organic pollutants. Nonetheless, these methods can not effectively eliminate toxic metals from leachate. The bioreactor treatment method is categorized into aerobic and anaerobic processes. The primary limitations of the biological method relate to the challenges with temperature regulation and the toxic effects of leachate on microorganisms. Anaerobic membrane bioreactors typically exhibit superior activity in treating leachate compared to aerobic methods due to the elevated COD levels of leachate. Along with biological methods, advanced oxidation methods i.e., Fenton reactions, electro-oxidation, and photocatalytic processes are also effective for the breakdown of various contaminants in leachate. The anaerobic membrane bioreactor for landfill leachate is shown in Fig. 9.

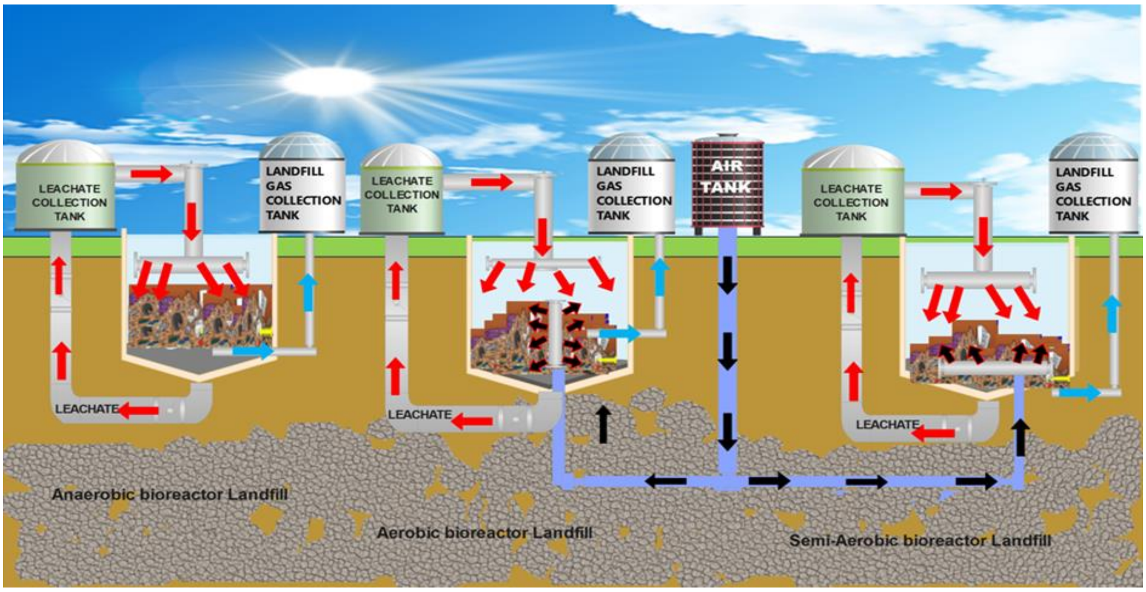

Fig. 9. Anaerobic bioreactor for landfill leachate treatment [52]

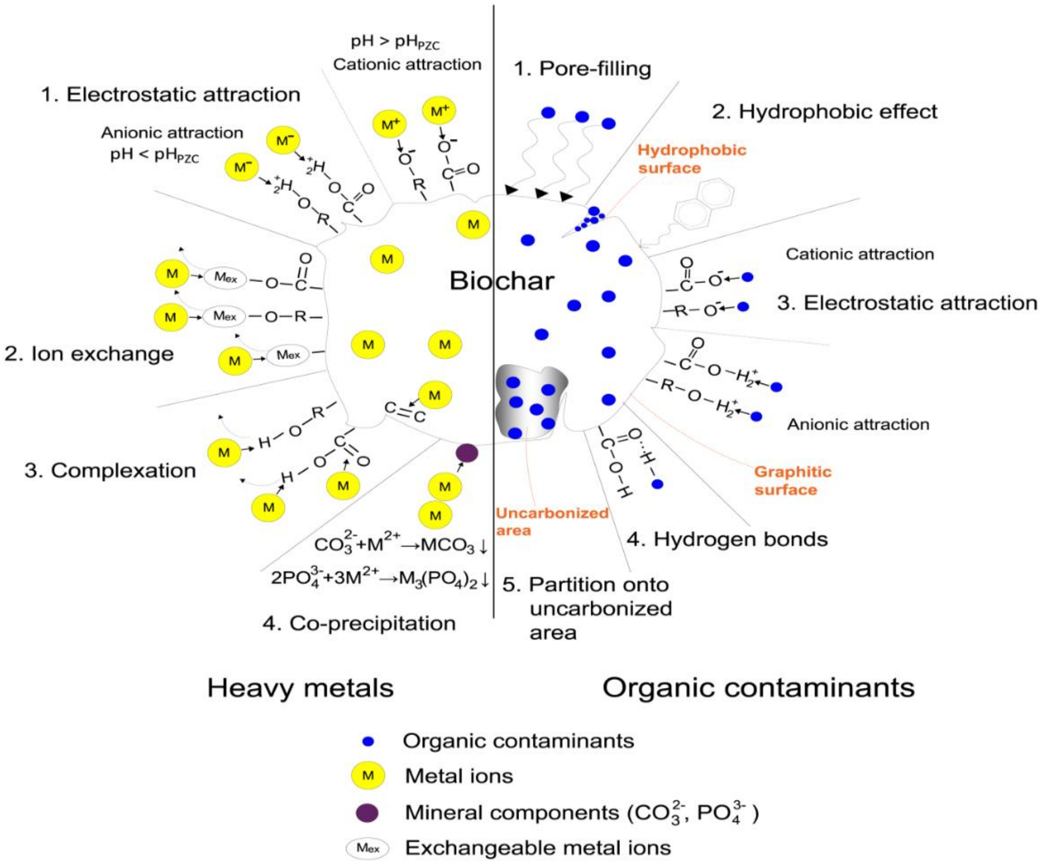

Fig. 10. Methods involved in the use of biochar to remove organic contaminants and heavy metals [59] (open access)

Heavy metal ion adsorption

Permeable reactive barriers (PRBs) are subsurface constructions designed to intercept and remove contaminants from groundwater before they enter water streams. Historically, AC and zero-valent iron have been the primary materials used in PRBs due to their effective contaminant adsorption capabilities, despite the high production cost of zero-valent iron hindering its broader use [53]. As a more cost-effective alternative, biochar has shown promising results in this field. Recent research has shown that using modified corn straw biochar as a PRB material is an effective way to prevent vanadium transport in subsurface environments. It demonstrates a three to five times greater capacity for removal than AC [54]. In contrast, biochar made from wood showed a relatively short lifespan as a potential PRB material for sites contaminated with e-waste when it was tested in column experiments [55]. In contrast, the incorporation of biochar made from coconut shells showed promising results in the elimination of lead (Pb) and cadmium (Cd) [56]. Biochar produced from MSW has been investigated for its ability to remove a variety of potentially hazardous elements, including arsenic (As) and chromium (Cr) in both the III and the VI oxidation state (As (III), As (VI), Cr (III), and Cr (VI)) [57, 58]. According to a number of studies, the amount of arsenic that can be adsorbed by biochar made from coconut husks is significantly lower than the amount of arsenic that can be adsorbed by biochar made from MSW, which shows that adsorption is 1.3 times higher [24]. The main processes using biochar to remove organic pollutants and heavy metals are depicted in Fig. 10. Balanced ion exchange, surface precipitation, electrostatic pull, complexation, and surface absorption are the processes that cause inorganic contaminants to adsorb on biochar. In this regard, a number of variables such as basicity, hydrophobicity, ion transfer capacity, and chemical composition, affect biochar's adsorptive properties. The absorption capability of biochar can also be changed by surface reactivity. Additionally, complexation occurs by the exchange of cations as a result of metallic ions replacing positive charge on the biochar surface. On the contrary, a number of distinct interactions can also be linked to the elimination of organic pollutants. Pore-filling, hydrophobic, electron donor and acceptor, partitioning, and electrostatic forces are the most common types of interactions [59]. Based on the literature that is currently available, electrostatic attraction is proposed as a likely mechanism for heavy metal adsorption onto MSW biochar. However, research on MSW biochar is still limited, particularly in characterizing its mineral and organic phases concerning pyrolysis temperature. It has been discovered that the quantities of polycyclic aromatic hydrocarbons and possibly hazardous elements in biochar produced from MSW are low and still within permissible limits. However, it is essential to take into consideration its derivatives, as well as the high concentrations of phenolic compounds that were discovered. More in-depth investigation and comprehension of these components are necessary to perform an exhaustive analysis of their applicability across a variety of contexts.

Material for landfill capping

Both the elimination of emissions of greenhouse gases and the control of offensive odors continue to be difficult problems to solve in the field of landfill management. To address these concerns, a number of different strategies have been implemented, including gas-accumulation systems [60], compacted clay [61], and composite covers [62]. Despite their initial efficacy, they have a number of drawbacks including shorter lifespans, susceptibility to cracking that can result in water percolation, and reduced methane oxidation as a result of limited oxygen-methane interaction. These drawbacks are compounded by the fact that compacted clay covers can crack easily. This has led to the development of biologically active coverings or filters as critical components of landfill gas mitigation infrastructure. Because of its useful properties, such as significant specific surface area and smaller particle sizes, biochar that is produced from MSW has garnered a lot of attention recently. Because of this property, the rate at which methane is oxidized is increased, and methanogenic microorganisms can interact more effectively with methane and oxygen [63]. In these kinds of situations, making use of biochar is not only beneficial in terms of its ability to effectively reduce pollution but also saves money by enabling the recycling of secondary resources. Biochar has found application in landfill cover engineering, leading to observed increases in CH_4 removal rates through oxidation as showin in Fig. 11, sometimes reaching up to 90% [64]. Additionally, Phyto-capping, a technique involving dense vegetation growth in the upper layer of soil, acting as a cover of the landfills, has been used to mitigate landfill gas emissions [65]. The presence of vegetation helps regulate water at waste disposal sites by absorbing surplus moisture through their root systems, thereby diminishing surface water flow and lowering the threat of leachate leakage. Plants absorb nutrients from the soil, aiding in the reduction of pollutants at waste disposal sites by assimilating and retaining them.

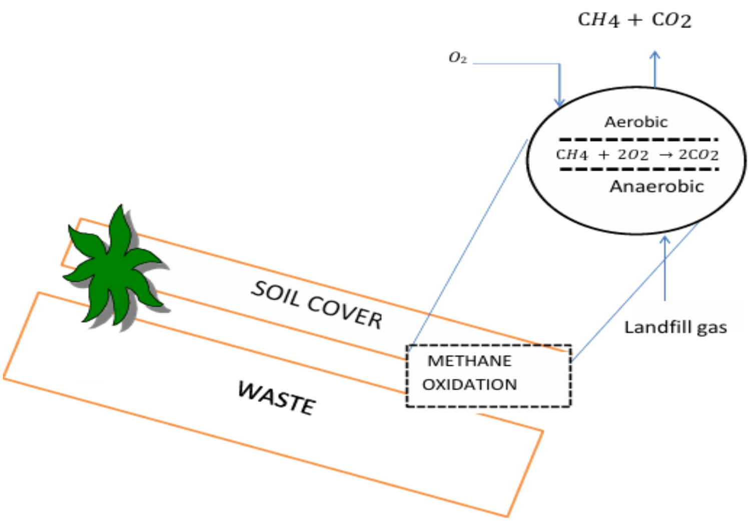

Fig. 11. Oxidation of mehane in landfill coverings [67] (open access)

Plants also encourage microbial metabolism, especially in the rhizosphere, where soil is impacted by root exudates and their associated microbes. These microorganisms can contribute to the decomposition of organic contaminants and improve soil structure. A significant drawback of phytocapping is its potential ineffectiveness in locations where evapotranspiration rates do not exceed precipitation levels, such as chilly and moist climates. Choosing plant varieties necessitates a thorough comprehension of location characteristics, local climatic trends, and soil characteristics specific to the area. There's also the potential for plants to reach buried debris, resulting in either their demise or the dispersion of pollutants into the surroundings, particularly if those chemicals are concentrated within the waste in greater amounts [66]. It's also important to ensure that the plant variants not only survive but also adapt to fluctuating arid and moist weather conditions, as well as endure associated challenges like vegetation fire. Studies have suggested that combining biochar with the soil layer can further enhance methane oxidation in this process. Ultimately, the integration of biochar into landfill management strategies shows promise in enhancing methane oxidation, reducing greenhouse gas emissions, and managing odors, presenting a cost-effective and environmentally friendly solution in mitigating pollutants emitted by landfills.

Retention and recovery of nutrients

Biochar made from MSW has been shown to improve soil quality because of its high organic carbon content [68]. This biochar has been shown to improve soil chemistry and biology. Soil mineralization has been found to shift after biochar synthesized from MSW was added, as a result of the biochar's extensive porous structure. Because of its improved structure, plants are better able to withstand damage from abiotic oxidants and microbial enzymes, and crop yields are raised as a result of less nutrient runoff and greater carbon sequestration. Additionally, biochar's sorbent properties enable the retention of additional nutrients from pesticides and fertilizers [69]. The incorporation of MSW-derived biochar into soils has been shown to improve soil pH, and cation exchange capacity, and directly contribute to enhanced plant growth, as shown in Fig. 12. The use of a mixed variation in feedstock biochar production significantly enhances soil buffering capacity, moistness, and water-holding capability. Moreover, several results show that trace metals in MSW-derived biochar are notably low, making it a viable option for soil application without further contamination. Biochar has also found utility as an additive to catalyze the composting process, enhancing aerobic conditions and facilitating complexation with anions and cations exchanged within the compost [70]. While trace metal concentrations in the biochar may form complexes with soils, these are generally insignificant and do not re-contaminate soils but instead facilitate retention rates. The pH modification and reduction potential changes brought about by the addition of biochar have been beneficial in neutralizing acidic soils and enhancing soil fertility, water retention, and nutrient availability, especially in arid and acidic soil conditions. Pyrolysis temperature and the organic and inorganic sources of the MSW used play significant roles in improving soil quality and catalyzing compost formation.

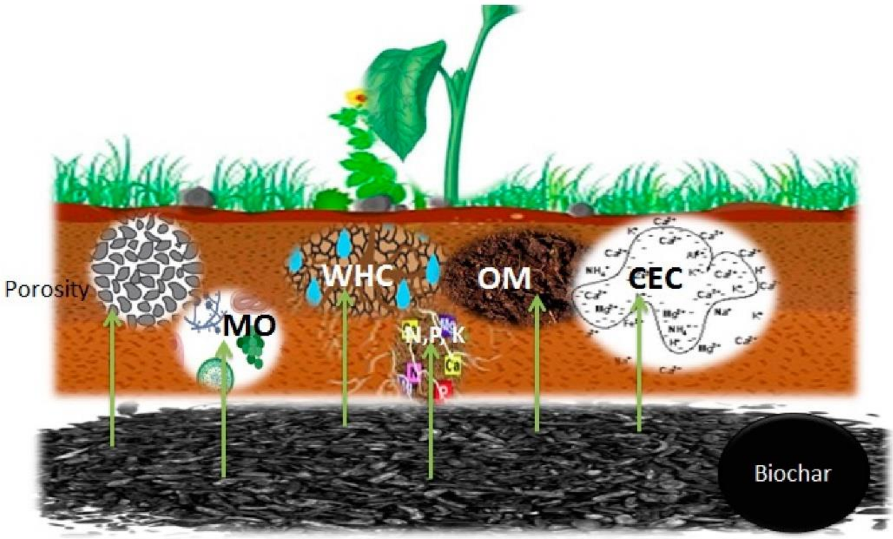

Fig. 12. Use of biochar on soil quality. WHC = water holding capacity; OM = organic matter; CEC = cation exchange capacity [71] (open access)

The nutrient value of biochar derived from biomass *via* pyrolysis depends on the type of biomass feedstock and the pyrolysis temperature. Elevated temperatures typically induce increased breakdown of organic substances present in the biomass. This can result in a low nutrient value of biochar. Biochar generated through low-temperature pyrolysis contains a high proportion of carbon derived from biomass. The combination of high carbon content, along with strong adsorption capacity, large surface area, and highly alkaline nature, renders the incorporation of biochar into the soil a viable and efficient method for improving soil fertility. The alkalinity of biochar, coupled with high carbon content, improves cation exchange capacity, resulting in increased capacity to adsorb toxic metals, thereby enhancing soil fertility. The efficacy of biochar in retaining and releasing nutrients is influenced by soil properties. Biochar enhances the capacity to retain nutrients and water but these properties are contingent not only on the type of biochar but also on the soil's ability to retain. Additionally, biochar helps crops by encouraging the growth of soil microbes and helping them retain water even in stressful situations. Its gradual release of nitrate has also been researched as a potential method for providing plants with continuous nutrient delivery. This slow release behavior, including the reduction in chemical fertilizer release rates, contributes to the sustainability of agronomic systems utilizing biochar synthesized from MSW.

CONVERSION OF BIOMASS INTO ENERGY

Biochar is produced as a by-product during the process of direct conversion of MSW into energy. To produce usable forms of energy from MSW, a number of different conversion processes, including thermal, biochemical, and physicochemical, are utilized. Direct combustion of dry biomass generates heat, serving basic purposes like cooking. Gasification, conducted at higher temperatures (680–1500°C) and lower pressure with limited or no oxygen, results in the production of a gas mixture called syngas, containing H_2, CO, CH_4, and CO_2 (Fig. 13) [72]. Challenges in storing and maintaining syngas due to high associated costs are notable. Additionally, the formation of coke and tar substances during gasification can cause fouling in gasifier chambers. On the other hand, due to the high organic content and calorific value that it contains, MSW is an excellent candidate for the production of gas and liquid fuels at a cost that is significantly lower than it would be otherwise [73].

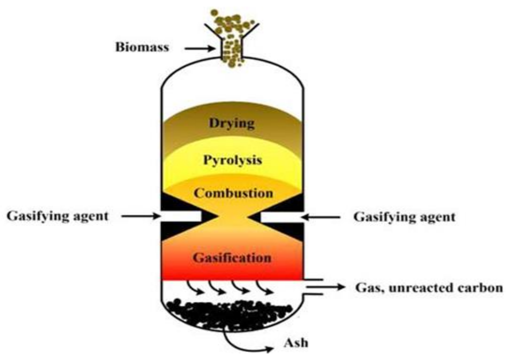

Fig. 13. Gasification of biomass [74] (open access)

Pyrolysis, conducted in limited or no oxygen environments, prevents the generation of toxic air pollutants like dioxins. This process is made more efficient by focusing on the organic materials from MSW.

Torrefaction is a thermochemical process that produces homogeneous densified pellets with properties that are comparable to those of coal. Torrefaction is conducted at temperatures between 200 and 300°C at a slower heating rate [75]. As a high-quality fuel for small-scale combustion, entrained flow gasification, and power plants, these pellets are an invaluable resource because up to 96% of the energy they produce is hydrophobic and resistant to biodegradation. Importantly, it's not just waste that generates biochar; biochar itself can serve as an energy source in various methods, contributing to the overall sustainable management of resources and waste materials.

CHALLENGES AND FUTURE DIRECTIONS

Although biochar made from MSW has a lot of uses, its drawbacks must be recognized and addressed for its efficient usage. The varied composition and quality of biochar obtained from MSW is one of its major drawbacks. MSW is made up of a variety of materials with distinct properties, such as paper, plastics, and organic remains. The characteristics and functionality of the final biochar can be impacted by this diversity. If impurities like toxic metals or organic contaminants are present in the substrates, they can be harmful to the environment if not appropriately controlled. Thus, to guarantee the efficacy and safety of biochar, thorough feedstock selection and strict quality control procedures are crucial. Another drawback is that improper usage or management of biochar can have detrimental effects on the ecosystem. For instance, excessive application of biochar or failure to take into account the particular soil conditions may result in unforeseen impacts like diminished bacterial activity, pH changes, or mineral imbalances. Furthermore, poor handling or removal of biochar scraps following use may cause land deterioration or environment pollution. To reduce the dangers and optimize the advantages of biochar, appropriate regulations and efficient procedures for management are required. Manufacturing and employing of biochar made from MSW on a big scale might be difficult in terms of profitability and scalability. Broad implementation may be hampered by variables including large upfront costs, the requirement for cutting-edge technology, and the creation of suitable logistics systems. In addition, to guarantee the financial viability of biochar programs, consumer demand, legal frameworks, and financial factors must be thoroughly assessed. More study and research are required to completely comprehend the long-lasting consequences and advantages of biochar made from MSW in various uses and settings [76]. Additional research is required to evaluate its effectiveness, longevity, and possible interactions with different soil kinds. For a thorough assessment of the environmental impact of biochar manufacturing, it is also essential to evaluate the net ecological and greenhouse gas (GHG) release consequences of the process, particularly the energy inputs involved. Biochar derived from MSW exhibits the potential to promote the worldwide sustainability goals through efficient waste management, encouraging environmentally friendly production and use, reducing global warming, and aiding in the preservation of land. For the more widespread use of biochar towards sustainable growth globally, more innovations in technology and governmental support are required.

CONCLUSION

The lack of sustainable waste management practices, which increases the risk to human health and environmental degradation, is the main reason why the rise in waste generation has become a global concern. Multifaceted approaches are needed to address this problem, and biochar—which is made from MSW—offers a creative and promising one. The method uses, and prospects of biochar as an environmentally friendly waste management option have all been covered in this article. Biochar offers a wide array of potential uses in waste management, like as an effective material for environmental remediation, an adsorbent for pollutant mitigation, and leachate treatment. Different thermochemical methods like slow pyrolysis, torrefaction, and pyrolysis, are used in the production process, and each influences the characteristics and yield of biochar [77]. These techniques provide different material qualities which affect the possible uses of biochar. By using biochar made from MSW, waste volumes can be decreased while maintaining a greener approach and a significant reduction in energy consumption. It is a versatile solution due to its effectiveness in eliminating hazardous substances from leachate treatment and its potential application in building PRBs for the removal of groundwater contaminants. Additionally, by promoting composting, boosting soil fertility, and aiding in plant nutrient uptake and retention, biochar improves soil quality. In addition to reducing nutrient loss, it raises the ion exchange capacity and acidity level of the soil. Biochar helps with odor control and lowering in atmospheric pollutants during landfill operations. It promotes methane oxidation as a landfill capping material, improving environmental health and lowering pollution costs. Increasing the production of biochar from MSW still requires overcoming significant financial and scalability obstacles [78]. These issues call for the development of large-scale production methods that are both economically viable and customized to fulfill particular application requirements. Biochar is a promising material with enormous potential, but more research is needed to maximize its application. Comprehensive utilization necessitates research on its complex properties, including yield, temperature-dependent surface area, and potential contaminants. In the end, biochar made from MSW is a ray of hope for the transformation of waste management techniques. Because of its many uses, it is a promising material for environmental remediation as well as waste reduction, promoting a sustainable and healthy future. To fully realize its potential and turn waste management and environmental sustainability into a ubiquitous and affordable solution, more research and technological advancements are essential [79].

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Statements and Declarations

Ethical Approval: *Not applicable.*

Competing interest: *The present study has no technical and financial conflict of interest.*

Author Contributions: *Rajesh Singh Gurjar performed the literature search and data analysis. Ms. Alisha Kakkar oversaw and improvised it and Dr. Sudesh Kumar read the manuscript. All authors read and approved the final version.*

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Design, development, and implementation of an automated system for cleaning overhead water tanks: a review

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This review explains how household tank cleaning maintains water quality efficiency and safety through improved methods and automated systems. Researchers detailed the development process for this thorough analysis, showing that automated tank cleaning remains vital for protecting health and quality while guaranteeing product characteristics and water quality standards. Research reveals diverse cleaning approaches starting with basic manual methods and progressing to specialized automated solutions for overhead water. When used with advanced brush gear motors and control mechanisms, automated systems demonstrate effective removal of biofilm sludge and other foul materials. Point-of-use water filtration systems deliver superior water quality and defend against hazardous contaminants found in water. The introduction of automated systems provides solutions to manual cleaning problems because it improves performance while guaranteeing protection and delivering environmental benefits to operations. Underdeveloped areas present ongoing challenges due to unsupportable cleaning and storage practices that cause microbial contamination problems. A solution to these gaps requires technological progress along with public education programs including complete governmental regulations. Automated cleaning systems for overhead water tanks require systematic creation followed by development and final deployment to achieve universal clean water safety. Through innovations and community participation, people will drive sustainability in water management which will secure healthier futures worldwide through industrial cleaning systems that service overhead water tanks. Modern automation fills a critical need to solve traditional problems while leveraging new technological advancements that boost water quality performance and efficiency levels. Visual illustrations of the tank design solutions and cleaning systems appear in the study to help readers better comprehend the information.

Keywords: Automation, robotics, tank cleaning, water contamination, cylindrical water tank.

INTRODUCTION

Overhead water tank cleanliness stands as a critical component for achieving both safe water storage and protecting health. Frequent tank maintenance protects against corrosive elements and foreign contaminants while blocking sediment accumulation which allows precise pollutant analysis together with reduced operational hazards. A designated cleaning program ensures safety at all times while decreasing potential risks to both people and the environment and provides vital access to pure safe drinking water. Every individual uses roughly 181.5 gallons of water during their yearly consumption. The Central Pollution Control Board partners with State Pollution Control Boards along with Committees to assess the water quality of aquatic resources at 4,484 locations spread throughout India's rivers, lakes, ponds, and tanks. Memorandum data shows that 57% of all inspected sites fulfill the biological oxygen demand (BOD) standards [38]. Widespread water contamination results in cholera, typhoid hepatitis, and gastroenteritis which, according to UNESCO's 2021 World Water Development Report, bring 829,000 deaths annually from diarrheal illnesses. The crisis of maintaining clean water reserves in household storage tanks becomes critical because 71% of Indians depend on such tanks. The combination of minimal understanding of expensive manual cleaning practices and inconvenient barriers facilitates the growth of pollutants like algae and silt. Water tank inspections show disturbing evidence that household tanks contain dangerous microbial infections alongside pollution from chemicals. These cross-contaminants endanger residents who depend on tank-stored water for their drinking and household needs. The widespread use of cylindrical overhead tanks throughout the world does not match their level of proper maintenance. The presence of pollutants in residential water tanks creates major public health problems. People who drink polluted water risk developing skin and respiratory infections along with cancer and several other health difficulties. Communities must make infrastructure improvements possible and enforce regular testing as well as maintain strict schedules to minimize these safety risks. Automated tank cleaning systems

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represent a promising innovation that solves current challenges while giving communities access to clean drinking water.

Impact of various contaminants on water quality

Microorganisms: Bacteria, viruses, and parasites are prevalent impurities encountered in water reservoirs, giving rise to waterborne ailments like cholera, typhoid fever, and dysentery. The introduction of these microorganisms into aquatic systems frequently occurs *via* sewage and agricultural runoff.

Chemical pollutants: Various chemicals, including heavy metals (e.g., lead, mercury, arsenic), pesticides, fertilizers, pharmaceuticals, and industrial chemicals, possess the capability to seep into water reservoirs from diverse origins such as industrial emissions, agricultural runoff, and improper household chemical disposal. These compounds have the potential to inflict harm on human health and the ecosystem, resulting in enduring health complications.

Nutrient pollution: Elevated quantities of nutrients, specifically nitrogen and phosphorus, have the potential to induce eutrophication in aquatic environments. This phenomenon arises when nutrient concentrations stimulate the proliferation of algae and various aquatic flora, culminating in the formation of algal blooms. These blooms can diminish oxygen levels within the water, leading to the mortality of fish and detrimental effects on other aquatic organisms. Nutrient pollution is frequently linked to runoff from agricultural activities, sewage discharges, and urban runoff.

Sedimentation: Erosion of soil from construction sites, agricultural fields, and deforested regions can result in sediment accumulation in aquatic ecosystems. Excessive sedimentation can compromise water quality by elevating turbidity, diminishing light penetration, and suffocating aquatic habitats. Moreover, it can facilitate the transportation of additional pollutants, including nutrients and heavy metals, that adhere to soil particles.

Acidification: The phenomenon of acidification is primarily attributed to acid rain, which is a result of the emission of sulfur dioxide and nitrogen oxides from industrial activities and vehicular emissions. This environmental issue can lead to the acidification of water bodies, especially freshwater ecosystems, consequently posing a threat to aquatic life, particularly delicate species like fish and amphibians, and causing disruptions to ecological processes.

Thermal pollution: Thermal pollution is characterized by the discharge of heated water from industrial operations and power plants into water bodies, increasing water temperature. This elevation in temperature can lead to thermal pollution, which in turn can decrease oxygen levels, enhance susceptibility to diseases in aquatic organisms, and induce changes in the distribution and behavior of species.

Emerging contaminants: The detection of emerging contaminants, including pharmaceuticals, personal care products, and endocrine-disrupting chemicals, is on the rise within water sources. Despite being present in low concentrations, these substances can pose significant risks to both human health and the environment. The long-term impacts of these contaminants are still under investigation.

Total dissolved solids (TDS) is a key parameter to identify the usability of water for various purposes which further influences consumer preferences. Elevated TDS levels in household water tanks can result from different factors, including poor water quality, lack of regular cleaning, and corrosion of tank materials. For example: the presence of arsenic in water, as observed in some regions, emphasizes the importance of effective water filtration systems like reverse osmosis (RO).

Elevated TDS levels in household water tanks can be attributed to several factors, including:

- Poor water quality: if the source water has high TDS levels, it can also lead to increased TDS in the stored water.
- Lack of regular cleaning: over time, contaminants in the water can accumulate in the tank, increasing the overall TDS concentration.
- Corrosion of tank materials: certain tank materials, such as galvanized steel, can corrode over time, releasing metals into the water and contributing to higher TDS levels.
- Understanding of TDS levels in drinking water for safe consumption:
- It has been established that a TDS level <50–250 parts per million (PPM) is to be considered low-level contamination, as it is deficient in minerals including zinc, magnesium, and calcium.
- The ideal TDS level for drinking water at 300 PPM and 500 PPM is considered perfect, as it is most likely that the water has minerals in it and doesn't taste flat.
- The water with 600–900 PPM is not considered very good and to filter such a TDS level, the use of a reverse osmosis system is required.

- The TDS level in the range of 1000 and 2000 PPM is extremely bad and drinking such water is not advised.
- Ultimately, water having TDS beyond 2000 PPM is not acceptable because it is considered hazardous and cannot be adequately filtered by standard home filters.

RO systems in households

Household reverse osmosis (RO) systems play a vital role in purifying drinking water by utilizing a semipermeable membrane to dissolve solid particles, including contaminants like arsenic. In various regions facing water quality challenges, residents commonly install RO systems as a precautionary measure. Connected to household water tanks, these RO systems act as a reliable defense against inorganic contaminants. Household reverse osmosis (RO) systems are often connected to household water tanks to provide a continuous and convenient supply of purified water for various domestic needs. The integration of RO systems with household tanks serves several important purposes as given below.

Continuous supply of purified water: RO systems are designed to remove impurities, including contaminants like arsenic, from the water. By connecting these systems to household water tanks, residents ensure a consistent and readily available source of purified water for drinking, cooking, and other everyday activities.

Storage and accessibility: Household water tanks serve as storage units, allowing residents to store a significant volume of purified water. This is particularly useful in situations where the demand for clean water may vary throughout the day. Connecting RO systems to these tanks enables the accumulation of purified water for later use [37].

Reduced dependency on municipal sources: In areas where the municipal water supply may not meet the desired quality standards, or in regions facing water scarcity issues, households often rely on RO systems to purify available water sources. By connecting RO systems to household tanks, residents can create a self-sustaining water supply system independent of external sources. Cost-effective solution: By connecting RO systems to existing household water tanks, residents can leverage their investment in infrastructure. This integration is often a cost-effective way to enhance the overall water quality in a household without the need for extensive modifications.

Cost-effective solution: Water contamination data underscores the essential health and safety: Maintaining a consistent supply of purified water is required for the health and safety of residents. Connecting RO systems to household tanks ensures that the water stored is free from harmful contaminants, contributing to the overall well-being of individuals and families. Water contamination data underscores the essential need for regular tank cleaning which consists of mainly two methods: traditional cleaning and automatic cleaning methods.

1. Improved water quality: RO systems effectively remove a wide range of contaminants, including chlorine, lead, arsenic, and other harmful substances, providing clean and safe drinking water.

2. *Better taste and odor:* By removing impurities, RO systems can enhance the taste and odor of water, making it more pleasant to drink.

3. Healthier drinking water: With contaminants removed, RO systems provide healthier drinking water, reducing the risk of consuming harmful substances that may be present in tap water.

4. Convenience: Having an RO system at home eliminates the need to buy bottled water, saving money and reducing plastic waste.

Traditional cleaning methods: Traditional cleaning methods, involving manual labor and mechanical systems like high-pressure water jets, are time-consuming and may not effectively remove contaminants. Manual cleaning poses health risks for workers exposed to chemicals and bacteria, and the overall inconvenience contributes to the neglect of tank maintenance. This underscores the necessity for an advanced solution, such as the proposed automatic tank cleaning robot. Despite the longstanding reliance on traditional cleaning methods, they are accompanied by various disadvantages. The manual labor involved in the scrubbing and washing of tanks, for example, is not only time-consuming but also labor-intensive. Additionally, the efficacy of these methods in eliminating persistent contaminants like biofilm and scale accumulation is frequently constrained. Furthermore, the dependence on mechanical systems such as high-pressure water jets may not consistently produce satisfactory outcomes. In certain instances, these techniques may lead to harm to the tank surfaces or fail to access specific areas, resulting in pockets of contamination being left behind.

Moreover, manual cleaning presents notable health hazards to workers who are exposed to hazardous chemicals and bacteria found in the tank environment. Inadequate protective equipment and ventilation systems can result in respiratory problems, skin irritations, or other health issues for workers. The inconvenience associated with traditional cleaning methods also contributes to the negligence of tank maintenance in some scenarios. Owing to the time and exertion demanded, cleaning timetables may be postponed or disregarded, culminating in the accumulation of contaminants and jeopardizing water quality. Given these obstacles, there is a distinct necessity for a sophisticated solution capable of surmounting the constraints of traditional cleaning methods. The suggested automatic tank cleaning robot provides a promising substitute. By capitalizing on automation and cutting-edge cleaning technologies such as robotic arms and sensor-based navigation systems, the robot can clean tanks efficiently and effectively without manual intervention.

Figure 1. The interior view of an overhead water tank

Automatic tank cleaning systems

Automatic tank cleaning robots emerge as a promising solution to address the shortcomings of traditional methods. These robots are equipped with sensors to assess the interior of tanks and high-pressure water jets to remove contaminants. The automation ensures thorough and uniform cleaning, eliminating the need for human intervention and making the process environmentally friendly. In addition to their sensor-equipped and high-pressure water jet functionalities, automatic tank cleaning robots frequently integrate sophisticated technologies such as machine learning and AI algorithms. These advancements empower the robots to adjust their cleaning approaches based on the specific attributes of the tank and the nature of contaminants present, thus enhancing both efficiency and efficacy.

Automatic tank cleaning systems commonly feature remote monitoring and control capabilities. This functionality enables operators to supervise the cleaning process in real-time, make necessary modifications, and receive detailed reports on cleaning performance. The implementation of remote monitoring not only boosts the overall efficiency of the cleaning operation but also reduces the likelihood of accidents or operational downtime. The utilization of automatic tank cleaning robots leads to decreased consumption of water and cleaning substances when compared to conventional techniques. Through precise targeting of cleaning areas and avoidance of unnecessary waste, these systems support water conservation initiatives and contribute to reducing the environmental impact associated with industrial cleaning procedures.

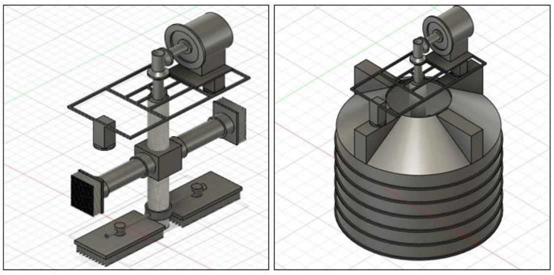

Figure 2. Design of automated tank cleaning system

Need for automation

The term a*utomation* covers a wide range of technologies, that seek to decrease human participation in the processes, human-centered approaches in automation, which focus on utilizing human abilities more efficiently rather than eliminating human involvement in production. This approach recognizes the need for highly qualified and motivated workers to operate, maintain, and repair automated systems [3]. These technologies mainly do this through predesigned controlling of actions, interconnecting subprocesses, and decision logic into machines. Improvements in reliability, completeness, efficiency, convergence, sensitivity, verification, and stability are the primary goals of automation research, which employs new methods, models, and approaches to achieve this goal [5]. The benefits of automation that have been mentioned include reduced production costs, increased efficiency, increased competitiveness, and higher productivity. Additionally, there is hope for a more pleasant work environment that is less burdened by physical demands and monotony [1]. Several fields have recognized the importance of automation, including intelligent control, learning, energy management, aerospace control, and manufacturing systems [2]. Upgrading existing machinery to increase automation is one way to lessen the impact of displacement, but it also increases the need for workers and their wages [4].

The application of robotics in these sectors aims to improve efficiency, accuracy, and productivity, as well as reduce costs and human error. In Manufacturing, robots can perform repetitive tasks with precision and speed, leading to increased production rates and improved product quality. In the services industry, robots can assist with tasks such as patient care, housekeeping, and information retrieval, enhancing the overall customer experience [6]. Robotics refers to the field of study and development of robots, which are machines capable of performing tasks autonomously or with minimal human intervention. Robotics is extensively used in the manufacturing industry to improve productivity and efficiency, and service robots assist human beings, typically by performing a job that is dull, distant, dangerous, or repetitive. Robots can perform tasks more efficiently than humans and can work continuously without breaks. They can also handle heavy loads and perform repetitive tasks with precision [7].

Service robots that are used in cleaning offer numerous benefits. They improve efficiency by working continuously without fatigue, ensuring consistency through pre-programmed routines, and accessing hard-to-reach or hazardous areas. Additionally, they save time and resources, enhance cleaning quality with advanced technology, and prove cost-effective in the long term. Furthermore, cleaning robots promote health and safety by reducing human exposure to hazardous environments, even service robots equipped with a LIDAR sensor and a web camera, allowing for the development of more complex methods for the cleaning robots to clean, uneven areas and designed for collision-free navigation [8].

Smart cleaning robot reduces the human interaction in the cleaning process, making it simpler and automatic [9]. Robotic cleaners have gained significant interest in recent years due to their effectiveness in assisting humans in floor and tank cleaning programs in various settings such as homes, hotels, offices, and hospitals. The use of robotics in cleaning saves labor costs and eliminates the need for human intervention, making it an affordable and efficient solution where the cleaning robot is a type of mechanical and electrical product designed for sweeping and dusting, offering a more convenient alternative to traditional vacuums [10].

Tank maintenance is crucial in many industries, including paint, oil, pharmaceuticals, and fast-moving consumer goods. Many small-scale enterprises still use manual tank cleaning, although it is a time-consuming and labor-intensive procedure [13]. In industrial processes, low performance and inefficiency have been caused by a lack of cooperation and planning for maintenance [11]. Tank capacity and product quality can be negatively impacted by the build-up of oil residue, particularly in the oil sector. As a result, it is essential to routinely clean the tanks and remove the oil sludge [12]. Several obstacles prevent Total Productive Maintenance (TPM) from being successfully implemented in organizations [4]. In the process industry, where dependability is essential for costly specialized equipment and stringent environmental regulations, maintenance plays a major role in the overall production environment [14]. The necessity for automated and more effective cleaning techniques is highlighted by the risks to worker safety associated with manual tank cleaning.

One of the drawbacks of manual tank cleaning is that it requires human operators to enter the tank, which raises safety issues [15]. Water is wasted during this labor-intensive manual procedure that necessitates emptying the tank before cleaning [16]. Tank leftovers from petroleum sludge can lower tank capacity and lower product quality in the oil sector [17]. High-efficiency robotic or automated cleaning techniques that minimize tank downtime and do not require personnel to enter limited locations are now needed in the oil sector [18]. These techniques, including the Martin systems and MEGAMACS, provide more safety, speedier cleaning, and the capacity to extract a sizable quantity of oil from the sludge [19].

Introduction to automatic tank cleaning robot (ATCR)

Automated tank cleaning robots, or ATCRs, are designed to clean tanks automatically, eliminating the need for manual cleaning. The ATCR is made up of many components, including a cleaning robot, water jet, suction pump, sensors, linear movement ladder, and rotating arrangement. A cleaning brush and water jet can be used to clean the base and walls of the tank while the suction pump removes the sludge deposits. ATCR technology was driven by the need to improve existing tank sludge cleaning processes. Early testing of the ATCR prototype has as its primary goal cleaning domestic water tanks. With the introduction of automated tank cleaning robots (ATCRs) what we know as the tank cleaning process has changed to a labor-free process. Consisting of different units such as cleaning robots, water jets, vacuum pumps, sensors, linear movement ladders, and rotating arrangements, ATCRs are specifically designed to eliminate tanks of different sizes and shapes from the inside. These robotic systems include cleaning brushes and high-pressure water jets that are used to clean tank surfaces very fast and effectively. The sludge deposits extracted by a suction pump are a guarantee of a thorough cleaning process. The development of ATCR technology is bearing on the need to improve existing tank cleaning techniques, especially given the obstacles that are inherent with sludge extraction. First, the initial testing of ATCR prototypes is mostly related to the cleaning of domestic water tanks, where the aim is to make water cleaner, safer, and easier to use. ATCRs are configured with advanced sensors that are capable of live tank readings and the status of the cleaning process. These sensors are an integral component of the identification of contaminants, measurement of tank levels, and detection of obstacles, thus guaranteeing precise and accurate clean-up actions. Besides that, the modular structure of ATCRs assures flexibility in terms of tank configurations to be used which makes them applicable to any cleaning job. In addition, the ATCR technology is an environmentally friendly tool that deals with efficient use of water and reduction of chemical usage during the cleaning process. Through minimizing water wastage and pollution, ATCRs promote eco-friendly actions and their compliance with environmental regulations. To summarize, the incorporation of ATCRs in tank cleaning technology marks significant progress in terms of safety, efficiency, and environment-friendliness while keeping the tanks clean and hygienic in the different fields of industry. Identified the need for automating tank cleaning to reduce downtime, improve safety, and ensure thorough cleaning of industrial tanks. Feasibility analysis was conducted to evaluate potential ROI and challenges.

Working mechanism of ATCR

Robotic cleaning and maintenance systems are equipped with a multitude of sensors and cameras for monitoring and navigational functions. These sensors allow the robot to change its location by determining how far it is from the surface. Furthermore, cameras are used to capture images of the robot's environment, allowing for real-time control and observation. The integration of cleaning tools and equipment is a crucial aspect of these systems. For example, cleaning robots are equipped with rags and brushes to clean the floor. Some systems even include spraying nozzles to apply cleaning agents to the surface. By combining these technologies, cleaning procedures become more effective and efficient, improving the overall cleanliness and user experience of the robotic systems. Besides the robot cleaning upgrade that is equally positive, it also comes with a lot of other effects such as high performance and efficiency that make the robots great providers of cleaning, and users have a good experience. ATCRs are the ones that would have the ability to do those works themselves by going to the tank locations where they will consider the right tools and methods to use in those areas. Besides, the system of remote monitoring will provide the operators with the possibility to look at the process of cleaning from a distance where they can see the process at a long distance. Similarly, they can speed up each phase with less time spent and swift resolution of any unanticipated problem. The ATCR application will help clean water tanks and in addition, it will make the water system to be safe and reliable.

CONCLUSION

Public health protection product quality maintenance and water quality compliance depend on automated tank cleaning procedures. Research sheds light on different cleaning strategies which extend from manual approaches and specialized automatic systems designed for industrial applications. Automated systems that integrate brush gear motors and control mechanisms can delete biofilm while removing sludge and contaminants for advanced water quality maintenance and hazardous substance protection. The systems overcome manual cleaning constraints through efficiency improvements and enhanced safety while delivering environmental advantages. Microbial contamination in addition to waterborne health risks occurs because underdeveloped regions struggle with improper cleaning techniques and insufficient storage measures. Bridging these gaps requires:

1. Automated cleaning solutions experience technological improvements.
2. Formatted public education materials need to teach people about how vital maintaining clean water standards is.
3. The government needs to establish complete regulatory frameworks to implement required standards.

The implementation of automated cleaning systems requires a systematic approach to design development and deployment to achieve universal water safety. Sustainable water management development depends on cleaning technology innovation together with community engagement in water-related activities. Societies benefit from technological advancements because these improvements create healthy societies while delivering safe water solutions to global communities.

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Performance evaluation of engineered cementitious composite utilizing manufactured sand

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Escalation of environmental concerns and depletion of natural resources have prompted a shift towards sustainable and innovative alternatives in construction materials. Addressing the same, this research explores the usefulness of utilizing manufactured sand (M-sand) and waste fly ash as a substitute for river sand and cement, respectively, in engineered cementitious composites (ECCs), with a focus on its effects on workability, durability and mechanical properties. The study investigated various combinations of M-sand and river sand in ECC mixtures, ranging from 0% to 100% substitution rates. Key rheological parameters like flowability were evaluated to determine the workability of mixtures. Various mechanical characteristics such as compressive strength, direct and indirect tensile strength, and flexural strength were assessed at varying curing durations. Additionally, durability parameters such as water absorption, chloride penetration, and sulfate-attack were examined. Critical rheological indices, such as flowability, were scrutinized to ascertain the workability of the compositions. Furthermore, diverse mechanical properties encompassing compressive strength, both direct and indirect tensile strength, and flexural strength were examined across different curing durations.

Keywords: Engineered cementitious composite (ECC), manufactured sand, fresh properties, mechanical properties, durability.

INTRODUCTION

Since many decades, concrete has been the backbone of innumerable structures, from towering skyscrapers to sprawling bridges, all over the world. Nonetheless, its inherent brittleness, a tendency to crack and break under tensile stress, has always posed a significant challenge. Recognizing this limitation, Professor Victor C. Li spearheaded a revolution in construction materials with the introduction of ECC which is abbreviated from Engineered Cementitious Composites known to be ‘bendable concrete’ [1]. ECC transcends the limitations of conventional concrete by employing the principles of micromechanics and fracture mechanics to achieve remarkable ductility [2]. Unlike its traditional counterpart, ECC incorporates specially engineered short fibers, typically made of polymers, that act as microscopic bridges within the cementitious matrix. When subjected to stress, these fibers strategically pull out and transfer the load, preventing catastrophic cracks from propagating. This remarkable phenomenon not only enhances the material's ductility, allowing it to deform significantly before failure but also significantly improves its crack resistance beyond its flexibility [3]. ECC boasts several other unique characteristics that set it apart from conventional concrete. The exclusion of coarse aggregates in its formulation makes it significantly lighter compared to traditional concrete. This translates to reduced dead load on structures, making it particularly advantageous in high-rise construction, where every kilogram saved contributes to structural efficiency and cost savings [1]. Additionally, the exceptional crack resistance of ECC makes it ideal for applications like bridge link slabs, by eliminating the need for traditional expansion joints, which are prone to deterioration and require frequent maintenance [1]. ECC offers a more durable and aesthetically pleasing solution for infrastructure projects. Delving deeper into the composition of ECC, a carefully selected blend of ingredients is imperative. The base typically comprises ordinary Portland cement (OPC), providing the foundation for the composite. Finely graded aggregates play a crucial role, such as river sand manufactured sand, or micro silica sand, contributing to the overall strength and workability of the mix. To enhance durability and sustainability, the inclusion of cementitious composites like fly ash (Class F) bagasse ash, or silica fume is encouraged [4]. These supplementary cementitious materials not only improve the material's performance but also offer environmental benefits.

To achieve the desired workability with lower water content, essential for optimal strength and durability, high range water reducers (HRWR),

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sometimes with a blend of viscosity modifying agents (VMA), are employed. Essential rheological parameters such as flowability were analyzed to determine the workability of the formulations. Additionally, a range of mechanical properties, including compressive strength, direct and indirect tensile strength, and flexural strength, were investigated over varying curing timeframes. Finally, the critical ingredient responsible for ECC's signature ductility is the fiber reinforcement [5]. While polyvinyl alcohol (PVA) fibers are commonly used due to their effectiveness and cost-efficiency, researchers are actively exploring other options like steel fibers, tier wire fibers, and even shape memory alloys (SMAs) for specific applications. Each fiber type offers unique properties and potential benefits, paving the way for further innovation and customization of ECC for diverse applications. The potential of ECC extends far beyond the traditional realm of concrete. Due to its exceptional fracture toughness and capacity for intricate geometries, this material is well-suited for diverse applications, such as seismic-resistant structural elements, precast segmental concrete bridge pier systems, damping elements, concrete repair systems, etc.

MATERIAL

In this experimental investigation, 43-grade ordinary Portland cement (OPC) sourced from Shree Cement, Phagwara, Punjab, was utilized. Fly ash of class F was procured from the Rajpura Thermal Power station located in Punjab. The specific gravity of fly ash was determined in accordance with the standards of IS 4031 part 1 and IS 1727. Tables 1 and 2 presents physical and chemical properties of the cement and fly ash. Two types of fine aggregates (FA) were employed in this investigation, river sand and manufactured sand. The river sand and manufactured sand were sourced locally from Sutlej River and Kunal stone crusher, Pathankot, respectively. The sieve analysis test for both fine aggregates was conducted in accordance with the specifications outlined in IS 2386 Part 1. Both fine aggregates were found to adhere to the specifications mentioned in IS 383, meeting the Zone-IV requirements. PVA (polyvinyl alcohol) fiber was used, and its properties are given in Table 3. Also, Auramix was utilized as a water-reducing agent, in Table 4 the details of its properties are presented.

EXPERIMENTAL PROGRAM

Material preparation

The ECC matrix was formulated utilizing conventional Portland cement, Class F fly ash, river sand, manufactured sand, tap water, and superplasticizer. Polyvinyl alcohol (PVA) fibers were incorporated to enhance the matrix's strength. The PVA fibers measure 12 mm in length and 40 μm in diameter, possessing a nominal fiber modulus of 40 GPa and a strength of 1600 MPa. Table 5 provides an overview of the blend ratios for the ECC.

A three-gear planetary mixer was utilized for the formulation of the ECC mixture. All components, excluding fibers, underwent dry blending for a duration of two min. To achieve the desired rheological properties, water and superplasticizer were introduced into the mixture at a low mixing rate for one min, followed by a medium mixing rate for an additional two min.

Table 1. Physical properties of cement and fly ash

Material	Specific gravity	Density
Cement	3.13	1410 kg/m^3
Fly ash	2.21	1230 kg/m^3

Table 2. Chemical properties of cement and fly ash

Component	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	K_2O	Na_2O	Others
Content % in cement	63.2	24.8	5.59	3.01	1.71	0.69	0.61	0.36	0.3
Content % in in fly ash	3.01	60.01	22.89	3.16	1.57	0.92	2.14	0.87	5.46

Table 3. Properties of PVA fiber

Characteristics	Elongation (%)	Young's modulus (GPa)	Tensile strength (MPa)	Fiber length (mm)	Fiber diameter (μm)
Value	6	40	1600	12	40

Table 4. Properties of Auramix 400

Type	Auramix 400
Appearance	Light yellow colored liquid
pH	Up to 6
Volumetric mass @ 20 °C	1.09 kg per liter
Alkali content	Less than 1.5 g Na_2O equivalent per liter of admixture

Table 5. Mix proportioning of all the ECC Mixes with Mix IDs

Mix ID	Cement (kg/m^3)	Fly ash (kg/m^3)	Sand (kg/m^3)	Manufactured sand (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)	Fiber (kg/m^3)
M0	586.03	613.46	681.62	0	323.86	5.99	26
M25	586.03	613.46	511.22	170.40	323.86	5.99	26
M50	586.03	613.46	340.81	326.43	323.86	5.99	26
M75	586.03	613.46	170.41	511.21	323.86	5.99	26
M100	586.03	613.46	0	652.87	323.86	5.99	26

For uniform dispersion of the short polyvinyl alcohol (PVA) fibers, they were gradually incorporated into the mixture at a low mixing rate for one min, followed by a medium mixing rate for three min [4]. Following this, the resulting mixture was poured into molds and underwent consolidation on a vibration table to reduce air entrapment. The specimens were demolded after one day and subsequently subjected to curing at predetermined intervals as per testing requirements.

TESTS

Workability

The workability of ECC mixtures was initially assessed using the mini-slump cone test, using a mini-slump cone with upper diameter of 70 mm, lower diameter of 100 mm, and height of 60 mm [6]. Following the prescribed procedure, ECC mixtures were prepared and poured into the slump cone positioned at the center of the base plate. Once filled, the cone was slowly lifted, allowing the ECC to spread on a plate. Following this, the diameter of the spread was measured and recorded as the slump flow value.

Mechanical strength tests

- *Compressive strength test.* In this experimental setup, ECC cubes were subjected to compressive forces to determine their compression strength, a crucial parameter for assessing the materials ability to withstand axial loads without deformation or failure. The dimensions of the ECC cube specimens were measured precisely at 70.6 mm by 70.6 mm by 70.6 mm [7]; and this test was conducted after different curing periods. The compression test apparatus utilized in this investigation boasts a high-capacity of 1000 KN. The testing process adhered to the standard rate of loading as prescribed by IS 4031-1988 (part 6). This standard dictates the speed at which the compressive force is applied to the specimens during testing.
- *Split tensile test.* The split tensile test serves as an indirect means of evaluating the tensile strength of concrete. In this method, a cylindrical specimen measuring 200 mm in height and 100 mm in diameter is positioned horizontally, and a radial force is exerted on the surface of the cylinder, resulting in the formation of a vertical fracture along its diameter [8]. The split tensile test for this experimental work was conducted in compliance with IS 5816 (1999).

Durability tests

- *Water absorption test.* The test for water absorption, in alignment with IS 1124 (1974), is crucial for measuring the amount of water absorbed by the concrete specimen. The experimental procedure entails the utilization of concrete cube specimens measuring 150 mm on each side. Initially, the specimen was dried until it reaches a constant weight as prescribed in the IS code, to ensure precise measurements. This weight of the specimen was taken as the initial mass. Following this, the concrete cube was submerged in water for a predetermined period, allowing it to absorb moisture. After the specified immersion time, the specimen was removed from the water and weighed again. The disparity between the weights before and after immersion indicates the quantity of water absorbed by the concrete.
- *Acid attack.* To assess the resistance to acidic conditions of ECC, cube specimens of 70.6 mm by 70.6 mm by 70.6 mm were cast and cured for days as per the requirement to conduct the test. After the curing duration, the moisture within the specimens was removed by exposing them to sunlight. Subsequently, the weight of the dried specimens was recorded. Subsequently, the ECC cube specimens were immersed in a solution of water mixed with 1% hydrochloric acid for a period of 180 days, as prescribed. During this period, the deterioration caused by the acid was monitored every 30 days by weighting the specimens and measuring the loss in weight [8]. Furthermore, a compressive strength assessment was conducted on the degraded specimens to evaluate the decline in strength.
- *Sulfate attack.* The test for sulfate exposure was conducted on cubic specimens measuring 70.6 mm on each side. Following the initial curing period, the specimens were submerged in water for 7 days as part of the hydration process. Subsequently, the

specimens were weighed and then immersed in a solution of water diluted with 5% sodium sulfate (Na_2SO_4) powder to initiate sulfate exposure testing [8]. Subsequent tests were conducted according to curing days to assess strength under compression.

FINDINGS AND INTERPRETATION

Workability

The slump flow measurements expressed in cm, for various replacement ratios (0%, 25%, 50%, 75% and 100% of manufactured sand in ECC) revealed distinct characteristics of workability. Notably, M50 exhibited the highest slum flow value at 40.1 cm, indicative of superior fluidity compared to other mixtures. Conversely, M100 demonstrated lowest slump flow value at 31.9 cm, suggesting reduced workability attributed to complete replacement of natural river sand with manufactured sand. Intermediate replacement ratios, such as M25 and M75, manifested moderate workability. The result is depicted in graphical form in Figure 1.

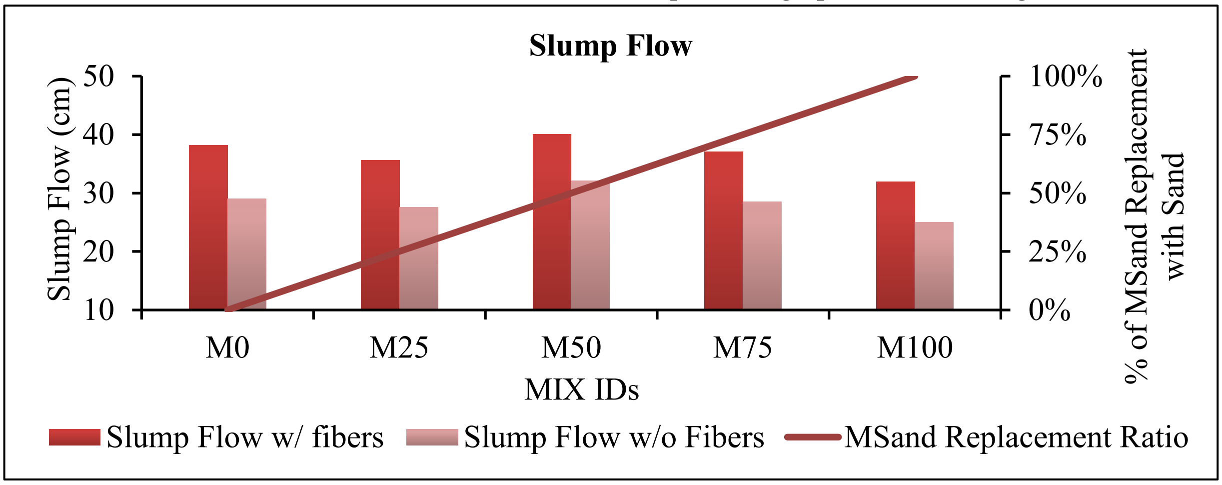

Figure 1. Slump flow of all five mixes with and without fibers

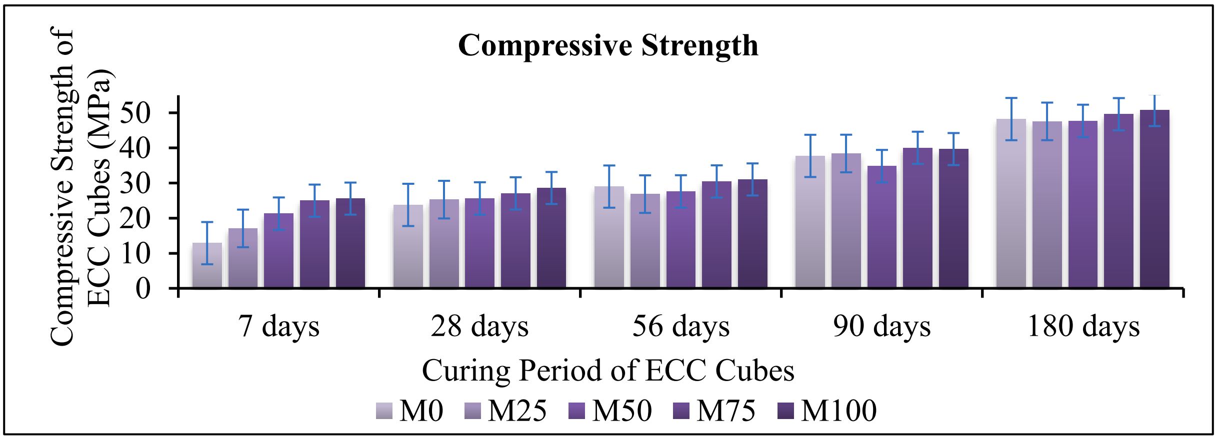

Figure 2. Compressive strength of all five mixes for 7, 28, 56, 90 and 180 days

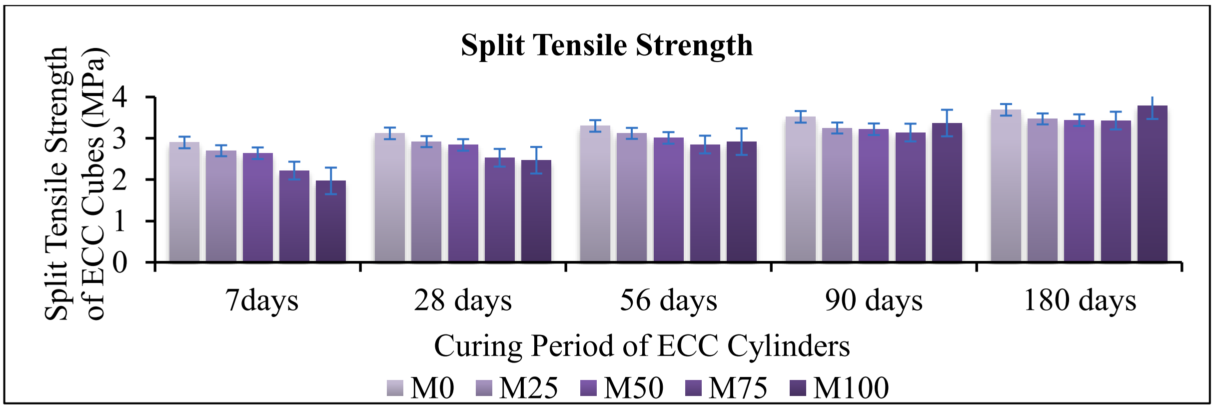

Figure 3. Split tensile strength of all five mixes for 7, 28, 56, 90 and 180 days

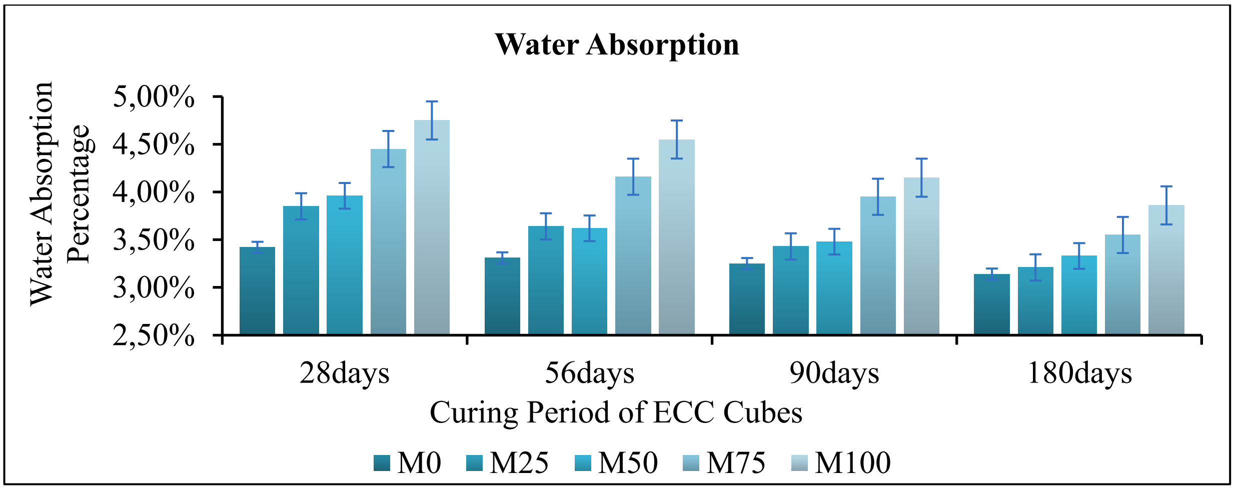

Figure 4. Water absorption rate of all five mixes for 28, 56, 90 and 180 days

Mechanical strength

- *Compressive strength.* The data regarding compressive resistance for five ECC formulations at intervals of 7, 28, 56, 90 and 180 days are depicted graphically in Figure 2. As illustrated in graphical representation and in tabular data the M100 mix exhibits a gradual increase in compressive strength over time, reaching 50.78 KN after 180 days, indicating excellent long- term strength development. Whereas the compressive strength on M75 mix peaks at 49.6 KN after 90 days, showing significant improvement compared to earlier stages. Again, with a peak strength of 47.68 KN after 180 days, the M50 mix demonstrates consistent strength development over the curing period. M25 mix achieves a compressive strength of 47.55KN after 180 days, showcasing steady strength gain throughout the curing duration. Among the mixes tested, the M100 mix attains the highest compressive strength of 50.78 KN after 180 days, indicating its superior performance in long-term strength development.
- *Split tensile strength.* The split tensile stress measurements for five formulations of ECC at a time interval of 7 28 56 90 and 180 days are visually represented in Figure 3. Across various concrete mixes, including M100, M75, M50, M25and M0, a consistent trend of improvement in split tensile strength is observed over the 180-day curing period. Specifically, M100 and M75 demonstrate gradual but steady enhancements, achieving 3.79 MPa, respectively, highlighting their effectiveness in withstanding tensile forces. Similarly, the M50 mix exhibits significant improvement, reaching a split tensile strength of 3.44 MPa after 180 days. Notably, M25 displays notable enhancement, peaking at 3.47 MPa, indicating improved tensile performance. Furthermore, M0 stands out with a split tensile strength of 3.69 MPa after 180 days.

Durability tests

- *Water absorption test.* The results of water absorption for various concrete mixes (M100, M75, M50, M25, and M0) at different curing periods indicate a consistent decrease in water absorption over time for all mixtures. Initially, higher percentages of water absorption are observed, gradually decreasing as curing progresses. Notably, the M0 mix exhibits the lowest water absorption rates across all curing periods, highlighting its superior resistance to water penetration as shown in Figure 4. This trend suggests that as the curing duration increases, the concrete mixes become denser and more impermeable, resulting in reduced water absorption capacities. These findings highlight the significance of extended curing in augmenting the durability and functionality of concrete structures, especially in addressing potential concerns associated with water penetration and moisture-induced deterioration.
- *Acid attack.* The compressive strength data for ECC samples with varying ratios of manufactured sand to river sand at different curing periods indicated distinct trends. Initially, at 28 days of curing, all mix ratios exhibited relatively high compressive strengths, with MO recording the highest value of 42.5 N/mm^2 and M100 the lowest at 26.4 N/mm^2. However, as the curing period progressed to 56, 90, and 180 days, a consistent decline in compressive strength was observed across all mix ratios. Notably, mixtures with higher proportions of river sand, such as M75 and M100, demonstrated the most significant reduction in compressive strength over time.

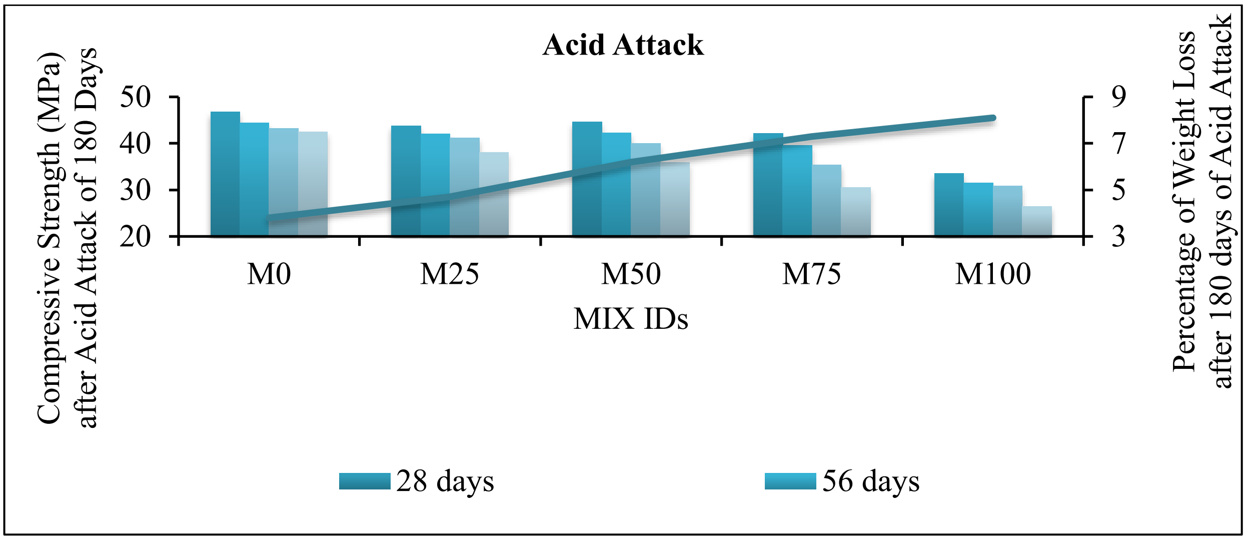

Figure 5. Acid attack results of all five mixes for 28, 56, 90 and 180 days

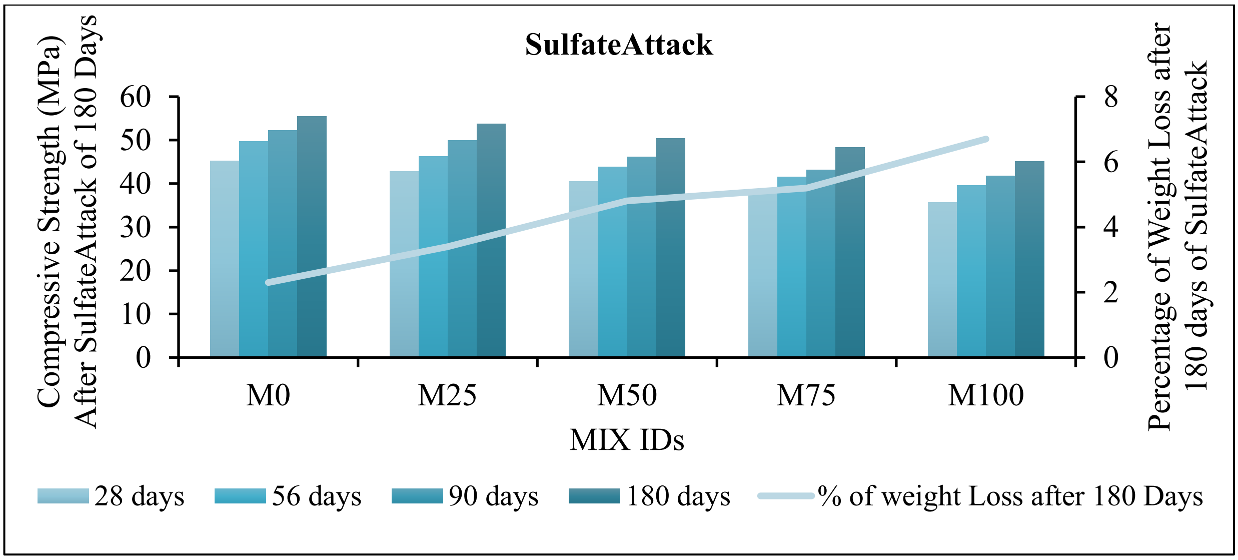

Figure 6. Sulfate attack results of all five mixes for 28, 56, 90 and 180 days

Similarly, as the curing period was extended to 56 days, 90 days, and finally 180 days, the weight loss percentage for all mixtures continued to rise, indicating degradation over time. Notably, at 180 days, the weight loss percentage ranged from 3.8% for MO to 15.3% for M100. This trend implies that the inclusion of river sand impacts the material's extended-term durability. The comprehensive findings are illustrated in Figure 5 depicting the fluctuations in compressive properties and mass degradation rate throughout diverse curing durations for each mixture ratio. These figures provide valuable insights into the performance characteristics of ECC with varying sand compositions, highlighting the importance of optimizing mix designs to achieve desired durability and strength properties.

- *Sulfate attack.* The sulfate attack test results for ECC samples exhibited a notable trend of decreasing compressive strength over time across all mix ratios. At 28 days of curing, all mix ratios demonstrated relatively high compressive strengths, with MO recording the highest value of 45.2 MPa and M100 the lowest at 35.7 MPa. However, as the curing period progressed to 56, 90, and 180 days, there was a consistent decline in compressive strength observed across all mix ratios shown in Figure 6. Mixtures with higher proportions of river sand, such as M75 and M100, demonstrated the most significant reduction in compressive strength over time. These findings suggest that the presence of river sand influences the susceptibility of ECC to sulfate attack, highlighting the importance of carefully optimizing mix designs to enhance the material's resistance to chemical degradation and ensure long-term durability in environments prone to sulfate exposure.

CONCLUSION

- The slump flow measurements demonstrate that the workability of ECC is significantly influenced by the proportion of manufactured sand, with higher ratios leading to decreased fluidity.
- Consistent improvement in compressive strength was observed over time for ECC formulations, with each mixture demonstrating distinctive long-term development patterns.
- Uniform improvement observed in split tensile stress measurements across ECC formulations over the 180-day curing period, with M100 and M75 demonstrating gradual but steady enhancements, while M50, M25, and M0 exhibit significant and notable improvements.
- Consistent decrease in water absorption was observed over time for various concrete mixes, attributed to prolonged curing enhancing concrete densification, thereby reducing water absorption capacities and improving durability and moisture resistance, with M0 mix demonstrating superior resistance to water penetration.
- The compressive strength data for ECC samples reveals that mixtures with higher proportions of river sand, such as M75 and M100, exhibit a significant reduction in strength over time, indicating susceptibility to acid attack. This deterioration is further supported by the increasing weight loss. These trends the influence of river sand content on the long-term durability of ECC against acid-attack, highlighting the necessity for precise mix design optimization to enhance resistance to chemical degradation.
- The sulfate attack test results indicate a consistent decline in compressive strength over time for all mix ratios of ECC, with mixtures containing higher proportions of river sand exhibiting more reduction in strength. This underscores the influence of river sand content on ECC's susceptibility to sulfate attack, emphasizing the necessity for mix design optimization to strengthen the resistance to chemical degradation and to ensure sustained durability in a sulfate-exposed environment.

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Integrating media and information tools for enhanced management of food and agricultural waste

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The escalating issue of food and agricultural waste management necessitates innovative approaches to minimize environmental impact and optimize resource use. This paper explores the role of media and information tools in improving waste management practices in the food and agriculture sectors. By leveraging digital technologies, social media platforms, and information dissemination networks, stakeholders can enhance waste reduction, recycling, and reuse strategies. The paper presents case studies, and a methodological approach like vermin compost and recycling into construction materials or the usage of RHA in treatment of water to illustrate the influence of media and information tools in transforming waste management processes. Techniques for managing floral waste, agro-industrial effluent, bagasse, and banana agro-waste have all been illustrated.

Keywords: information technology, sustainability, digital transformation, waste reduction and recycling, resource optimization

INTRODUCTION

The management of food and agricultural waste represents a significant challenge for the global community, with far-reaching implications for environmental sustainability, economic efficiency, and social responsibility [1–3]. As the world grapples with the consequences of waste accumulation, the integration of media and information tools emerges as a promising avenue for enhancing waste management practices.

Food and agricultural wastesencompass a broad spectrum of organic and inorganic materials generated from an assortment ofphases of the food supply chain, from production to consumption [1], [4]. It is estimated that just about one-third of all foodstuff produced for human consumption is lost or wasted (Figure 1), which not only stands for a noteworthy economic loss but also add to the ecologicaldreadful conditions through the emission of greenhouse gases and the inefficient use of natural resources [5]. Media and information tools have the potential to revolutionize the management of food and agricultural waste by providing platforms for knowledge exchange, fostering collaboration among stakeholders, and facilitating the adoption of best practices [3]. These tools can range from mobile applications that track and optimize resource use, to social media campaigns that raise awareness and encourage behavioral change [5].

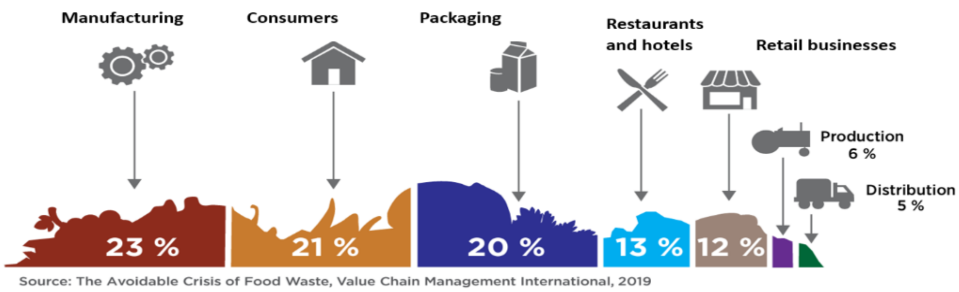

Figure 1. Unplanned (or avoidable) loss and waste of potentially edible food.

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The combination of media along with the information tools in waste management can lead to numerous benefits, including: (i)*Improved effectiveness*: By leveraging data analytics and real-time monitoring, stakeholders can identify inefficiencies and optimize resource allocation; (ii) *Enhanced collaboration*: information sharing platforms can facilitate partnerships across the food supply chain, leading to coordinated efforts in waste reduction; (iii)*Increased awareness*: media campaigns can educate the public on the importance of waste management and promote sustainable consumption patterns; (iv)*Innovation and development*: the use of these tools can spur innovation in waste management technologies and practices, driving progress towards sustainability goals.

Integrating media and information tools for the management of food and agricultural waste is not just a technological endeavor but a holistic approach that encompasses economic, environmental, and social dimensions. As we move forward, it is imperative to harness the power of these tools to create a more sustainable and resilient food system.

INTEGRATION OF MEDIA AND INFORMATION TECHNOLOGIES IN WASTE MANAGEMENT

The burgeoning waste management crisis necessitates innovative solutions to enhance sustainability and resource optimization [6, 7]. Despite the recognized potential of digital tools in sustainability, their application in waste management is not well-documented.

The integration of media and information technologies in waste management is an emerging field that promises to revolutionize traditional practices. While digital tools have been instrumental in advancing sustainability efforts, their role in waste management is yet to be fully realized (Figure 2).

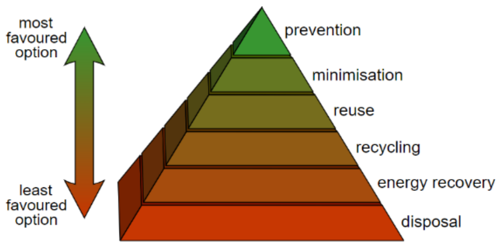

Figure 2. Pyramidal conception of waste management hierarchy.

This literature review examines existing studies to identify gaps and opportunities for leveraging these technologies to foster more efficient waste management systems.

Recent studies have begun to shed light on the transformative prospective of media and information technologies in waste management. Czekała *et al.* [8] discuss modern waste management technologies, emphasizing not only technological advancements but also the sociological impact through media platforms, which can significantly influence ecological consciousness and awareness. Similarly, Gupta *et al.* [9] presents an integrated approach to waste management, highlighting the applications of digital tools in creating sustainable solutions from waste.

Digital platforms and waste management

Efficiency Innovative digital platforms are recognized for making waste management more efficient, transparent, and accessible. The use of technology has become more tech-savvy and humane, allowing for the recovery and recycling of scarce natural resources, reducing landfill waste, and protecting our planet [5, 8]. Different studies further elaborated on how advanced sensors and monitoring systems can track waste generation and disposal practices, offering valuable insights into behavioral trends.

Data-driven waste management

The integration of technology in waste management addresses immediate challenges and unlocks possibilities for optimization [5]. A data-driven approach enables enhanced decision-making and resource allotment, optimizing the entire waste management process. This sentiment is echoed by other studies, that discuss the strategic approach to cost reduction and resource optimization through digital technologies.

AI and IoT in sustainable waste management

The prospective of Artificial Intelligence (AI) and the Internet of Things (IoT) in rebellion waste management put into practice is immense. Sharma [10] explores the effectivenessenhancements crosswaysa variety of aspects of waste management, including observing, compilationpath optimization, and recycling processes, facilitated by AI and IoT technologies.

METHODOLOGICAL APPROACHES

This work uses a mixed-methods approach, combining quantitative data analysis with twoqualitative case studies. The data sources include industry reports, and academic publications on the food and agriculture sectors.

- *Awareness about the method of vermicomposting.* Vermicomposting (worm composting) relies on earthworms/segmented worms'biodegradation/microorganism break down organic matter activity to move nutrients from one classification to the other. All the micro along with macroorganisms in the huge microflora can convert organic waste into usable resources. Earthworms help to break down cellulose, promote soil formation, and accumulate humus. Earthworms have a deleterious impact on the biological, chemical, and physical properties of soil. Earthworms are unique in with the purpose of feeding on natural/organic wastes but only use a small portion of them for growth, excreting the bulk in a partlyabsorbed form. This is due to the presence of microbes, hydrolytic enzymes, and hormones in earthworm intestines that encourage the rapid collapse of partly ingested food. The porosity promotes root saturation, ventilation, water absorption, and drainage. Earthworms and associated microorganisms generate soil aggregates that help to maintain soil ecology[11]. Vermicomposting is a non-thermophilic, bio-oxidative process in which soil-dwelling earthworms and other microbes produce extremely rich compost. Earthworms speed up soil healing by reintroducing beneficial microbes. Vermicompost has a thinlyalienated, peatlike, absorbentquality, good ventilation and drainage, lofty water holding ability, and improved microbial action and buffering competence, among other biophysical properties.
- *Awareness about treatment of groundwater and wastewater using RHA.* Numerous studies have demonstrated the effectiveness of RHA in groundwater treatment. The high silica content and porous nature of RHA make it an excellent adsorbent for various contaminants, including heavy metals and organic pollutants [12]. The utilization of inconsequential materials such as bamboo, condensed earth blocks, fly ash bricks, and glass fiber–unbreakable concrete has the potential to enhance the sustainability and cost-effectiveness of constructed edifices [13].

The biofiltration mechanism plays a crucial role in the elimination of various contaminants during the treatment using rice husk asks.The procedure of biofiltration encompasses several phases in the elimination of contaminants from air or water. Initially, the contaminated air or water is introduced into the biofilter setup, where the contaminants adhere to the biofilm or cellular membrane of the biofilter bed. The contaminants are then elated to the divan media in the aqueous phase [14, 15]. These contaminants serve as a source of carbon, acting as food for microorganisms [16]. Through efficient metabolism, microorganisms thrive and form colonies, ultimately leading to the degradation of the contaminants [14].

CASE STUDIES

Case study 1: Social media and digital platforms for food and agricultural waste recycling

For analyzing social media or platforms that connect farmers with waste processing facilities, enhancing recycling and reuse of agricultural by-products, thecase of rice huskash (RHA) can be considered. Rice husk is an agricultural byproduct available in huge quantities, particularly in the Democratic Republic of Congo [6] (see Table 1). The future of cleaner production is centered around the objective of mitigating the release of solid waste [17].The alleviation of environmental contamination has elicited a growing interest among researchers and scholars, as evidenced by the increasing focus on the advancement and application of solid waste management [18].

Table 1. Storage of crop residues in Africa according to different surveys carried out, difficulties and different management methods

Crop residue storage practice	Yes No	67% 33%
Type of crop residue stored	Cowpea tops Peanut tops Rice straw Cereal tops and straw Cereal stalks Cowpea and peanut tops	22.2% 1.3% 16.7% 38.9% 13.5% 7.4%
Crop residue storage period	Rainy season Cold dry season Hot dry season After harvest Dry season Anytime Rainy season and cold dry season	1.9% 62% 1.9% 13.2% 9% 10.8% 1.3%
General perceptions on the problem of agricultural waste management		
Agricultural waste consists of crop residues, straw, manure, and other organic materials produced by farms and agricultural operations. Agricultural waste can be composted or used to produce energy, but often it is thrown into landfills or burned, which can have negative effects on the environment and human health.		

Agricultural waste can pollute soil and groundwater, release greenhouse gases and harm biodiversity. Burning agricultural waste can also release toxic substances into the air, which can cause respiratory problems for local people.
Key steps to reduce agricultural waste
1 – Crop Planning: Crop planning can help reduce agricultural waste by ensuring that crops are grown efficiently and sustainably. Sustainable agricultural practices, such as crop rotation and water management, can also help reduce agricultural waste. 2 – Reduction of food losses: Reducing food losses can help reduce agricultural waste by ensuring that agricultural products are used efficiently. Food losses can be caused by storage, transportation, and distribution problems. Food preservation technologies, such as refrigerators and freezers, can help reduce food loss. 3 – Recycling and composting: Recycling and composting can help reduce agricultural waste by transforming organic waste into soil nutrients. Agricultural waste can be composted to produce compost, which can be used as a natural fertilizer. Recycling plastics and other non-organic materials can also help reduce agricultural waste. 4 – Use of renewable energy: The use of renewable energy can help reduce agricultural waste by transforming organic waste into energy. Agricultural waste can be used to produce electricity, heat, or biofuel. This approach can help reduce greenhouse gas emissions and promote agricultural sustainability. 5 – Awareness and education: Awareness and education are essential to encourage farmers, producers, and consumers to reduce agricultural waste. Training and education programs can be implemented to encourage sustainable agricultural practices and efficient use of resources. 6 – Collaboration and cooperation: Collaboration and cooperation between farmers, producers, governments, and environmental organizations can help promote the reduction of agricultural waste. Partnerships between agricultural stakeholders can encourage the implementation of sustainable practices and the creation of innovative solutions to reduce agricultural waste.

RHA's pozzolanic properties enhance the strength and durability of construction materials, reducing the dependence on traditional, resource-intensive components. Physically described as grey in color, irregular shape texture, non-crystalline and odorless with particle size of <45 μm, Hossain and Islam [19] assert that the incorporation of RHA as a supplementary cementitious material contributes to the production of newly mixed concrete.

As the phenomenon of global development continues to surge, in conjunction with the rapid growth of the global population, there has been a significant need for the establishment of architectural structures and essential infrastructure. Cement, the fundamental element that binds concrete, serves as its most crucial and costly component [20].

Case study 2: Information systems for waste tracking and management

Bananas, a maincollide crop in India, generate a lot of rubbish. Earthworms (*Eudriluseugeniae*) were employed to blend organic waste with cow manure. It was determined that a combination of 200 g banana waste and 800 g cow dung resulted in the optimum enlargement and duplicate. The earthworm didn'tstay alive during the treatments containing 1000 g banana waste alone or 800 g banana and 200 g cow manure mixed. Furthermore, the mixture of 200 g of banana waste and 600 grammes of cow dung resulted in improved development and reproduction. If the proper amount of cow dung (CD) is added, vermicomposting is a straightforward approach to deal with banana waste. Accordingly, employing a lot of banana waste in nourishing is detrimental [21–23].

Vermicomposting can reduce agro-industrial waste water's C/N ratio by 69-79% and soluble chemical oxygen requirements by 20-88%. Vermicompost was created when extremelytainted wastewater from a palm oil plant was cleansed using earthworms [11, 21]. Rice straw has been shown to be a better amendment and absorbent than soil because of its higher nutritional content, greater reduction in soluble chemical oxygen demand (COD), and lower C/N ratio. The pH, electrical conductivity, and nutritional content all rose drasticallyfor the period of the vermicomposting process [23] According to one study, the most excellentevaluation vermicompost with a high nutritional value was formed by combining rice straw and palm oil mill effluent. Earthworm growth was similarly delayed in all compost piles utilized in the study.

During the vermicomposting process, earthworms are introduced and break down the natural/organic materials, producing castings that can be used as fertilizer. *Eisenia foetida*'s digestive enzymes break down organic matter at a temperature of 26 °C and 62-82% moisture content [24]. In comparison to compost and initial agro-industrial waste, vermicomposting reduces carbon emissions while raising nitrous oxide levels in the soil (bagasse). Additionally, VM costing improves the biological, chemical, and physical properties of soil.

A study in Indore, India [25] investigated how flower debris was treated in temples. Typically, these wastes are biodegradable and readily available for microbial growth. Vermicomposting technology was employed to manage temple waste. The procedure involves combining cow manure and waste items and allowing them to decompose for 45 days at 30 ºC. After 45 days, the ideal conditions for vermicomposting floral waste are: 25 ºC, pH 8.0, electric conductivity 200 microSiemens/cm, and C/N ratio of 12.3. The costs of this system were assessed, and its suitability for the city of Indore was also demonstrated.

CONCLUSION

Integrating media and information tools into food and agricultural waste management offers promising opportunities for enhancing sustainability and efficiency. This paper highlights the need for continued innovation and collaboration to address the pressing issue of waste in these critical sectors. Thus, management of food and agriculture waste relies on crop planning, reduction of food losses, recycling and composting, use of renewable energy, awareness and education, and collaboration and cooperation. Thereat, integrating media and information tools for the enhanced management of food and agricultural waste is a significant step towards sustainable development. By leveraging technology, stakeholders can improve waste tracking, optimize recycling processes, and promote efficient resource use. This integration not only helps in reducing the environmental impact of waste but also contributes to the economic viability of the agricultural sector by transforming waste into valuable products. Ultimately, such initiatives can lead to a more informed and responsible approach to waste management, aligning with global efforts to combat climate change and foster a circular economy.

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Advancing environmental protection with sustainable financing: a case for waste management through superfund policy in India

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Rapid urbanization has contributed to the growing issue of waste generation. It has been well-documented that the process of disposal of hazardous waste can harm human health and environment if not managed properly. Uncontrolled waste generation impedes the realization of SDGs and affects India's ambition to achieve net zero emissions by 2070, ultimately impacting India's mission to fulfil its obligations made during the Paris Agreement in 2015. Therefore, the Indian Government has adopted a multifaceted approach to regulating waste disposal, which includes using waste technology, capacity building, citizen participation, etc. However, the major challenge faced is the inadequate funds to implement these regulations. The Government of India supports the financing of these efforts through grants, loans, tax exemptions, and other mechanisms, yet there is a need for more effective and sustainable financing.

The paper analyses the trends and mechanisms of financing waste management in India. The paper further delves into the case study of the Love Canal Disaster in the USA. It discusses the need and feasibility of creating a Superfund policy to address the challenges of waste management. Furthermore, the paper evaluates best practices from across the globe and concludes with viable recommendations to improve and enhance financing for waste management and environmental protection.

Keywords: environmental protection; love canal disaster; superfund; sustainable financing; waste management.

INTRODUCTION

The growing world population and the longing urge for development have led to many issues in the present times. One of the major problems is that of waste generation. The present production-consumption model generates a lot of waste, out of which India alone produces 62 million tons of waste annually, with 70% of the waste being collected and only 12 million tons treated, while 31 million tons end up in landfills. With the changing production and consumption pattern like online food delivery, etc. digitization and advancement in technology including public services, there is a likelihood of three times surge in waste generation by 2030.

Recent data from the Central Pollution Control Board (2024) indicate that India's waste generation has increased by 25% since 2021, reaching approximately 77.6 million tons annually. Urban areas contribute disproportionately to this volume, with metropolitan cities generating 55% of the total waste. The implementation of digital India initiatives and the rapid growth of e-commerce have led to a projected 40% increase in e-waste generation by 2025 [1]. This escalating waste crisis presents both environmental challenges and opportunities for sustainable waste management solutions.

The member states of United Nations through its sustainable development goals Agenda 2030 have pledged to reduce waste like the solid waste generated from cities (11.6.1), food waste (12.3.1), chemical waste (12.4.1), hazardous waste (12.4.2) by proper and adequate treatment. Since there is a diverse range of waste generated through human activities, therefore one fit for all formula will not be able to resolve the problem, thus, the member states have tried to cater to the issue of waste generation through various law and policy initiatives.

Effective waste management has been a challenge for developing countries. India exemplifies the issue through its diverse demography and demographical requirements with different production consumption habits and diverse requirements of the waste for its management. Apart from an international effort to minimize and manage the waste, the Indian Government has tried to regulate waste by catering to various techniques of waste segregation, waste disposal, waste treatment, etc. using various law and policy instruments. However, the results of these efforts are still desired. One of the major reasons for the same is the lack of funds to carry out the process of waste management. More than three-fourth of solid waste management budget is allotted to collection and transportation, leaving little for processing or resource recovery

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and disposal [2].

A multifaceted approach is required to address the financing issue which will involve public-private partnerships, government incentives, and innovative funding mechanisms to ensure sustainable management of waste and safeguard the environment for future generations. Therefore, there is a need to devise sustainable financing mechanism which can generate sufficient funds for waste management infrastructure, recycling techniques and facilities, awareness campaigns, research and development and other initiatives to do away with the possibility of waste leakage.

The paper adopts a doctrinal method of research for exploring mechanism for financing waste management. The paper highlights the need for financing mechanism for waste management. The paper also delves into the mechanism and challenges of financing waste management in India. The paper explored various best practices used across the globe for managing waste to find out the possibility of adopting one for India. To determine a framework for financing waste management, the paper probes the effectiveness of a Superfund created in US by studying the love canal disaster. The paper further examines the need and feasibility of creating a Superfund in India for financing waste management and thereby protecting the environment and preventing health hazards.

While extensive research exists on waste management technologies and policies, there remains a significant gap in understanding sustainable financing mechanisms specifically adapted to India's unique socio-economic context. Previous studies have focused primarily on technological solutions [3] or policy frameworks [4], but few have examined the intersection of policy, finance, and implementation in the Indian context. This research aims to:

1. Evaluate existing financing mechanisms for waste management in India;
2. Analyze the applicability of global best practices in the Indian context;
3. Develop a framework for implementing a Superfund-style policy adapted to Indian conditions;
4. Propose sustainable financing solutions that integrate public, private, and community stakeholders.

LITERATURE REVIEW THROUGH BIBLIOMETRIC SURVEY USING SCOPUS DATABASE

The literature review is performed through bibliometric analysis by analyzing the existing published literature on financing waste management in India. The study was conducted using SCOPUS database which is a global abstracting and indexing database which consists of all the high-quality published documents. The literature review highlights the linkage between Waste Management and Financing Strategies. Various were used to identify the relevant published documents to remove the possibility of excluding relevant documents.

Search strategy

The SCOPUS database was searched using various keywords to get the relevant data on clean air and sustainable development. The database was searched using the category of “Abstract, Article Title, and Keywords”. This category was used as it is most useful in identifying the relevant documents and avoiding misleading results.

The flowchart below explains the search strategy used to identify the relevant literature.

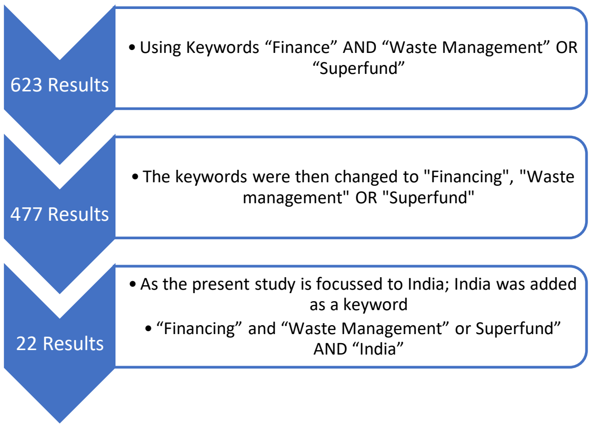

Fig. 1. Search strategy applied on SCOPUS database

All the results were manually scrutinized to check the relevance of the results to the topic. All the documents were found relevant to the subject and thus, all the documents are being considered for the bibliometric analysis and no documents from the search result have been excluded.

Quantitative analysis of the literature

The study first of all conducts a quantitative analysis of the present literature by analyzing the publication trend during the timeline from 1991 till date and then focusing on the subject area of the research. The survey shows that although there has been a lot of study already done on the topic Waste management, however, the there is a lack of study about the financing strategies for waste management. At global level, several researchers have focused on the financing strategies for managing the waste but India lacks behind in the same. The results show mere 22 publications during the whole timeline.

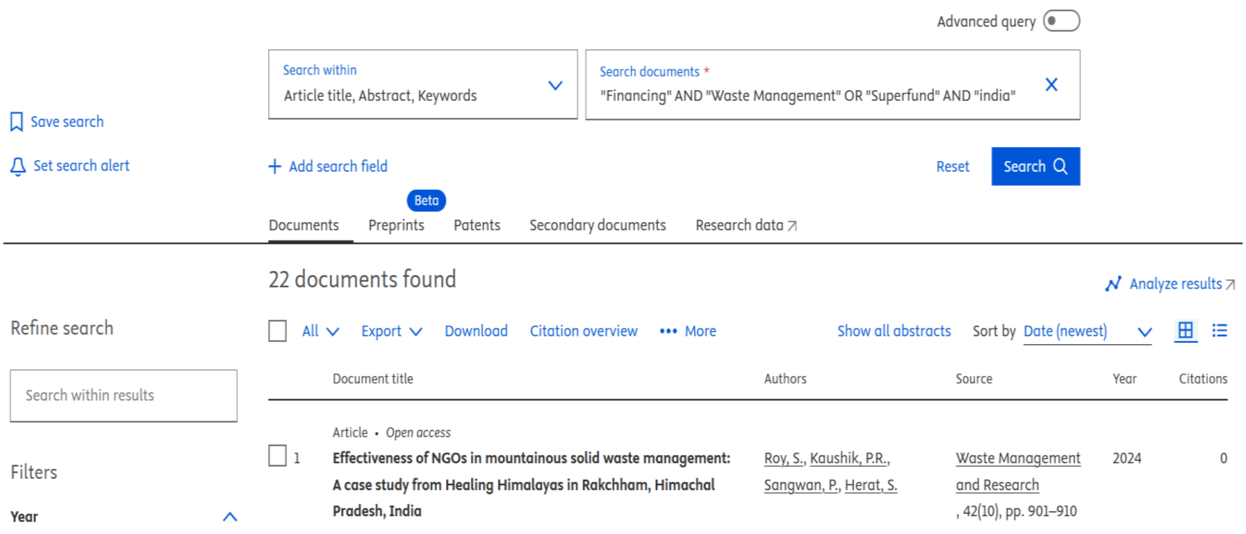

Fig. 2. 22 documents found using the search strategy (SCOPUS database)

The topic did not gain much attention of the researchers in any year except 2011 and 2021 wherein three research publications have taken place in both the years which is quite an insignificant number as compared to the significance the topic holds in the present times (see Fig. 3).

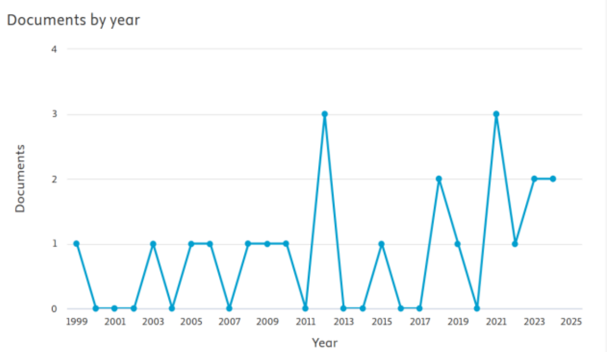

Fig. 3. Publication trend in the field of financing waste management in India (SCOPUS database)

Furthermore, the analysis shows that 35.7% of the total publications focuses on the environmental science domain and only 14.3% of the research is from social science perspective. A manual scrutiny of the present documents showcase that a very little research has taken place from a legal and a policy aspect on financing waste management and protecting the environment and human health.

Qualitative analysis

Research has been conducted on effective methods for waste management in various sectors like banks, corporates, educational institutes, etc. and it has been found that now everyone uses an active management method of waste management [5]. With changes in types of waste generated there have been changes in the methods and means to manage the same.

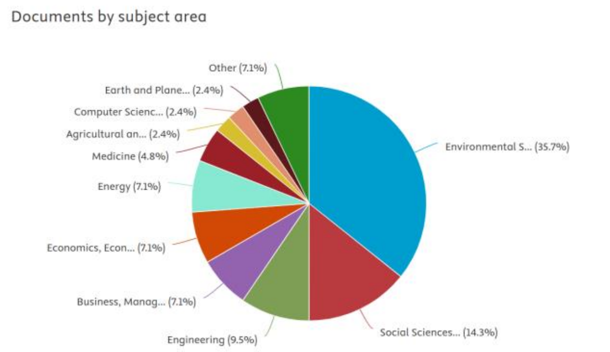

Fig. 4. Subject domain in which research on the topic has been conducted (SCOPUS database)

Technological advancements have made it easier to manage the waste by using technologies like blockchain technology to regulate e-waste as one of the competitive waste management techniques. [6] The concept of waste management is as challenging as it is significant in the present world. There have been many challenges like data availability, education in sustainable consumption and production (SCP) patterns, financing of SDG targets and data use which act as obstacles to monitoring and achieving target 12.3 [7].

One of the significant questions often raised is how to finance these waste management strategies. Various financing mechanisms are listed by conventions like Stockholm conference, Paris Agreement, etc. [8] Most of the developing countries have been devising strategies for revenue generation like levying of tax, charging of fees, etc., on waste generation depending upon the volume of waste generated, however, it has restricted implementation due to less government support, weak policy structure, unawareness among consumers, and poor extended producer responsibility (EPR) system [9].

In India, the source of capital has been the major problem since the present "tipping fees" charged for managing waste are very low and inadequate to make the operation profitable and thus attract private investors [10]. Various other techniques have been devised to facilitate key policy objectives for generating economic growth and reducing environmental impacts. However, the implementation phase requires revenue mobilization and collection [11] which cannot be done only by a long-term financing protection through government subsidies to cover higher capital cost [12]. Therefore, there is a need for innovative financing to direct investments into waste management [13], which would require policy-based reforms to strengthen the financing mechanism [14]. Some researchers have suggested alternative modes to address the issue of financing like policy instruments such as a deposit-refund system, [15] viability gap financing through PPP [16] however feasibility of such programs is under discussion.

Recent systematic reviews of waste management financing [17] indicate three emerging trends in sustainable financing: blockchain-based waste tracking systems, green bonds for infrastructure development, and community-based micro-financing initiatives. Analysis of 156 peer-reviewed articles published between 2020-2024 reveals that while technological solutions have received significant attention, financing mechanisms remain understudied, particularly in developing economies. The following thematic areas emerge as critical:

a) Public-private partnership models (35% of studies);

b) Innovation in financial instruments (28%);

c) Policy integration and implementation (22%);

d) Stakeholder engagement and community participation (15%).

Though there has been sufficient literature that highlights the need of financing waste management for sustainable development and environmental protection, however the present literature is insufficient to provide an effective and a feasible measure to ensure sustainable financing for waste management in India.

FINANCING WASTE MANAGEMENT

Increased waste generation has a significant impact on the planning and readiness for waste management and infrastructure development [18] and unplanned and unscientific way of managing the waste can significantly impact the environment and can have multiple health hazards [19]. Usually, the waste generators tend to dump and burn waste proceeds due to the easy and feasible availability of land. This leads to high emission of hazardous chemicals and poorly managed waste poses threats to the environment and has adverse impact on public health, thus necessitates waste management for providing a welfare society.

Waste management is a complex process which includes waste segregation, waste disposal, waste treatment, waste recycling, conversion of waste to energy, etc., however what is essentially required at each stage of waste management is funds. The data about the collection and expenditure of waste-related revenue is inadequately available in public domain however various studies suggest that the expenditure incurred on waste specific services has always been more as compared to the public revenue generated for the same. The developing countries with high level of environmental taxes collect a very low amount (around 0.02%) of global GDP on average as solid waste related charges [20].

Earlier, the sustainability efforts were limited only to cater to the environmental issue, however, now there has been a shift in the approach where scholars are adopting concept of triple bottom line which includes environment, economic and social methods towards sustainability [21]. The economic component which includes the cost incurred on environmental protection and revenue generated through environmental protection policies are significantly market-driven. A study by United Nations Environmental Programme (UNEP) suggests that expenditures incurred on waste management are around 0.5 percent of global GDP [22].

The major roadblock in financing waste management is the lack of cost assessment and implementation of techniques. Key challenges also include limited financial resources, inadequate infrastructure, lack of advanced treatment facilities and need for context-specific solutions like efficient wet waste management [23]. There are various costs involved in the entire process of waste management some are direct cost [24] which includes the cost of cleaning up sites, recycling, segregation, etc., another is indirect cost which is incurred due to the loss of health [25], etc., which is most difficult in measuring and monitoring. The Global Wastes management Outlook (GWMO) emphasizes on considering many factors while estimating the cost as the capital required for various disposal facilities varies with technology.

In most countries, the local government is vested with the responsibility of waste management which constitutes majority of their expenditure. In India, local governments are responsible for their provision but are hindered by poor finances and implementation capacity. However, it is a general trend that the waste expenditure is often more than the revenue generated by local government and their spending capacity. The most common source is the revenue collected through property tax which on an average is 0.7% of global GDP. Property tax merely contributes to 1.1% of the total GDP in a developed country while the share in a developing country is even less to around 0.4% of the GDP [26]. Another problem in financing waste management is that the general people are under an impression that waste disposal is free and thus they do not bother to pay for the meagre fee charged. The budget analysis observed increasing investments, but inadequate financing is reflected in the poor service levels of infrastructure [27].

Due to the low level of waste related revenues, many countries have tried to expand their revenue source to help finance the increasing waste. The Government has started to generate revenue through grants, taxes, exemptions, loans, voluntary contributions and various other mechanisms. Various countries have also started collaborating with private entities to expand their revenue base. Several countries have a dedicated environmental fund which comes from environmental taxes and charges. Several other countries use external public financing for the same to support low-income countries.

It is suggested to adopt an integrated method of financing which includes external funding through various organizations, Private funding including companies and Government funding [28]. However, Government funding has always been insufficient to cater to the costs involved. Private funding has been much difficult to procure and external funding in the form of loans burdens the government and ultimately an individual. The present system of financing has weak institutional capacity, a lack of transparency in accounting systems, and limited revenue streams. It is even more difficult for developing countries to cater to their increasing need of waste generation especially in a country like India which has a vast and diverse population. This stresses upon a need to investigate the present framework for waste management and the challenges thereof.

FINANCING WASTE MANAGEMENT IN INDIA: TRENDS AND ISSUES

India is the second most populous country in the world with 1.27 billion people out of which 68% live in rural areas and 32% in urban. However, with rapid urbanization, urban population is at an increase. Population explosion and rapid urbanization have led to increased waste generation in India. India generates an approx. solid waste of 133,760 tons per day, of which 68% gets collected and only 19% is treated [29].

The Indian Government has taken various steps to manage waste to preserve the environment and to protect human beings from its adverse effects. Waste is a general term that encompasses various types like solid waste, plastic waste, chemical, and hazardous waste and with the advancement of digital India and the E-governance system, there is E-waste generated. The Constitution of India, through Article 51A, has given to all its citizens the duty to protect the environment and it has become a directive for the state to safeguard the environment. [30] To manage different types of waste there have been various laws and policies enacted by the government. The Environmental Protection Act, 1986 acts as an umbrella legislation that enables and empowers various central institutions for waste management. At the same time, it makes the polluter responsible for any expenses incurred for the damages caused to the environment due to discharging pollutants [31]. Responsibilities of waste generators have been established by the Solid Waste Management Rules, 2016. Other rules provide a framework for waste management for different types of waste like Plastic Waste (The Plastics (Manufacture, Usage and Waste Management) Rules, 2009), Hazardous Chemical Waste (The Hazardous Wastes (Management, Handling and Transboundary Movement) Rules, 2008), E-waste, (The E-Waste (Management and Handling Rules) 2010), etc. In 2014, The Government of India has launched Swachh Bharat Abhiyan which aimed at 100% waste collection and processing in all towns and cities across India. During the last decade, the government has launched the Clean India Mission, Smart Cities, Amrut Cities, and Digital India to improve living standards. E- and waste management are core infrastructure elements of these missions [32].

Governance and citizen services, urban mobility, affordable housing, health, education, water, energy, with sufficient laws and policy in place, the pertinent question to answer is the source of revenue to finance the processes. The inadequacy of funds for waste collection, segregation and treatment and lack of government finance regulatory framework are major barriers to achieving effectiveness in waste management in India [33] After the 73rd and the 74th Constitutional Amendment Act, the Municipal Corporations, i.e. the local bodies have been entrusted with the task of waste management [34]. From planning to execution, this function is performed by the local bodies. This means that the responsibility to raise revenue for waste management is primarily on the municipal corporations. Generating the required revenue is a major challenge faced by the local bodies. Under the 12th Five-Year Plan (2011), the Working group on financing urban infrastructure suggested that urban local bodies can raise their own funds through taxation, collection of fees, intergovernmental transfers, public private partnership model, commercial borrowings, etc., for financing their needs. Figure 5 shows that the majority of funds are generated through taxes and cesses levied by the central, state and local governments. Out of which the share of revenue generated by local government which form their own source of revenue is substantially less. Overall, municipal infrastructure has largely depended on fiscal transfers provided by central and state governments, with modest contributions coming from their own source of revenue or commercial financing.

The major source of local bodies' revenue are property tax and user charges. Most of the Indian States that are performing better as compared to other states, collect very small amounts as compared to global standards. [35] Since the property tax is not a buoyant source of revenue, another mode of generating revenue was User Charges which is a fee imposed on the household/ user who generates waste and is taken to collect the same. The user fee is charged as per the bye laws made by the local government. However, the percentage of collection of user fee in ranged from 0 to 35.89% only [36]. Loans taken from various international agencies like the World Bank, public-private partnerships (PPP), and corporate social responsibility activities are the major funding sources to develop the waste infrastructure in ULBs.

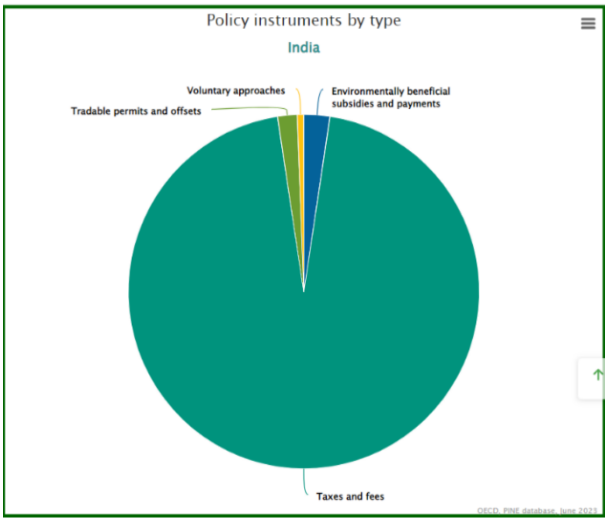

Fig. 5. Type of policy instruments in India to generate revenue for environmental needs (OECD Open Data)

User charges and revenue from waste recovery is are negligible in most of the urban local bodies. The literature shows that the local bodies are in dire need of finance to discharge their duty of waste management and are barely able to do the same with the existing funds available with them. Most of the Local bodies are largely dependent on the Grants from the central and the state government [37].

Therefore, another mode of financing waste management is Government Grants. The Central Government, by way of grants or through centrally sponsored schemes, provides grants to the Municipal Bodies for expenditure on waste management. Under Swachh Bharat Abhiyan, the government has allocated around 11 billion dollars for solid waste management project [38]. Apart from direct funding from central and state governments, special taxes and cess have been implemented to finance these projects. During the FY 2015-16, the government has enabled the implementation 2% tax on services to fund the clean India initiative and a tax of 0.5% on all taxable services was officially notified. [39]. Various grants have also been sanctioned by the Indian Government under the 12th and 13th Finance commission, various projects like JnNURM, UIDSSMT, Swachha Bharat Abhiyan, etc. [40], however, the grants are given in sharing pattern where the center shares 25% and state funding is around 12-12.5% and the local bodies have to bear the remaining financial burden of 65-67% which most of the ULBs are incapable of.

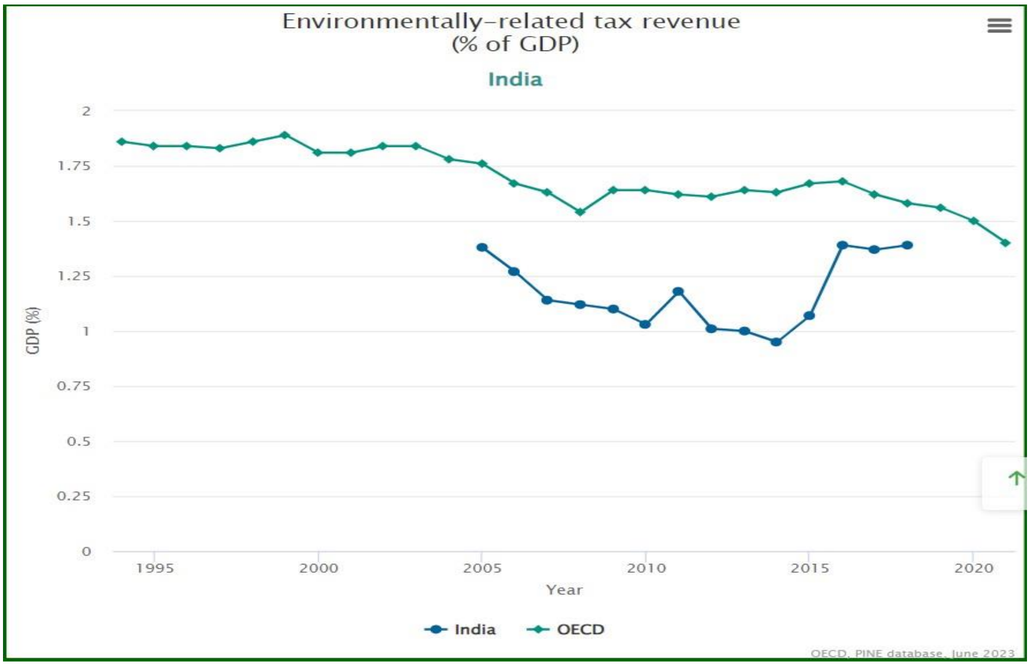

Fig. 6. Trend of Environment-related tax revenue collection in India (World Data: Open Access Source)

Under the 12th Finance Commission, government has released funds to local bodies for development of infrastructure for collection and transportation of waste. Design-Build-Operate-transfer (DBOT) and Design-Build-Finance-Operate-transfer (DBFOT) modes were implemented to develop projects for waste treatment and waste disposal. The PPP models are successful in a lot of local bodies but the rationale behind Public private partnerships is to gain efficiency, expertise, and technology, not finance. [41]. Under the Companies Act 201 r 3, Companies are mandated to spend 2% on Public Welfare under their corporate social responsibility [42]. However, these CSR funds are not restricted to merely Waste Management but the companies may contribute to the same. Therefore, private investments, in the present framework, are a source of funding for waste management however are not a sustainable source of finance due to the risk of market failure.

Recent policy developments have significantly impacted waste management financing in India. The National Clean Air Programme (NCAP) 2024 update has allocated ₹12,000 crores specifically for waste management infrastructure. Additionally, the Green Finance Initiative 2024 has introduced new mechanisms for municipal green bonds and waste-linked securities. Key policy innovations include:

- *Municipal Green Bonds*: Successfully implemented in cities like Pune and Indore, raising ₹1,200 crores for waste processing facilities;
- *Waste-to-Value Credits*: A new market mechanism allowing trading of waste processing certificates;
- *Digital Waste Exchange Platform*: Facilitating direct trading between waste generators and processors.

Filling this funding gap has been identified as a key objective of sustainable finance and therefore, there is a need for a mechanism for sustainable financing in India.

SUSTAINABLE FINANCING MECHANISM FOR WASTE MANAGEMENT THROUGH POLICY EFFORTS: PRACTICES ACROSS THE GLOBE

Many technological innovations have taken place for waste management which includes methods of waste segregation, waste collection, waste disposal, waste recycling etc. An important element of these innovation has been spending upon the infrastructure and technology. The traditional model of funding across the globe cast a burden on government to finance the waste management models through public spending. It has been already seen that how government funds are insufficient to manage the huge waste generated. Therefore, a new model of financing has involved privatization and public private partnership to cater to the financial needs of the current waste management program. This new model of financing and involving the private sector for furthering the public agenda has paved way for sustainable financing method. Sustainable financing means integration of the environmental, social and governmental aspects while investments or making lending decisions [43].

There have been various changes in the public policy globally however, policy agendas specific to sustainable financing are contingent on a country's social, political, economic and cultural conditions. Therefore, under this part, best practices across the world shall be studied to reach at a feasible solution which can be adopted in Indian scenario.

Various transnational efforts have been made by the United Nations as a measure for financing member states to achieve their agenda of attaining net zero waste [44]. An Environment fund is managed by United Nations Environment Program to provide funds to their partners globally to support areas like green technology transfer, capacity building, research, planning and management etc. In 2019, they have provided a support fund of $70 million for the same [45].

There have been various measures across the world to enhance efficient and outcome-based funding mechanisms for waste management. Some of the best practices are discussed as under.

One of the oldest ways of financing waste management was through taxes. Landfill taxes are the taxes charged on the companies who would want to dispose the waste in the landfills (instead of recycling and reusing it or disposing it as per policy). European Union member states along with Switzerland and Norway have imposed taxes for the amount of waste sent to landfills. The tax is imposed over and above the cost that has been charged for sending the waste to landfills and it is collected by tax and custom authorities, environmental agencies or municipalities [46]. The poor collection of property tax has already been discussed above. Italy has spiked its waste related revenue by replacing the property tax to waste management tax.

Jamaica is another example of increasing the finances for waste management by introducing Jamaica's Environmental Protection Levy (EPL). This imposed an *ad valorem* charge of 0.5% to offset the cost of waste material, especially plastic waste [47].

Various countries have also turned their face to private sectors for financing their waste management like Japan has increased involvement of private sector for collection and segregation of waste. Israel has involved private sector finance for waste to energy plants. Estonia also has started involving private sector in investment decisions for new waste treatment facilities. One successful, large-scale PPP waste management project in the private sector was developed in Serbia in 2019.

External funding is another major source of funding used by the countries. Like Estonia has used the grants from the EU Funds which have been used for remediation of old landfills for mining and industrial waste and abandoned industrial areas.

Another best practice is introduction of the Credit guarantee schemes for providing fixed capital for waste management projects. A credit guarantee scheme involves three parts, i.e. the borrower, the lender and the guarantor. The borrower which usually is the company or any individual who is seeking finance for establishment of a waste management model/ infrastructure seeks finance from the lender who usually are banks or ending agencies.

Ideally, the banks do not provide loans till they see any profit coming from the business model, however, under this scheme the government becomes the guarantor through various institutions like credit guarantee corporations, etc., and therefore, the loan sanction becomes more likely.

Initially CGS was implemented in Japan, South Korea and Hong Kong. Later, European Union has agreed to become a guarantor for 90% of loans for member states which later increased to 100% [48]

Another best practice in financing waste management was by involving community for funding. There have been various ways wherein the community has been involved in funding projects for waste management. Many countries involve the community in the form of either by taxing them or by levying user fees. While Japan has created an investment by way of Hometown funding known as Hometown investment trust (HIT). HIT funds were introduced with the objective of connecting the local investor with projects in their locality keeping their personal knowledge and interest in mind. Individual investors choose their preferred projects and make investments *via* the Internet. Investments are encouraged *via* advertisements from various sectors like corporate sector, municipal governments, international government, etc. Although it was a voluntary mechanism of financing, however, this was well accepted in countries like Cambodia, Vietnam, Peru, and Mongolia [49].

Another way of involving community was by charging Advanced Disposal Fees. In furtherance to the polluters' pay principle, ADF's charge product-based fee at the end of the life of the product by adding the same to the cost of the product thereby internalizing costs that are often externalized to the environment. Unlike deposits, they are non-refundable to the consumer. Unlike the HITs, it is more compulsory in nature and therefore leaves no leeway for lesser collection of funds.

There is a view that instead of burdening the common producer, there is a need to identify the polluter and then they should be mandated to pay for the cost of waste management. This idea was implemented through Extended Producer Responsibility. Through EPR, the producers who generate waste due to the production of goods cover the costs of collecting and processing the waste generated during production and packaging of their goods when they reach the end of their lifecycle their products and packaging once they reach the end of their lifecycle.

Ireland has imposed a tax called 'Latte Levy' on single-use plastic (coffee cups) and the income raised from the scheme was used to develop a system of recycling and reusing the same (Single-Use Foodware and Litter Reduction Ordinance). Similarly, Wales and Scotland have imposed a mandatory charge on carrier bag irrespective of their material [50]. In Japan, the owner or polluter not only has to pay for the remediation of the contaminated sites but here are also potential liabilities on the company due to contamination in their annual balance sheet. Similarly, Columbia has put an onus of remediation of site on the companies.

The measures taken worldwide have been great and significantly helped in increasing revenue for waste management. However, all these measures are burdening a single stakeholder, be it the government, the people, or the companies. Thus, OECD suggests use of blended finance for waste management which will include all the possible stakeholders to contribute to financing of waste management. Blended Finance is "the strategic use of development finance to mobilize additional finance towards sustainable development in developing countries" [51]. Blended finance can be useful in increasing finance for those countries which are in dire need of investments. It acts as a bridge for grants and donors to invest for waste management and can add value by shifting funds towards more sustainable self-financing approaches. Various agencies like IMF and GEF have used Blended finance in the climate change mitigation space to finance new technologies in renewable energy, energy efficiency, urban transport, and other related fields [52].

Another model of blended financing can be in the form of Environmental Impact Bonds. EIBs are models wherein the public agencies work with the private entities. EIBs are structured in a similar ways as traditional bonds where the private entities purchase Environment impact bond raising the revenue and it can be returned back with interest based on the environmental benefits incurred due to their project. EIB's work with the pay-for performance repayment mechanisms [53].

Korea is one example for the use of blended finance where they have used financial aid from sources like government subsidies, tax credits and long-term low-interest loans for constructing a waste-to-energy plant. Another example is Poland, funds from various agencies like private sector, EU funds, national funds have been taken to construct an incinerator [54]

Sustainable financing can also be achieved by setting up of Environmental Fund like the United Nations. Various countries have set up their environmental funds like Estonia's environmental investment Centre; The Czech Republic's State Environmental Fund and Poland's national and regional environmental fund. These funds receive the proceeds of environmental charges and use the revenue [55].

Various best practices are seen across the world to finance waste management. Some best practices are based on a policy however, most of them are voluntary in nature or without any legal backing to enforce the same. It is clear that levying of compensatory payments is not a substitute for a policy framework and thus, we need to look for a policy-oriented framework for financing waste management.

SUPERFUND: A CASE STUDY OF LOVE CANAL DISASTER

Love canal case study

An aborted canal project, named Love Canal because of its shape, is situated near Niagara Falls in New York. Since it is an aborted project, it remained unused for a long period of time and therefore was used as a dumping ground for urban waste. Apart from urban waste, waste generated due to World War II was also dumped there.

Around 1940s, a company named Hooker Chemical Company used this place to dump chemical waste of around 21000 tons. Later in the year 1953, the land was sold to the Education Board for a token amount of $1 with the caution of a huge waste dumped underneath. The Board has then established a school on it and the nearby land sold off to build the residential societies. While the construction was going on clay cap of the canal was breached which damaged the metal barrels.

After the construction, the chemicals were inactive for many years, however in late 1970s the waste began to seep to the surface. The residents started complaining about noxious fumes and oozing toxic sludge. The toxins also started to pollute the groundwater leading to various issues of miscarriage, birth defects and other health hazards. The superfund aims at two core aspects of waste management, i.e., remedial and removal. A core aspect of the Superfund is the principle of "polluter pays," which holds current and past owners/operators of contaminated sites financially liable for clean-up costs. As per this policy, it is first identified that who is the polluter which is known as the potentially responsible party (PRPs). PRPs fall into four categories: the current owner or operator of the site, anyone who owned or operated the site before, anyone who arranged for hazardous wastes to be dumped on or treated at the site, and anyone who transported hazardous wastes to the site. Seldom there is an involvement of one single party. Usually the identified PRP helps in identifying other responsible parties so as to distribute the liability. If a PRP can't be found, it's considered an orphan site and Superfund pays for the entire cleanup.

After conducting the initial tests, the state of New York declared the state of emergency in 1978 and evacuated around 200 families from neighborhood. This led to a huge national outcry and highlighted the lack of federal regulation and funding to address such environmental catastrophes.

As a result, to this state of emergency, the Comprehensive Environmental Response Compensation and Liability Act was passed. This is known as Superfund policy. The Superfund policy provides resources to clean up contaminated areas considered to pose substantial risk to human health or the environment. The superfund was initially funded by the taxes imposed upon the chemical and petroleum industries wherein they identify the responsible parties and make them pay for the remediation of the sites [56].

The Superfund program has successfully identified over 47000 potentially hazardous waste sites across the country, out of which 1900 were on the National Priority list. Till 2023, The EPA has completed the construction at 1375 of these NPL sites. Forty-five years after Superfund's inception, the EPA had cleaned up almost 1200 NPL sites. It has become a cornerstone of environmental protection policy, giving the federal government the authority and resources to hold polluters accountable and remediate contaminated areas. The Superfund program has had a measurable impact on hazardous waste management in the United States, though the full extent of its effectiveness can be difficult to quantify**.**

Superfund

The superfund is unique in its own kind as unlike all other funds created, this policy addresses environmental problem that traverse through several medium like water, air, soil, etc. This policy has created a superfund to finance cleaning up the waste disposal sites which causes environmental and health problems.

The EPA has been able to recover over $48 billion in clean-up costs from these responsible parties over the life of the program. This cost recovery helps offset the funding burden on taxpayers and the Superfund budget.

Financing Superfund

When it was passed, CERCLA—Diverse Enforcement Authorities was funded by a $1.6 billion five-year fund that taxed petroleum products and 42 chemicals on a limited basis, targeting industries with a history of producing the majority of hazardous waste. By 1986, however, due Congress's desire to substantially expand the fund and due to the concern for international competitiveness in the chemical industry, many believed that the tax should be redistributed more broadly. A political compromise was reached after a struggle between stakeholders and the revenue sources employed over the next five years came to $8.5 billion total: $2.75 billion from an altered levy on petroleum products, $2.5 billion from a 0.12 percent tax on corporate income over $2 million, $1.4 billion raised by adjusting taxes associated with chemical feedstocks (as raw materials or ingredients from which other compounds are made), $1.25 billion contributed through general revenues of the Treasury Department's "pocket", $0.6 billion obtained through cost recoveries from liable parties associated with CERCLA violations plus interest accrued or accruing thereon upon any unexpended portions [57].

For 26 years, federal policy has allowed entire industries to shift the financial responsibility of cleaning up Superfund sites away from themselves and onto individual American citizens who bear no direct responsibility for their creation and operation. Originally finance by the "polluter pays" laws that taxed petroleum and chemical industries, trust fund monies augmented by these levies were supposed to support Superfund clean-up efforts across the country [58].

In 1995, however, congressional "polluter pays" taxes levied on petroleum or hazardous chemicals expired, after which the program began relying substantially upon annual congressional discretionary spending decisions. Consequently, funding levels for Superfund declined over time while cleanup costs increasingly became an obligation shouldered by taxpayers in general as opposed to those entities actually responsible for creating toxic waste sites. Between 1993 and 2021, it would cost roughly $1.3 billion a year (not adjusted) just to deal with these contaminated sites alone let alone any others. Within this same period specter was hovering closely around zero due largely to unreplenished revenue pouring another log on the fire after expiration took hold thus stopping progress towards full realization but reaching out towards achieving greater success because past gains had been substantial despite setbacks endured along way according success also revolved funding readjustment once more. Past revenue from these taxes kept the Trust Fund's unobligated balance above zero until 2003, but shortly after the policy expired, cleanup progress at Superfund sites dropped [59].

The Bipartisan Infrastructure Law of 2021 and the Inflation Reduction Act of 2022 restored the Superfund "polluter pays" taxes—thereby putting the program on firm financial ground for the future. In addition to reinstating these taxes, the Congress provided $3.5 billion annually through the Bipartisan Infrastructure Law from user fees.

FINANCING WASTE MANAGEMENT THROUGH SUPERFUND POLICY: A CASE FOR INDIA

As already discussed, the inadequacy of finance is a major constraint in Waste Management in India. Apart from the fact that funds received from the government and funds collected through taxation and Fees are insufficient, the authorities also lack flexibility to spend funds as there are spending restrictions put by the State Government. The lack of financial resources led to inadequate infrastructure to deliver their responsibilities.

Need for a Policy Framework

Financing waste management puts a massive toll on the government. The urgency and intricacies involved in waste management necessitates a strong, coherent and coordinated fiscal response by the government. The need is to create a policy framework to mobilize finance from various stakeholders for waste management solutions in India. A fund which focuses on investing on waste management plays a significant role in dealing with the twin issues of environmental degradation and deteriorating human health. A superfund can raise capital from multiple stakeholders and will play a pivotal role in harnessing economic and environmental potentials.

Framework

India has existing environmental laws and regulations, such as the Environment Protection Act, 1986, and the Municipal Solid Waste Management Rules, 2016, which could provide a legal foundation for establishing a Superfund policy. However, a dedicated legislation or amendment to existing laws may be necessary to create a comprehensive legal framework for the Superfund policy, defining its scope, funding mechanisms, governance structure, and enforcement mechanisms.

Implementing a Superfund policy would require a robust administrative and institutional framework, including a dedicated agency or authority responsible for managing the fund, prioritizing projects, and overseeing implementation. Existing institutions, such as the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs), could potentially be empowered or restructured to take on this role, or a new dedicated agency may need to be established. Capacity building, training, and skilled human resources would be essential for effective implementation and management of the Superfund.

Successful implementation of a Superfund policy would require extensive stakeholder engagement, including industries, civil society organizations, environmental experts, and local communities. Addressing concerns, ensuring transparency, and gaining public support would be crucial for the policy's acceptance and effective implementation. Awareness campaigns and educational initiatives could help build public understanding and support for the Superfund policy.

Financial Viability

Establishing a Superfund would require significant financial resources, which could be challenging given India's fiscal constraints and competing priorities. However, Potential funding sources could include levies or taxes on polluting industries, fines for non-compliance, dedicated budgetary allocations, and contributions from public-private partnerships.

Blended approach can be taken to finance superfund in India. The superfund could be setup using seed funding from the Government (A fixed percentage of the revenue raised through taxes) and finances from the corporations who are highly likely to be the PRPs. Another important channel through which the private sector can improve air quality is via investments made through the Corporate Social Responsibility (CSR) route. Similar to CSR, corporations can be entrusted with Environmental Responsibility wherein they can be mandated to share a percentage of their income based on the waste generated by them (applying the principle of Extended Producer Liability) to the Superfund.

Superfund policy in India: A Probable Framework

- *Objectives*

The policy aims at establishing a National Waste Management superfund for sustainable financing of waste management activities in India thereby promoting environmental protection and human health.

The policy aims at bringing together probable polluters and holding them liable for remediation and cleaning up of contaminated site. The fund further aims at development of waste management infrastructure using the contribution from various stakeholders in Waste management.

1) *Establishment of a Superfund*:

a) The fund shall be named National Waste Management Superfund (NWMSF); b) It must be non- lapsable and non-transferable, managed by an appropriate authority or Board known as a Superfund Management Authority.

2) *Constitution of Superfund Management Authority:*

a) Superfund Management Authority should consist of a chairperson with not less than 20 Years of experience in handling environmental issues and 8 other members committed to the cause of environmental protection; b) Superfund Management Authority shall have members from Central and State Ministries of Environment, Urban Development and Finance. Members must also be from NGOs, Corporations and External Agencies.

3) *Regional and Local Offices*:

a) Regional Offices shall be established as per the rules framed by the Superfund Management Authority to facilitate effective implementation and monitoring of waste management initiatives at the state and local levels; b) These offices shall work in coordination with the respective state governments, urban local bodies, and other relevant stakeholders.

4) *Roles and Responsibilities of Superfund Management Authority*:

a) Formulating policies and guidelines for effective implementation and management of Superfund; b) Determining the criteria and procedure to allocate funds from the superfund of any waste management initiative; c) Determining key performance indicators and targets for waste management initiatives funded by the Superfund; d) Monitoring and evaluating the progress and performance of the funded project; e) Monitoring and Evaluation of the performance of Superfund; f) Formulating ways to increase the finances in the superfund; g) Conducting periodic reviews; h) Promoting research and development for research and development on waste management process and techniques fostering innovation; i) Facilitating capacity building amongst professionals, industries and community by organizing training and awareness program to promote sustainable waste management practices; j) Coordinating and collaborating with Central, state and local government for waste management; k) Preparation and submission of annual reports to the central government to maintain transparency and accountability in management and disbursement of Superfund; l) To ensure periodic financial, social and environmental audit.

5) *Source of revenue for Superfund*: a) The Superfund shall consist of revenue generated through levying of environmental taxes and cesses on:

- Industrial and commercial waste generators;
- Municipal waste generators (households and businesses);
- Landfill operators;
- Importers of certain waste-generating products (e.g., packaging materials, electronics);

b) Revenue generated through User Charges imposed for availing waste management services or Fines and Penalties imposed for not complying with the rules for waste management; c) Revenue generated through Environmental Responsibility of Corporates; d) Revenue generated through Environment Impact Bonds; e) Revenue generated through voluntary contributions; f) Revenue generated through external funding received for waste management.

6) *Allocation and Utilization of Funds*: a) Fund from Superfund can be used for the purpose of waste management in

- Development and Upgradation of Waste Management Infrastructure;
- Cleaning of landfills, dumping sites or any other contaminated sites;
- Research and Development Projects;
- Public Awareness Campaigns, Capacity Building Programme.

7) *Implementation framework*: a) Financial structure which includes Core funding in the form of 0.5% cess on corporate profits; Matching grants from central and state governments; Green bonds and environmental securities and International climate finance integration; b) Governance Mechanism: The Independent regulatory board should have representation from Ministry of Environment, Forest and Climate Change, Ministry of Finance, State Pollution Control Boards, Industry representatives and Environmental experts.

CONCLUSION

The Sustainable development goals have been embraced by all the government; however, its success depends upon the cooperation and collaboration amongst all stakeholders like Government, corporations, individuals, civil society, etc. We cannot allow commercial interests to overpower natural wealth and it must be ensured that the use of natural resources remains as per the standards of sustainability [60]. Addressing the issue of sustainable finance for waste management in India requires a multi-pronged approach that combines sustainable financing mechanisms, policy reforms, public awareness campaigns, and technological innovations.

Although the government is majorly responsible for providing clean environment, however, the entire financial burden cannot be borne by the government alone. There is a need for equitable distribution of the financial burden amongst all stakeholders. Additionally, Policy intervention is necessary for moving towards a system of sustainable financing wherein the policy imposes some responsibility on the stakeholders for contributing for waste management in different capacities.

In conclusion, implementing a superfund policy in India modeled after Superfund Policy in USA appears to be a viable solution to the financial challenges to waste management in India. A Superfund Policy is a wholistic solution which promotes collaboration, holds the polluters responsible and not only generates revenue for cleaning up but also incentivize industries for adopting cleaner mechanisms for development. This also helps in reducing the burden on the Government and the taxpayers.

The present research proposes a skeleton draft for the Superfund policy leaving scope for further research for determining ways for resolving the administrative and regulatory, hurdles in enforcement and coordination between the stakeholders. The potential benefits in terms of environmental protection, public health, and long-term economic savings make it a compelling option worth exploring. By learning from the successes and challenges of similar programs in other countries, India could tailor a Superfund policy to its unique context, paving the way for a more sustainable and resilient waste management system.

The implementation of a Superfund policy in India represents a transformative approach to waste management financing. While challenges exist in terms of institutional capacity and stakeholder coordination, the proposed framework provides a viable pathway for sustainable financing. Success will depend on:

1. Strong political will and legislative support;
2. Effective stakeholder engagement and participation;
3. Robust monitoring and enforcement mechanisms;
4. Integration with existing environmental programs;
5. Continuous innovation in financing instruments.

Future research should focus on developing detailed implementation guidelines for specific urban contexts and exploring innovative financing mechanisms that can complement the Superfund approach.

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Anti-diabetic potential of selected fruit and vegetable waste – an appraisal of current literature

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Diabetes mellitus is a widespread and rapidly growing health problem throughout the world. Fruit and vegetable waste in the form of peel, seed, skin, pomace, etc. possesses many compounds with potential hypoglycemic effects. Every year large amounts of vital components are lost in the form of discarded fruit and vegetable waste. The current literature reviews the anti-diabetic potential of these waste materials. It also makes an effort to cover the different mechanisms involved in which they exhibit these properties. The key findings indicate that the bioactive components like flavonoids, carotenoids, and polyphenols, and agents like allicin and tannins, not only protect β-cells and insulin sensitivity but also regulate the GLUT4 and PPARγ genes. This brings insight into the fact that these components can act as a potential tool to fight against oxidative stress-related diseases like diabetes. The extracts from mango peel, pomegranate seed, onion peel, and garlic reduced the glucose levels of blood in *in vitro* and *in vivo* studies. This review also finds the gap in the lack of standardization of these procedures and the challenges to commercializing these components More studies are required to get more information about the effective utilization and the commercialization of fruit and vegetable waste-based products. The findings of this research lead to a stepping stone for further research that optimizes the standardization of the extraction procedure to its full harness of using these natural resources in nutraceuticals and therapeutics.

Keywords: Fruit waste; valorization of waste; anti-diabetic potential; nutraceuticals; functional foods

INTRODUCTION

Fruits and vegetables contain various bioactive compounds exhibiting high antioxidant activity and potentially have several health advantages. These compounds are effective against different health and disease conditions, *viz*., obesity, diabetes, infections, and allergies in preclinical and clinical trials [1-3]. These chemicals include compounds like polyphenols, phytosterols, saponins, dietary fibers, and other compounds with high antioxidant activity [4]. Owing to consumer demand and better agricultural practices, fruit output climbed to around 108.34 million tons in the year 2022–23 from 107.51 million tons production in 2021–22, whereas vegetable production jumped to about 212.91 million tons in 2022–2023 from 209.14 million tons in 2021–22 [5]. Since both fruits and vegetables have a short shelf life, it is reported that one-third of the products goes to waste. The major waste generated from fruits and vegetables is in the form of peels, seeds, pulp, overripe or spoiled fruits and vegetables. The peel of most fruits and vegetables is removed before processing, while the extraction of juice from pulp results in the production of pulp residue. Both of these, along with the seeds, constitute a major part of the waste generated from the fruit and vegetable processing industry. For example, apples contain 10.9% of seed, pulp, and peel as by-products. Minimal processing treatments like dicing produce only 53% of the fruit as the final product, and the rest is waste in the form of peel, seed, and unusable pulp. Similarly, pineapple processing produces approximately 50% of waste in the form of peel, core, top, and pulp (14, 9, 15, and 15 percent, respectively). In mangoes as well, only 58% of the fruit is utilized. In the case of apples, these components constitute approximately 11% of the total weight. During dicing operation for minimal processing, only 53% of the total fruit is utilized. Similarly, in pineapple processing, only half of the total fruit weight is edible, and the rest is discarded.

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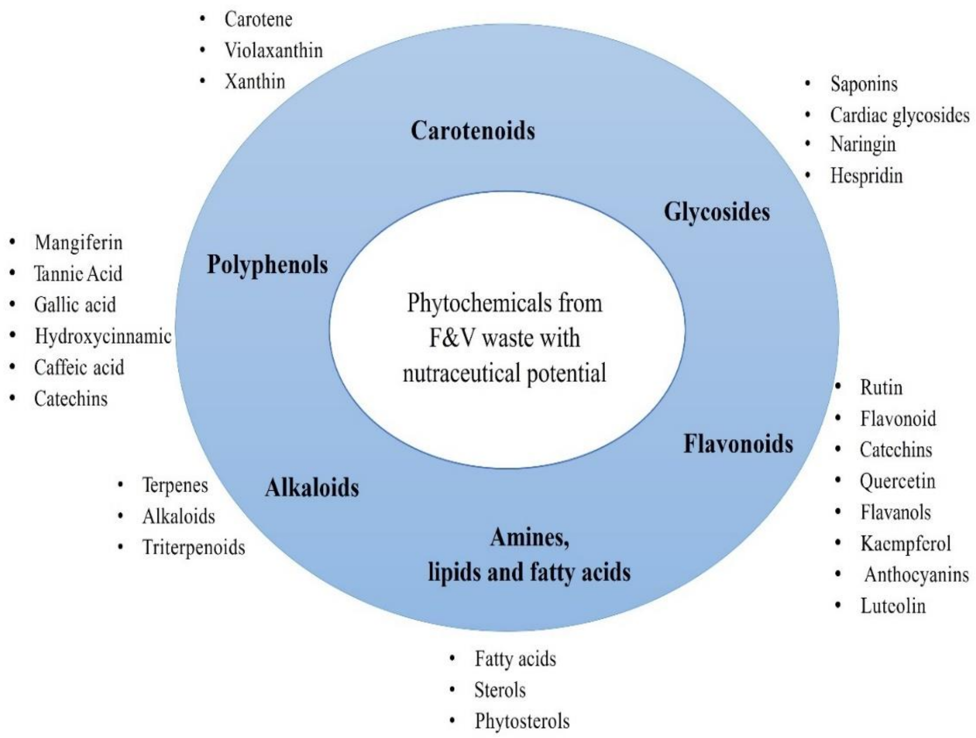

Fig. 1. Major phytochemicals identified from fruit and vegetable waste having anti-diabetic activity.

For mango consumption, only 58% of the fruit is used. Fruit and vegetable waste parts are generally not eaten in their native form and contribute to environmental burden. Management of this huge waste is a challenge and is currently tackled by either incineration or landfill since these are biodegradable in nature. Improper management leads to the production of toxic compounds and gases like methane, which poses not only environmental but also health hazards. Fruit and vegetable waste is rich in useful components that are highly effective against various health conditions (Fig. 1). Extraction, isolation, and purification of phytochemicals from these parts can reduce the issues and help to develop new-age functional foods, sustainable packaging materials, and nutraceuticals [6].

Diabetes is a metabolic condition that involves elevation of blood glucose levels [7]. According to the latest edition of the IDF Diabetes Atlas, 537 million individuals had diabetes in 2021, with a drastic increase predicted to 783 million in 2045. More than half of the cases go untreated in developing and underdeveloped countries. In addition, 541 million people are prone to the risk of type 2 diabetes. About 1.2 million children have type 1 diabetes. Diabetes killed 6.7 million people in 2021 and costed $966 billion in healthcare costs, accounting for 9% of global healthcare spending. High blood glucose levels during pregnancy affect one in every six live births (21 million) [8]. Major management of this disease condition is done using synthetic drugs. There is a great need to use natural remedies to manage and treat this disease spreading like an epidemic. Recent research indicates that these components, like polyphenols, flavonoids, catechins, etc., possess anti-diabetic activity.

Regardless of these findings, the field is still underexplored, especially in explaining the hypoglycemic mechanism behind each component. Also, the development of value-added products from waste materials can enhance the economic viability of the food industry while addressing public health concerns. However, limited research has explored the large-scale industrial processing and consumer acceptance of these functional products, highlighting the need for further studies to bridge this gap. This review tries to close important gaps in the existing literature by offering bioactive compounds that are obtained from fruit and vegetable waste about diabetes management. Even though there are studies on the role of these bioactive compounds on mechanisms of mRNA expression, β-cell protection, and insulin sensitivity, the source of these compounds and their value-addition opportunities are underexplored. The overview is unique because of the comprehensive evaluation of bioactive connections of waste as sustainable resources for industrial applications and therapeutic active ingredients. This work emphasizes how these natural connections have the potential to transform the diabetes supply by addressing a significant problem of public health and reducing environmental waste.

This review also points out the relationship between the scientific background of these compounds and their potential industrial applications for the utilization of this waste in therapeutic and nutraceutical products like herbal teas, infusions, etc. This study gives a framework for the need for subsequent studies on consumer acceptability and large-scale processing.

MECHANISM OF ANTI-DIABETIC EFFECT

Beta cells which belong to pancreatic islet cells, are responsible for the production and secretion of insulin hormones to maintain blood glucose levels. Glucose enters into the blood after each meal. Then the glucose goes to the beta cell *via* glucose transporter Glut2 and is utilized through glycolysis, raising the intracellular ATP/ADP ratio and closing the ATP-dependent potassium (KATP) channels in the plasma membrane. This leads to membrane depolarization and opening of voltage-gated calcium channels, that allow Ca^{2+} to enter the cell, initiating insulin exocytosis, and releasing insulin into the circulation [9]. Based on the above mechanism, antidiabetic agents generally control glucose metabolism in four major ways: 1) intestine-related, 2) liver-related, 3) pancreas-related, and 4) muscle-related [10].

Polyphenols like catechins, gallates, caffeic acid, etc. from mangoes, pomegranates, potatoes, and red bell peppers inhibit glucose metabolism through the inhibition of carbohydrate-digesting enzymes like α-amylase and α-glucosidase, which reduces the absorption of glucose. This will lead to a reduction of postprandial glucose by the same mechanism as that of the drug acarbose [11]. Alkaloids like d-1,4-dideoxy-1,4-imino-D-ribitol, 6-O-β-D-gluco-pyranosyl-1-deoxynojirimycin from mulberry latex and leaves showed anti-diabetic activity through the same way as that of polyphenols. These compounds reduce alpha-amylase activity by interfering with the catalytic residues of its active site. This leads to the loss of ability of the enzyme to bind with the substrate responsible for glucose digestion [12]. Carotenoids work basically on insulin sensitization through PPARγ expression. The antioxidant property of carotenoids also influences diabetic activity as radical production and oxidative stress influences insulin secretion and resistance to the hormone [13]. AMP-activated protein kinase (AMPK) plays a vital role in the regulation of glucose metabolism. Quercetin and glycosides increase the phosphorylation of AMPK, which significantly elevates the translocation of glucose transporter (GLUT4) that spikes glucose uptake in muscle and adipose tissues [12]. The main mechanism of the hypoglycemic effect of flavonoids is *via* the binding to peroxisome proliferator-activated receptor gamma (PPARγ) and glucose transporter 1 (GLUT1) receptors stimulating lipid metabolism/, glucose uptake, increased insulin action on glucose utilization, and improved glucose tolerance in diabetic animals and humans [14].

NUTRITIONAL, PHYTOCHEMICAL COMPOSITION AND ANTI-DIABETIC POTENTIAL OF VARIOUS FRUIT WASTES

Fruits like jamun, mango, pomegranate, etc. have been shown to have an impact on the management of diabetes. However, recently, it has been concluded in studies that even the waste generated from these fruits has an impact on diabetic regulation. Fruit waste having anti-diabetic properties is discussed in this section.

Mango (Mangifera indica)

Mango, which belongs to the family *Anacardiaceae* and order *Sapindales*, is a tropical stone fruit. With over 1000 varieties, it is grown in over 87 countries and covers over 3.7 million hectares globally [15]. After China, India is the topmost producer of mangoes. During the period 2015-2016, India's mango cultivation covered approximately 2.22 million hectares, resulting in a production of approximately 20 million tons and an average productivity of 8.8 tons per hectare [16]. The three primary parts of a mango are the pulp, skin, and kernel. The pulp contains aromatic compounds, sugars (reducing and non-reducing), amino acids, and other components, including vitamins, minerals, anthocyanins, polyphenols, soluble and insoluble fibers, etc. During mango processing, edible portions are taken, and peels and kernels are often thrown away. These by-products are regarded as bio-wastes with nutraceutical value, indicating their potential use beyond simple disposal [17].

The proximate composition of all byproducts of mango is provided in Table 1. Mango leaves also contain several phytochemicals, like polyphenols, terpenoids, carbohydrates, sterols, carotenoids, vitamins, fatty acids, and amino acids. Phenolic compounds like tannins, terpenoids, phenolic acids, xanthones, benzophenones, and flavonoids are especially prevalent among the peel and kernels [18]. The major phytochemicals in the leaves of mangoes are mangiferin, iriflophenone 3-C-β-glucoside, epicatechin, rhamnetin, catechin, gallic acid (2.98 ppm), chlorogenic acid (3.79 ppm), quercetin (1.08 ppm), m-coumaric acid (0.18 ppm), ferulic acid (2.63), and benzoic acid (1.67 ppm) [19]. In a study, when Egyptian mango seeds were subjected to high-resolution liquid chromatography (HPLC) examination, the presence of various phenolic compounds and acids, like mangiferin, quercetin, gallic acid, and caffeic acid, was observed. Vanillin and tannins were discovered in high quantities, with tannin being the most prevalent at 20.7% [20].

Table 1. Proximate analysis of common fruit waste

S. No	Fruit	Parts	Carbo-hydrate (%)	Protein (%)	Fat (%)	Fiber (%)	Moisture (%)	Ash (%)	Ref.
1	Mango	Peel	80.70	3.60	2.20	8.40	10.50	3.00	[17]
		Seed	43.31	2.62	2.76	24.75	50.03	1.29	[24]
2	Pomegranate	Peel	64.84	7.80	1.20	19	69.70	5.60	[26]
		Leaves	19.60	11.60	0.96	-	6.50	4.90	[27]
3	Orange	Peel	40.47	16.40%	14.35%	12.47	10.00%	5.51%	[28]
4	Mulberry	Leaves	13.43	9.96	1.51	---	76.68	5.33	[29]
		Pomace	62.8	---	4.90	1.58	14.4	---	[30]
5	Avocado	Seed	48.21	19.94	15.73	4.10	13.27	0.92	[31]
6	Jamun	Seed	21.90	6.40	4.53	16.40	53	1.50	[32]
		Peel	15.35	0.12	0.80	----	79	0.91	[33]
7	Banana	Peel	50.5	5.3	1.60	19.2	6.70	8.8	[34]
8	Watermelon	Peel	32.16	12.42	12.61	26.31	6.44	5.03	[35]
		Seed	32.16	17.75	27.83	43.28	8.50	3.00	[36]
9	Guava	Seed	3.08	11.19	13.93	63.94	6.68	1.18	[37]

Table 2. Major bioactive compounds that exhibit anti-diabetic property in fruits waste

S. No	Fruit	Part	Bioactive compound	Ref.
1	Mango	Leaves	Mangiferin, Iriflophenone 3-C-β-D-glucoside, Quercetin	[38,19, 12]
		Peel	Chlorogenic acid, Mangiferin, Gallic acid, Kaempferol,	17 ,24,39]
		Seed	Gallic acid, Caffeic acid, Chlorogenic acid and Tannic acid	[17,40]
2	Pomegranate	Peel	Catechins, Sterols, Gallic acid, Rutin, Flavanols, Punicalagins,Quercetin, Flavones, and Anthocyanidins	[41-44]
		Leaves	Tannins, Flavones Glycosides like Apigenin and Luteolin	[44,45]
3	Banana	Peel	Phytosterols, Hydroxycinnamic acids, Flavonoids, Lutein, Isolutien, Alpha & Beta carotene, Violaxanthin, Auroxanthin, Neoxanthin, Beta-Cryptoxanthin, Anthocyanins, & Phytochemical.	[46-49]
4	Orange	Peel	Saponin, Flavonoid, Resins, Terpenes, Cardiac glycosides, Hesperidin,Naringin, Neohesperidin, tangeretin, Sinensetin and Narirutin	[50-51]
5	Mulberry	Leaves	1- Deoxynojirimycin, Quercetin, Kaempferol, Glutamine, Lactic acid,Pyruvic acid, Oxalic acid, 5-methoxy tryptamine, Alanine, Gallic acid,Valine, Chlorogenic acid, D-galacturonic acid, Tricetin, Moracin C and α-Glucosidase inhibitors	[52,53]
		Pomace	Cyanidin-3-O-glucoside, Cyanidin-3- rutinoside and Anthocyanin	[54]
6	Avocado	leaves	Tannins, Quercetin-3-Glucoside, Saponins, Triterpenoids	[55]

		Seed	Phenols, Alkaloid, Flavonoids and Saponins, Phytosterols	[56]
7	Jamun	Seed	Gallic acid, Quercetin, Ellagic acid, Flavonoids, Anthocyanin,catechins	[57-58]
		Peel	Gallic acid, Tannins, and Anthocyanin	[59]
8	Watermelon	Seed	Reducing sugar, Flavonoids, Anthraquinones, Alkaloids, Tannins,Terpenoids.	[60]
		Peel	Alkaloids, Saponin, Cardiac glycosides, Flavonoids	[61]
9	Guava	Seed	Phenolic compounds, Carotenoids, Ascorbic acid, and Tocopherol	[62]

Table 3. Overview of the anti-diabetic potential of fruit waste through animal model supplementation studies

S. No	Fruit Part	Compound	Experimental animal	Dosage	Inference	Ref.
1	Mango					
	Peel	Mangiferin	Alloxan induced diabetic rats weighing 100-150 g	Group I: Control Group II: Alloxan+ Extract treatment (200 mg/kg body weight for 21 days) Group III: Alloxan + Mangiferin (20 mg/kg body weight for 21 days orally)	Lower weight gain and more effective reduction in plasma glucose levels in Group II.	[25]
	Seed	Mangiferin, gallic acid, quercetin	Streptozotocin induced diabetic rat	Treatment with mango kernel extract (250 mg, 500mg, and 1000 mg/Kg body weight)	Reduced fasting glucose levels, total cholesterol, and LDL improved β pancreatic function.	[105]
2	Pomegranate					
	Peel	Punicalin, Punicalagin	*In silico* approach	Punicalin, Punicalagin, and ellagic acid were docked against 9 protein targets important for protein metabolism- GFAT, PTP1β, PPAR-γ, TKIR, RBP4, α-amylase, α-glucosidase, GCK, and AQP-2.	All three compounds exhibited significant binding scores.	[106]
	Rind and seed	Punicic acid	Alloxan-induced diabetic rat	Subcutaneous injection of peel and rind ethanolic extract	Reduction in blood glucose levels (p=0.0295), cholesterol, and triglycerides.	[107]
3	Banana peel		Oral administration to alloxan-induced diabetic rat	Dosages of 100, 200, and 400 mg/kg/day administered orally for 21 days in different groups	Decreasing plasma glucose by utilization of peripheral glucose and by boosting liver glycogen synthesis	[45]
4	Orange					
	Peel	Saponin, Flavonoid, Terpenes, Cardiac glycosides and terpenes	Male albino Wistar rats	Group I- control Group II-10% peel (w/w) Group III- corn oil (20% w/w, 8 weeks) Group IV- corn oil 20% for 8 weeks; followed by 10% orange peel remedial diet for 4 weeks Group V- 20% Corn oil and	Protective effect of the liver for group IV and V diets	[108]

				10% orange peel remedial diet for 12 weeks followed by histological examination		
5	Mulberry					
	Pomace	Cyanidin, ,4,6-trihydroxybenzaldehyde, and taxifolin	*Caenor habditis elegans* used as model system	-	Reduction in glucose content and ROS. Extract led to activation of DAF-16/FOXO and SKN-1/Nrf2	[109]
6	Jamun					
	Seeds	Gallic acid, quercetin, ellagic acid, flavonoids, anthocyanin, catechins	Hydroethanolic seed extract in a Wistar rat model	100, 200, or 400 mg/kg of ethanolic extract from jamun seeds	Reduction in blood glucose, increase in pancreas weight, improved beta cell function, and reduced insulin resistance	[88]
7	Avocado					
	Leaves	Flavonoids, tannins, quercetin-3-glucoside, saponins	Alloxan monohydrate-induced diabetes mellitus	100-200 mg/kg body weight of aqueous extract	BGL reduction in a dose-dependent manner leads to a 60% reduction in blood glucose after the first dosage	[55]
	Seed	Luteolin, Myricetin	Alloxan-induced diabetes mellitus	36 male rats into 6 groups and treated for 4 days	Significant decrease in blood glucose, and triglyceride. Improved pancreatic function, Activation of P13K/Akt pathway, and inhibition of β cell death	[110]
8	Watermelon					
	Seed	Catechin, Spartein, Lunamarin, Quinine	83 rats with a weight of 125-200 g	Diabetic rats were treated with a dosage of 100-600 mg/Kg of the extract for 21 days.	Reduced anti-diabetic effect	[111]
	Peel	alkaloids, saponin, cardiac glycosides, flavonoids and phenols	Streptozocin-induced diabetic rats	Watermelon rind extract (250-1000 mg/Kg) for 8 days	Blood sugar and triglyceride reduction	[112]
9	Guava					
	Seed	Polyphenols, flavonoids, saponins	Albino rats weighing approx. 190 g	Concentration of 200 and 250 mg/kg/bw fed orally with basal diet	Improvement in blood glucose and lipid profile	[113]

All these phytochemicals have pharmacological properties like anti-inflammatory, anticarcinogenic, antimicrobial, antioxidant, antidiabetic, etc. Several researchers have investigated the hypoglycemic properties of *Mangifera indica* (mango) leaves and seed kernel extracts. In diabetic rats and mice, the extracts drastically helped in lowering the fasting blood glucose and serum cholesterol. Long-term dosages of these extracts stabilized the glucose levels in diabetic rats; however, single oral doses had strong hypoglycemic effects in type 2 diabetic rats. The extracts also show antihyperglycemic properties in several diabetes model animals [21]. Mangiferin is found to regulate a key enzyme in gluconeogenesis, i.e., fructose-1,6-bisphosphatase. This regulation leads to a decline in glucose synthesis in the liver and thereby helps in controlling blood glucose [2].

From a study, the levels of yeast α-glucosidase were inhibited by mango leaf extract in a dose-dependent manner, wherein IC50 values were found to be 0.0503 and 0.5813 mg/ml, respectively [22].

During the *in vitro* diabetic property analysis of mango peel extract, significant antidiabetic properties were found effectively by inhibiting pancreatic enzymes. Strong potential in maintaining the levels of blood glucose was shown for the dose-dependent inhibition, with IC50 values of 4 μg/ml for α-amylase and 3.5 μg/ml for α-glucosidase. Most importantly, IC50 values of peel exhibited higher efficiency against glucosidase compared to α-amylase and were notably lower than those reported for other plant extracts [23].

In another study conducted by Lasasno *et al*. on mango peels and seed kernels, kernels exhibited a high inhibitory effect against α-amylase and α-glucosidase. Compounds like mangiferin, naringenin, and isovitexin in the peel, as well as beta-glucogallin, theogallin, and 2-hydroxy-3,4-dimethoxybenzoic acid in the seed kernel, were detected in LC-MS analysis. Both portions of the fruit are strong in minerals, vitamins, and fiber, indicating their potential as functional additives in the food sector due to their significant anti-diabetic qualities. Mango peels are also a rich source of crude fiber (8.4%) and carotenoids, both of which have been reported to improve insulin function and metabolic profile and regulate blood glucose [24].

In Table 3, we have displayed the three groups of alloxan-induced diabetic rats (weighing 100-150 g) that were taken for a study: Group I (Control), Group II (alloxan + extract therapy at 200 mg/kg body weight for 21 days), and Group III (alloxan + mangiferin at 20 mg/kg body weight for 21 days orally). A weight gain of 8.81% in Group I and 3.3% in Group II was observed. There was a drastic decrease in plasma glucose from 310.5 to 88.5 mg/dL in Group II and from 310.5 to 91.16 mg/dL in Group III. The LD50 of mango peel extract was greater than 2000 mg/kg body weight, whereas the LD50 of mangiferin was 300 mg/kg when ingested orally. Additionally, lipid profile improvements were observed [25].

Pomegranate (Punica granatum)

Punica granatum, commonly called pomegranate, belongs to the family *Punicaceae* and is mostly found in Iran, which is thought to be its major source of origin [63]. The production of pomegranate juice creates large byproducts, such as peels and seeds, which provide disposal issues and contribute to waste management issues. Pomegranate peels account for around 24% of the total fruit weight [64]. The proximate composition of dried pomegranate peel is presented in Table 1. Pomegranate peel is also rich in phytochemicals and contains catechins, sterols, gallic acid, rutin, flavonols, quercetin, fatty acids, punicalagin, quercetin, flavones, and anthocyanidins (Table 2). The anti-diabetic effect of the fruit extract that includes bioactive compounds like ellagic acid deoxy hexoside, cyanidin-3-O-glucose, and vanillic acid derivatives was investigated using the albino mouse of type 2 diabetes induced by streptozotocin (STZ). The anti-diabetic activity of the extract was shown by STZ injection significantly increasing serum glucose levels, consistent with previous findings, which can be attributed to its high phenolic content. The extract's efficacy is associated with compounds such as valoneic acid dilactone (VAD) and flavonoids, which play a key role in diabetes management [65].

The peel extract of pomegranate also shows superior inhibition of α-glucosidase, an enzyme responsible for digesting dietary carbohydrates due to the presence of saponins, known for their impact on diabetic complications and hypoglycemic effects through mechanisms such as insulin response restoration and α-glucosidase activity inhibition. Additionally, phenols and flavonoids present in the extracts contribute to their significant α-glucosidase inhibition, highlighting the therapeutic potential of pomegranate peels for managing diabetes [66].

Orange (Citrus sinensis)

Orange is from the family *Rutaceae* and is majorly cultivated in tropical and subtropical climates, with a global production of 120 million tons. According to statistics for 2021, citrus fruits are the second major fruit cultivated globally, totaling 161.8 million tons and covering an area of more than 10.2 million hectares. Oranges, a predominant citrus variety, accounted for the majority, with a production of 75.57 million tons, representing 46.7% of the total citrus fruit produced, from an area of 9.93 million hectares [67].

The orange waste consists mainly of three different portions: flavedo or exterior peel, albedo or interior peel, internal tissue, and seeds, in which peels contribute to the largest portion of the waste, which is 40-45%. However, the portion of the peel is abundant in polysaccharides such as cellulose, hemicellulose, and pectin [68]. The proximate composition of orange peel is presented in Table 1. Compounds identified from the orange peel that possess anti-diabetic potential include neohesperidin, hesperidin, narirutin, naringin, sinensetin, tangeretin, and other flavonoids and phenolics [69] (Table 2). The flavonoids, like hesperidin and naringin, decrease the activities of glucose-6-phosphate and phosphoenol pyruvate.

One of the mechanisms involved in anti-diabetic properties is the inhibition of peroxidation that reduces the activity of the α-amylase enzyme. This enzyme is responsible for converting complex carbohydrates to glucose, increasing hepatic glycogen content, stimulating insulin secretion, and repairing secretory defects in pancreatic β-cells [70]. In the study conducted by Ahmed *et al.* (2017), anti-hyperglycemic, anti-hyperlipidemic, and antioxidant effects of orange peels were observed. Rats were induced to have type 2 diabetes by nicotinamide/streptozotocin (STZ). They were then treated orally with peel extracts and flavonoids for antioxidant treatment, effectively improving various diabetic markers in the diseased rats. The treatments improved insulin production, restored liver glycogen content, normalized liver enzyme activities, improved lipid profiles, and enhanced antioxidant defense mechanisms. It was also observed that administration of the extract increased mRNA expression of insulin receptor β-subunit, GLUT4, and adiponectin in adipose tissue. Overall, the extract and flavonoids exhibited potent antidiabetic effects by enhancing insulin action and improving insulin signaling pathways in adipose tissue [71] (Table 3).

Mulberry (Morus Alba L).

Mulberry comes from the family *Moraceae*, which is commonly found in Asia. They are not only used for culinary purposes but also have great recognition for their medicinal properties. These contain different nutrients and bioactive compounds such as anthocyanins, rutin, quercetin, and chlorogenic acid, which have proven bioactive properties. The fruits are sorosis. The color of the immature fruits is generally green, and as the fruit matures, it turns to violet and black [72].

Mulberry leaves are used for the treatment of hypertension and diabetic individuals who are obese [73]. The moisture content of fresh leaves ranged from 71.1 to 77% approximately, crude protein ranged from 4.7 to 10%, and crude fat was found in the range of 0.6 to 1.5%. Ash content was observed to be in the range of 4.2 to 5.3%, and carbohydrates ranged from 8.0 to 13% [30, 74] (Table 1). Mulberry pomace is the remaining mass left after juice extraction, and it corresponds to approximately forty percent of the whole weight of the fruit. Mulberry fruit has an essential amino acid score of 100 or higher, making it an excellent nutritional product and a significant source of minerals and vitamins, according to the World Health Organization (WHO) [75]. Fresh mulberry fruit contains a larger amount of protein than raspberries and strawberries and is almost equivalent to blackberries. Furthermore, its anthocyanin concentration exceeds that of blackberry, blueberry, blackcurrant, and redcurrant. Furthermore, *M. alba* fruit includes both necessary and non-essential amino acids [76].

Mulberry pomace is obtained by pressing mulberry biomass. It contains trace amounts of minerals like sodium, potassium, nickel, etc., which act as a substrate for citric acid production [77]. Mulberry leaves are found to have iminosugar alkaloids, especially 1-deoxynojirimycin (DNJ), which inhibits mammalian glucosidase enzymes. The concentration of DNJ varies amongst mulberry types. Chemical analysis reveals a variety of antioxidative substances, including phenolic acids (e.g., caffeic, gallic) and flavonol compounds (e.g., rutin, isoquercitrin). Mulberry leaves have high quantities of total phenolics and flavonoids, according to quantitative analysis [78].

A study investigated the hypoglycemic effects of mulberry leaf extract and mulberry leaf polysaccharides against an alkaloid called Ramulus Mori in mice having type 2 diabetes (Table 3). Morusin, kuwanon C, and morus Yunnan in mulberry leaf extracts act as potential agents accountable for hypoglycemic activity. The study showed that both the leaf extract and polysaccharide helped treat diabetes in mice [79]. The flavonoid quercetin and the alkaloid 1-deoxywildixamycin (DNJ) are also found to have a major role in the anti-diabetic properties of mulberry leaves [80], Table 2.

Mulberry marc extract (MMA) was administered to diabetic rats that had been induced with streptozotocin for a period of 4 weeks. And it's been shown that the treatment significantly reduced the blood glucose level. Decreased oxidative stress led to a lowering of insulin resistance (Fig. 2) [81]. Another observation made from the study is that the content of anthocyanin in mulberry marc is much higher than in the juice, which can be the probable reason for its high anti-diabetic potential [81].

Avocado (Persea Americana)

Avocado is a member of the *Lauraceae* family of plants and is found in tropical regions including Nigeria. Avocados are generally green to yellow in color and have a single large seed. The edible portion of the fruit comprises 50-80% of the total fruit weight [82]. Avocados are rich sources of mono- and polyunsaturated fatty acids, vitamins and minerals [83]. Proximate analysis of seeds showed moisture content ranging from 8.6% to 34.28%, fat content ranging from 0.33% to 16.54%, fiber content ranging from 2.87% to 26.33%, ash content varying between 2.40% and 3.82%, with some samples showing higher mineral content.

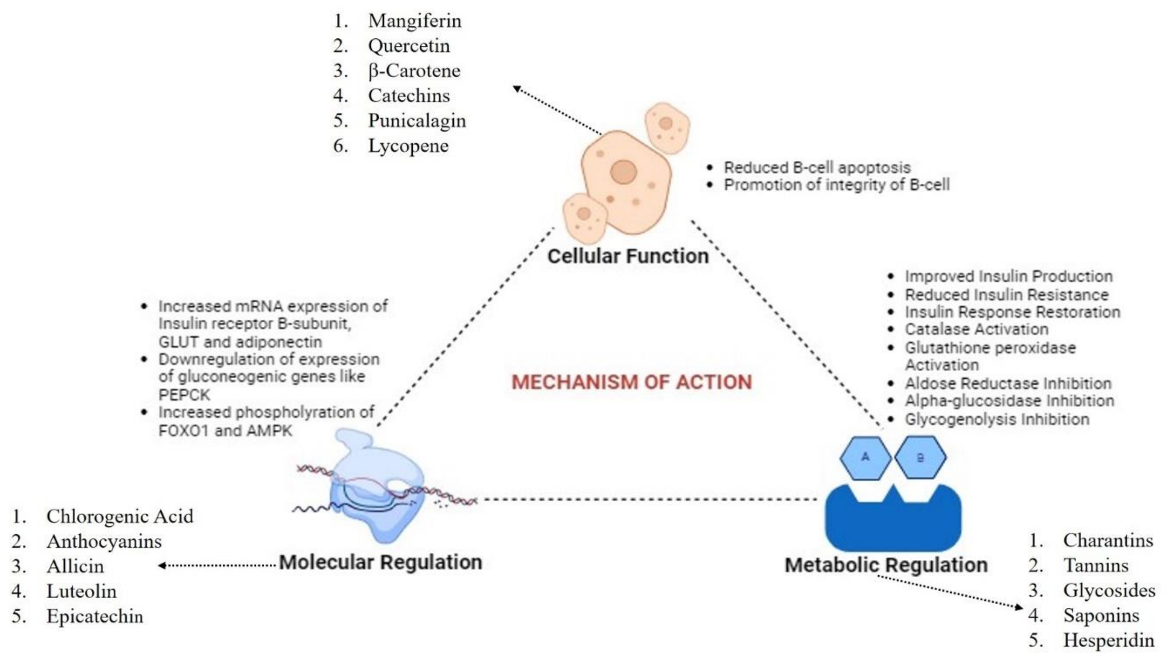

Fig. 2. Mechanism of action for blood glucose regulation exhibited by various phytochemicals extracted from fruit and vegetable waste.

Protein content ranged from 1.33% to 17.94%, and carbohydrate content from 7.75% to 44.70% demonstrating considerable variability in proximate composition among the different seed samples [84]. Avocado leaves, apart from being anti-diabetic in nature, are also well known for their antimicrobial, and anti-inflammatory properties. These consist of approximately 5% moisture, and 4% fat. They are rich in protein and fiber (25.54±2.52% and 38.40±5.12 %, respectively) (Table 1) [31]

Kouame *et al.* (2019) studied the effect of glucose regulation properties of avocado leaves extracted with methanol in type 2 diabetes rats. The study was conducted for a period of approximately 30 days and showed a reduction in intestinal glucose levels. The components that reduce the levels are saponins, polyphenols, notably flavonoids, etc. The mechanism of anti-diabetic action is either by reducing the rate of absorbing the glucose present in the intestine or by inhibiting the glycogenolysis mechanism. Another method mentioned is by promoting the integrity of beta-cells and enhancing the release of insulin [85].

Jamun/ Indian blackberry (Syzygium cumini)

Syzygium cumini belongs to the family *Myrtaceae* and is generally cultivated in the tropical and subtropical regions. Major countries producing jamun are Bangladesh, Pakistan, Nepal, Sri Lanka, Indonesia, Malaysia, India, South America, and Eastern Africa [86]. Jamun is a tree with silky smooth leaves, with shoots that may reach a height of 8 to 15 m. Its glossy, leathery leaves are opposite, obovate to oval or elliptical in shape. The dark purple fruit and seeds have precise measurements: the fruit is 31 mm long, 28.7 mm wide, and weighs 18.32 g; the seed is 18.20 mm long, 11.05 mm wide, and weighs 1.62 g [87]. Jamun seeds contain an abundance of nutrients such as dietary fibers, anthocyanins, chlorophyll, phytosterols, amino acids, vitamin C, and B-complex vitamins. They also include minerals (calcium, iron, salt, magnesium, zinc, phosphorus, chromium, vanadium, potassium), essential oils, albumin, and lipids. The fatty acid profile indicates the existence of several fatty acids, with β-sitosterol being the main phytosterol [88].

The proximate composition of jamun seeds varies as follows: moisture content ranges from 9.34% to 16.34%, carbohydrates constitute 31.62% to 41.4%, total dietary fibers range from 2.3% to 16.9%, crude fat content varies from 0.83% to 1.18%, and ash content is approximately 2.18%. The acidity level falls between 0.02 and 0.06 gm/L while the pH ranges from 3.79 to 4.83. The energy value is estimated at 335.64 Kcal, and total soluble solids (TSS) measure at 3.7 °Brix and crude protein content varies from 1.97% to 8.5% [89]. The proximate composition of jamun seed and peel is given in Table 1. The whole jamun fruit possesses significant quantities of antioxidants like flavonoids, phenolic acids, and anthocyanins. The seeds are rich in protein, fat, glycosides, alkaloids, ellagic acid, gallic acid, and minerals like zinc and chromium.

In a clinical trial, an aqueous ethanolic extract of jamun dried and powdered seeds was administered to Sprague-Dawley rats. The extract effectively halted hyperglycemia and reduced serum triglyceride and total cholesterol levels. This antidiabetic effect is attributed to the seed's ability to lower free radicals, enhance pancreatic beta-cell function, and activate enzymes like catalase and glutathione peroxidase [88]. Terpenoids, glycosides, saponins, flavonoids, phenols, etc., are some of the key constituents responsible for inhibiting glucose in jamun seeds. Extracts from jamun seeds, including gallic acid, valoneic acid dilactone, rubuphenol, and ellagic acid, inhibited aldose reductase (AR) with IC50 values of 0.77, 0.075, 0.165, and 0.12 μg/mL, respectively [88].

Banana (Musa acuminata)

Banana is the world's most productive fruit crop, producing 127.3 million tons. It is also the fourth most valuable agricultural product, worth USD 63.6 billion, after rice, wheat, and milk [90]. Banana is a member of the *Musaceae* family and is said to have evolved in the tropical areas of Southern Asia. These are grown as a food source and possess a high nutritional value [91]. Peel is one of the prominent wastes produced in large amounts from banana fruit and accounts for approximately 40% of the total fruit weight. Peels from ripened bananas have been analyzed to contain crude protein, soluble sugars, and total phenolic compounds (8%, 13.8%, and 4.8%, respectively). Major functional components extracted from banana peel include cellulose, hemicellulose, and pectin along with other low-molecular-weight compounds [92].

Banana peels are a major source of garbage in households, and they cause a foul odor because of the gases emitted by digestion in the absence of air. The peels are highly susceptible to microbial contamination and mechanical damage. The proximate composition of banana peel is given in Table 1. The peels contain high moisture and low lipid content [33]. The prevalence of phenolic substances like gallocatechin and anthocyanins like peonidin and malvidin in banana peel is also reported [93].

In a study it was found that the groups treated with banana peels had serum blood glucose levels ranging from 11.12 to 12.57 mmol/dl. The insulin treatment group showed similar results (11.25 ± 10.2 mMol/dl), supporting *Musa paradisiaca* peels' hypoglycemic effects [94]. In a similar study, different concentrations of dried banana peel (5%,10%, and 15%) and a control group with a basic diet were supplemented to diabetic Sprague-Dawley strain albino rats. It was found that diabetic rats (positive control) had significantly higher mean VLDL-C levels (41.33±3.51 mg/dl) compared to the negative control group (29.33±1.15 mg/dl). Adding dried banana peels at levels 1, 2, or 3 significantly decreased VLDL-C levels ($P<0.05$) in comparison to the positive control group. Interestingly, the group at level 5 had the lowest decrease, with a mean value of 33.66±5.68 mg/dl [95].

Watermelon (Citrullus lanatus)

Watermelon is a creeping herbaceous plant that originated in South Africa and belongs to the *Cucurbitaceae* family. The propagation of watermelon is done using seeds, and the growth is favorable towards warm temperatures (25°C). Only half of the fruit is eaten; the rest is in the form of seeds and rind. The seeds and peels of watermelon are the major waste generated. This section gives an account of the antidiabetic potential of watermelon waste [96].

Protein, vitamin B, many essential minerals like magnesium, potassium, phosphorus, and fat, as well as phytochemicals, are all abundant in watermelon seeds. Seeds are rich in protein, carbohydrates, fats, fiber, and ash (17.75%, 15.3%, 27.83%, 43.3%, and 3%, respectively) [35]. The interior regions of fruit peels, which are usually pale green or white, are edible and high in nutrients. The rind has been found to include alkaloids, saponins, cardiac glycosides, flavonoids, phenol, moisture, protein, fiber, and carbs. This emphasizes the nutritional benefits and various chemicals found in the inner peel layers [97]. Watermelon peels are high in protein, fat, ash, fiber, salt, potassium, calcium, copper, iron, magnesium, zinc, and phosphorus. Furthermore, the peels have considerable antioxidant characteristics, including free radical scavenging activity (IC50 of 147.30 mg/kg) and a high total phenolic content of 2.47 g/100 g. This shows that watermelon peels might be an excellent source of natural polyphenols, antioxidants, and minerals [98].

Clinical studies evaluated the anti-diabetic potential of watermelon seeds. A study was carried out on alloxan-induced diabetic rats to evaluate the hypoglycemic activity of watermelon seeds. The components in the seeds were extracted by using methanol. The results demonstrate that different concentrations of the seed extract lowered blood glucose levels by 57.9 mg, 66.4 mg, and 93 mg, respectively [99], Table 3. The methanolic extract of the peel was dissolved in dimethyl sulfoxide of various concentrations in an *in vitro* investigation of watermelon peel. In a Tris-HCl buffer (2 units/ml), porcine pancreatic-amylase was also added to the solution. This *in vitro* study suggested that watermelon peel extract imparts its anti-diabetic activity by inhibiting alpha-amylase activity, a carbohydrate-digesting enzyme [100].

Guava (Psidium guajava L.)

Guava is a member of the *Myrtaceae* family and belongs to the genus *Psidium*. It is a fruit that is largely grown in different regions of the world. After India and China, Brazil is the world's third-largest producer [101]. Guava is well known for its medicinal properties, especially related to the gastrointestinal tract. Recently it was found to have anti-inflammatory, anti-microbial, antispasmodic, and anti-viral properties in addition to antidiabetic properties [102]. The major byproducts obtained from the guava processing industry are seeds. Twelve percent of the total fruit weight is comprised of seeds [103]. Guava seeds contain nutraceuticals that have medicinal importance, like polyphenols, flavonoids, tannins, and saponins. Guava seed oil has a considerable amount of polyunsaturated fatty acids (especially linoleic acid), an adequate amount of monounsaturated fatty acids (mostly oleic acid), and a modest quantity of saturated fatty acids. Physicochemical parameters of oil imply stability, with low acid and peroxide levels. The oil is high in tocopherols and carotenoids, which contribute to its significant antioxidant activity of 58.90% [104] (Table 2).

NUTRITIONAL, PHYTOCHEMICAL COMPOSITION AND ANTIDIABETIC POTENTIAL OF VEGETABLE WASTE

Vegetable waste is rich in phytochemicals, carotenoids, and other components that contain antioxidant and anti-diabetic properties. This section deals with the anti-diabetic potential of vegetable waste. Also, other parameters like nutritional composition are discussed.

Lemon (Citrus limon)

Lemon (*Citrus limon*) is a member of the *Rutaceae* family. Citrus fruits have many phytochemicals and bioactive components like α-/β-pinene, sabinene, β-myrcene, d-limonene, linalool, α-humulene, and α-terpineol [114]. Lemon peel is a rich source of protein (9.42%). Apart from protein, it has a moderate amount of fat (4.98%), a high amount of ash (6.26%), and fiber (15.18) (Table 4). It is rich in macro and micronutrients like sodium (755.5 mg/100 g), potassium (8600 mg/100 g), calcium (8452.50 mg/100 g), iron (147.65 mg/100 g), magnesium (1429.50 mg/100 g), and phosphorus (6656.25 mg/100 g) [115]. In research on β-cell-specific toxin-induced diabetic rats, a methanolic extract of lemon peel was administered fortnightly, resulting in a substantial reduction in the glucose level of blood as compared to control groups. The study concluded that the presence of flavonoids like naringin and hesperidin is related to their antidiabetic properties [116].

Another study which contains groups that received low-dose and high-dose lemon peel extract (500 mg/kg BW), showed a reduction in glucose levels as compared to the control groups (Table 6.).

Table 4. Proximate analysis of vegetable waste

S. No	Vegetables	Parts	Carbohydrates %	Protein %	Fat %	Fiber %	Moisture %	Ash %	Ref.
1	Lemon	Peel	----	9.42	4.98	15.18	81.23	6.26	[118]
2	Potato	Peel	4.97	10.76	4.98	68.73	8.01	10.56	[119]
3	Drumstick	Seed	48.26	36	39	2.87	9.56	8.24	[120]
		Leaves	8.1	25.4	6.00	33.2	7.5	9.2	[121]
4	Red bell Pepper	Seed	3.35	14.1	6.66	32.4	88	2.06	[122]
5	Bottle gourd	Seed	8.30	35	39	59.05	17.5	5.08	[123]
6	Bitter gourd	Seed	51.29	14.30	11.50	20.5	8.50	2.9	[124]
7	Pumpkin	Seed	26.46	5.63	38	49.83	9.00	2.50	[125]
8	Coriander	Stem	---	12.58	9.12	37.0	6.2	8.53	[126]
9	Onion	Peel	80.60	3.90	3.20	26.84	91.05	11.46	[127]

Table 5. Major bio-active compounds that exhibit anti-diabetic property in vegetable waste

S. No	Vegetable Name	Part	Bioactive compounds	Ref.
1	Lemon	Peel	Hesperidin and naringin & flavonoids	[117]
2	Drumsticks	Seed	Glucomoringin, flavonoids, catechin Chlorogenic acid, quercetin, kaempferol, gallic acid, ellagic acid and ferulic acid	[128-130]
		Leaves	Polyphenols, flavonoids, quercetin, chlorogenic acid and isothiocyanates	[131-133]
3	Red bell pepper	Seed	Sterols (Campesterol, Stigmasterol, β-Sitosterol), triterpenes (betulinic acid), tocopherols, luteolin, quercetin and capsaicin	[134,135]
4	Bottle gourd	Seed	Flavonoids, terpenoids	[123]
5	Bitter gourd	Seed	Hydroxycinnamic, quercetin	[136]
6	Coriander	Stem	Gallic acid	[137]
7	Pumpkin	Seed	Flavonoids, tannins, phenolic and saponins.	[138]
8	Potato	Peel	Polyphenols (caffeic acid and gallic acid), flavonoids (chlorogenic acid, quercetin)	[139]
9	Onion	Peel	Phenolic and flavonoids	[127]

Table 6. Overview of the anti-diabetic potential of animal waste through animal model supplementation studies

S. No	Vegetable part	Bioactive Compound	Experimental design	Dosage	Inference	Ref.
1	Potato peel	Polyphenols	Male Wistar rats were given streptozotocin to develop diabetes. Potato peel was shown in two different concentrations 5% and 10%	Six rat groups: control, 5% and 10% potato peel, STZ-treated, and STZ with 5% or 10% potato peel. Pellet diets with or without potato peel were given for 4 weeks.	Potato peel powder lowered blood glucose and reduced liver and kidney hypertrophy in diabetic rats.	[45, 173] [174]
2	Lemon peel	Polyphenols	Rats weighing 240–280 g were chosen for the study.	Animals were divided into four groups: control (normal and diabetic), low-dose, and high-dose lemon peel extract (500 mg/kg BW).	Low blood glucose observed for high lemon peel extract dosage	[117, 175]
3	Drumsticks					
	Seed	Glucomoringin, along with flavonoids	Adult albino rats having streptozotocin-induced diabetes	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated with moringa seed powder (50 and 100 mg/Kg body weight)	A dose-dependent relationship was observed between seed powder and glucose level.	[129, 176]
	Leaves	Polyphenols and flavonoids	Male Sprague-Dawley rats having streptozotocin-induced diabetes	Animals were divided into 5 groups- Control (Both diabetic and normal), and treated (glibenclamide- 2.5 mg/Kg body weight and moringa leaf extract 300 mg/day)	Notable drop in glucose levels for extract-treated animals	[147, 177]

4	Red bell pepper seed	Carotenoids, tocopherols, luteolin, quercetin and capsaicin	Male mice were divided into 4 groups each containing 4 mice.	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated (Red bell pepper seed extract- 200 mg/Kg body weight and metformin 150 mg/day)	Extract administration improved the glycaemic control biomarkers.	[151]
5	Bitter gourd seed	Triterpenoids, saponins, flavonoids, alkaloids	Alloxan-induced male Albino Wistar rats (120 mg/kg BW)	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated (glibenclamide- 0.07 mg/Kg body weight and bitter gourd seed extract 150 mg/day body weight) for 30 days.	The high anti-diabetic potential was observed for extract-treated animals.	[158]
6	Bottle gourd					
	Seed	Ascorbic acid, Carotenoids, Vitamin B-complex, Cucurbitacins, Flavone C-glycosides, Saponins	Six adult albino female rats having diabetes induced with alloxan (100 mg/kg BW) were chosen for the study.	Diabetic groups were treated with bottle gourd pulp extract (250mg/kg BW) and seed extract (250 mg/kg BW)	The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottle gourd seed extract.	[155]
7	Pumpkin seed	Hypoglycemic proteins and seed oils	Streptozotocin-induced adult male mice (55 mg/kg BW)	In total, five groups were made including Control (Normal and diabetic) and treated (Metformin - 65 mg/kg; Ethanolic pumpkin flesh extract -150 mg/kg and seed extract - 150 mg/kg)	The blood glucose levels reduced from 304.67 mg/dl to 74.33 mg/dl on the 14th day.	[162, 178]
8	Coriander stem	Antioxidants and Phenols	Alloxan-induced (150mg/kg BW) male and female Wistar Albino rats weighing 150–180 g were used.	Groups: Control (Normal, Diabetic), Treated (Glibenclamide 5 mg/kg/day, Coriander Leaf 150 mg/kg, Coriander Stem 200 mg/kg)	Group 4 showed hypoglycemic effects with a blood glucose level of 124.40 ± 1.66 mg/dL, while the positive control (Group 2) had 256.47 ± 1.61 mg/dL.	[166]
9	Onion					
	Peel	Quercetin and other total phenolic compounds	Overnight fasted Alloxan-induced Sprague Dawley rats (120mg/kg BW).	Groups: Control (Normal, Diabetic), Treated (1%, 3%, 5%, 7% OPE)	Reduction in blood glucose level for 3% OPE treated group	[172, 179]

The study examined four groups: normal and diabetic controls, along with treatment groups. Group 1 exhibited a noticeably elevated FBG level of 283 mg/dl. Continuing from thirty-five days of LP extract treatment markedly lowered blood glucose levels of rats with diabetes from 280 mg/dl to 180 mg/dl with a low dosage of lemon peel extract and from 277 mg/dl to 155 mg/dl with a high dosage of lemon peel extract [117].

Potato (Solanum tuberosum)

Potato is a member of the family *Solanaceae*, and it has been marked as the fourth in the world's most utilized food crop after rice, wheat, and maize [140]. The major producers of potatoes in the world are China, followed by India and Russia, with an annual production of 88, 45, and 30 million tons, respectively. During processing, 15 to 40% of waste is generated as potato peel, which can be beneficial in many ways [141].

Potato peels contain much more protein, fiber, ash, and minerals (except magnesium) than the flesh of the tuber. Amongst microminerals, potassium is the most abundant element in both portions of the potato tuber, followed by P, Mg, Ca, Fe, Zn, B, Mn, and Cu [142]. The proximate composition of potato peel is given in Table 4. Some of the phenolic acids present in potato peel are caffeic acid, protocatechuic, gallic acid, chlorogenic acid, vanillic acid, ferulic, and salicylic acid. Major flavonoids isolated from potato peel include quercetin, catechin, epicatechin, and naringenin. Among these, chlorogenic acid, quercetin, gallic, and caffeic acid have potential antidiabetic properties [143] (Table 5).

An *in vitro* study suggests that the potato peel possesses potent antioxidant properties, making it suitable for use in functional or healthy foods to mitigate oxidative stress, which has been identified as a major contributor to the pathophysiology of diabetes mellitus. In β-cell-specific toxin-induced diabetic rats, potato peel has been shown to impact both antioxidant status and glycemic index. A four-week diet supplemented with potato peel powder lowered the levels of the blood of infected rats. The aqueous extract of potato peel contained 3.93 mg/g of polyphenolics on a dry weight basis [144].

Another study, which contained 6 groups of male Wistar rats that were induced with diabetes using streptozotocin (STZ), showed a significant reduction in blood glucose levels. It had a control group, two groups receiving 5% or 10% potato peel, an STZ-treated group, and two groups treated with STZ along with either 5% or 10% potato peel. The treatment was administered through pellet diets over four weeks. It showed a significant reduction in blood glucose levels in rats that were fed with potato peel powder. Additionally, the treatment helped reduce liver and kidney hypertrophy in diabetic rats, indicating its potential protective effects. [145] (Table 6).

Drumstick (Moringa oleifera)

Drumstick is a member of the family *Moringaceae;* it has white, sweet, scented flowers, and it's very commonly found all over India. Moringa trees have remarkable nutritional value and medicinal properties [146]. Many phenolic compounds like lignans, flavonoids, and phenolic acids are present in the moringa plant. Medioresinol, quercetin, and caffeoylquinic acid derivatives are also present in moringa plant. Research has shown that moringa leaves can cure Type 1 and Type II diabetes [133].

The proximate analysis of *Moringa oleifera* leaves showed high protein content and low levels of fat, fiber, and ash. They also contained significant amounts of vitamin C, calcium, phosphorus, and potassium. Functional properties like water absorption capacity and foam stability were observed [121]. A study conducted on male Sprague-Dawley rats with streptozotocin-induced diabetes showed that the leaf extract resulted in a significant hypoglycemic effect, with fasting blood glucose levels decreasing from 236.8 ± 62.84 mg/dL to 171.8 ± 52.69 mg/dL by day 14, representing a 26% reduction. Groups in total for this study were 5: normal and diabetic controls, along with treatment groups receiving glibenclamide (2.5 mg/kg BW) and moringa leaf extract (300 mg/day) [147].

Few studies have established anti-diabetic effects of moringa seed powder in animal models, especially in streptozotocin or alloxan-induced diabetic rats. Animals were divided into 4 groups—control (both diabetic and normal) and treated with moringa seed powder (50 and 100 mg/kg body weight). The fasting blood glucose levels in animals fed with moringa seed powder (5%) were recorded at 174.17 mg/dl, while in Group 4, they were measured at 148.83 mg/dl. A dose-dependent relationship was observed [129]. Quercetin is reported to impart a hypoglycemic effect and is found to inhibit α-glucosidase activity. Similarly, when β-cell-specific toxin-induced diabetic male albino rats were administered an aqueous extract of drumstick seed, the sugar levels in blood were considerably lower in all groups in comparison to the control group. In addition, it was also found in the study that after drumstick seed extract administration, the levels of creatinine, urea, and albumin were also controlled and were effective against diabetic nephropathy [148].

Red bell pepper (Capsicum annuum L)

Red bell pepper belongs to the family *Solanaceae*. *Capsicum annuum* fruits contain a complex chemical makeup that includes capsaicinoids such as capsaicin and dihydrocapsaicin, which are responsible for their intense flavor. Leaves include alkaloids, tannins, and flavonoids, whereas roots contain steroids, alkaloids, coumarins, glycosides, and triterpenoids [149]. The extract of pepper shows the potential of decreasing postprandial hyperglycemia by delaying the production or absorption of glucose, and it has also been linked to the antioxidant property too [150].

In a study, male mice were divided into 4 groups, each containing 4 mice, and animals were divided into 4 groups: control (both diabetic and normal) and treated (red bell pepper seed extract—200 mg/kg body weight and metformin—150 mg/day). Group 3 fasting glucose was 429 mg/dl, whereas Group 2's fasting glucose was 544 mg/dl. Red pepper seed extract supplementation improved glycemic control, including regulation of insulin levels. The extract downregulated the gene expression of genes PEPCK and GP6Pase. These are involved in gluconeogenesis. This anti-diabetic effect was attributed to increased phosphorylation of transcription factors. Overall, RPSE shows promise in improving the control of glycemic index by inhibiting glucose formation in the liver in ObD mice [151].

Bottle gourd (Lagenaria siceraria)

Bottle gourd is a member of the *Cucurbitaceae* family and has huge applications in pharmaceutical and dietary developments [152]. The fruit is very rich in vitamin C; it also includes sterols, terpenoids, and flavonoids that have high medicinal properties [153]. The bottle gourd extracts inhibited alpha-amylase with an IC50 of 1.35 mg/mL, which is equivalent to that of the Acarbose (IC50-1.26 mg/mL). The study on the anti-diabetic potential of bottle gourd stalk showed that the aqueous extract has a strong inhibition capacity on α-amylase with an IC50 value of 1.35 mg/mL. This was higher than the inhibition observed for the antidiabetic drug Acarbose (IC50-1.26 mg/mL) [154].

In another study, six adult albino female rats with diabetes induced by alloxan (100 mg/kg BW) were chosen. Diabetic groups were treated with bottle gourd pulp extract (250 mg/kg BW) and seed extract (250 mg/kg BW). The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottled gourd seed extract [155].

Bitter gourd (Momordica charantia)

Bitter gourds are vegetables that have been researched most for their health-benefiting properties. They contain triterpenes, phenols, flavonoids, isoflavones, terpenes, anthraquinones, and glucosinolates, all of which contribute to their peculiar bitter flavor. Major anti-hyperglycemic activity in bitter gourd is reported to come from charantins, insulin-like peptides, and alkaloids [156]. The fruit is rich in both fat-soluble and water-soluble vitamins and a variety of B vitamins, including B1, B2, B3, and B9 (folate) [156] (Table 5). Bitter gourd seeds contain polypeptide K and include nine necessary amino acids, with glutamic acid, aspartic acid, arginine, and glycine being the most prevalent. Stearic acid was found in abundance in the seed oil, as well as oleic and linoleic acids. Polypeptide K and seed oil inhibited pancreatic enzymes responsible for glucose absorption in vitro, which shows the capacity as hypoglycemic drugs [157]. Six adult albino female rats with diabetes induced by alloxan (100 mg/kg BW) were chosen for the study. Diabetic groups were treated with bottle gourd pulp extract (250 mg/kg BW) and seed extract (250 mg/kg BW). The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottled gourd seed extract [158].

Pumpkin (Cucurbita maxima)

Pumpkins belong to the family *Cucurbitaceae.* They cannot tolerate heat but contain plenty of beneficial components such as carotenoids, alkaloids, flavonoids, polyphenols, tannins, tocopherols, phytosterols, and cucurbitacin. These components have many therapeutic properties that also include the regulation of diabetes [159]. Pumpkin fruit contains vitamins niacin, phylloquinone, thiamine, riboflavin, and minerals including potassium, phosphorus, magnesium, iron, and selenium [160] (Table 5). Pumpkin seeds contain polysaccharides that improve insulin signaling, activate critical pathways, and reduce β-cell malfunction. These polysaccharides have significant anti-diabetic properties by controlling blood glucose in diabetic rats [3]. The bioactive compounds in pumpkin seeds, such as flavonoids, triterpenoids, and polysaccharides, contribute to their hypoglycemic effects by interfering with various methods in diabetes mellitus. Additionally, pumpkin seed polysaccharides and proteins have been implicated in lowering blood glucose levels. The presence of pectin, a dietary fiber, in pumpkin seeds regulates blood glycemic levels, making them beneficial for diabetic patients [161].

Diabetes was induced in male and female Wistar albino rats (150-180 g) using alloxan (150 mg/kg BW). In total, five groups were made, including control (normal and diabetic) and treated (metformin—65 mg/kg; ethanolic pumpkin flesh extract—150 mg/kg; and seed extract—150 mg/kg). The study reveals the very high anti-diabetic potential of pumpkin seed extract. The blood glucose levels were reduced from 304.67 mg/dl to 74.33 mg/dl on the 14th day [162] (Table 6).

Coriander (Coriandrum sativum)

Coriander is an annual plant in the *Umbelliferae* family that is valued for its spice, fragrance, nutritional, and medicinal qualities [163]. Coriander is regarded for its therapeutic characteristics, which include antibacterial, antifungal, and antioxidant activity, as well as its digestive effects. Coriander's phenolic chemicals have been found and investigated across the entire plant, including vegetative portions, leaves, stems, and seeds [164]. It contains 18% protein, 6.86% fat, 34.7% fiber, 2.77% moisture, and 9.83% ash (Table 4). Antioxidant and free radical scavenging properties are attributed to polyphenols, ascorbates, and flavonoids. The antidiabetic potential of coriander stem extracts is responsible for the overall oxygen scavenging activity and phenolic content, indicating that coriander stem is a valuable source of natural antioxidants with health-protective properties [163].

Evaluation of the anti-diabetic properties of coriander leaf extract showed significant results in insulin-deficient mice induced by alloxan. The leaf extract regulated the levels of blood sugar, and further study showed that it also maintained the β cell levels of the islets of the pancreas. In the in vitro study, coriander leaf extract demonstrated an IC50 value of 32.376 ppm for inhibiting α-glucosidase activity, compared to 82.272 ppm for acarbose, the standard drug [165].

Diabetes was developed in male and female Wistar Albino rats that weigh between 150 and 180 grams by using alloxan (150 mg/kg BW). There were 5 groups for the study: normal and diabetic controls, as well as treatment groups given glibenclamide (5 mg/kg/day), coriander leaf extract (150 mg/kg), and coriander stem extract (200 mg/kg). The results show that the coriander stem extract has hypoglycemic properties, as evidenced by the blood glucose level of 124.40±1.66 mg/dl. (group 4), while group 2's positive control group's glucose level is 256.47±1.61 mg/dl [166] (Table 6).

Onion (Allium cepa L.)

Onion is a member of the family *Amaryllidaceae*, and it is the second most-grown vegetable globally [167]. Onions, which have been known for their therapeutic virtues from ancient times, have been historically used to cure a variety of diseases. Experimental studies show that they have a variety of pharmacological actions, including lowering cholesterol, preventing platelet aggregation, and acting as a neuroprotective and anti-carcinogenic drug. Onions have anti-inflammatory qualities, activate the immune system, and have been shown to help prevent osteoporosis [168]. Onions contain a wide range of phytochemicals, which include sulfur-containing organic compounds, compounds that have phenol groups, etc. [169].

Peels are the major waste from onions. The nutritional content of onion peels is presented in Table 4. Apart from its good nutritional value, it is a rich source of polyphenols, including anthocyanins. The hypoglycemic effect of onion peels was observed in the administration of onion peel extract in different concentrations [170]. Onion peel extracts exhibited inhibitory activity against tyrosine phosphatase, alpha-glucosidase, xanthine oxidase, and alpha-amylase [171].

A study included seven groups of overnight fasting Sprague Dawley rats that have been supplied with alloxan (120 mg/kg BW) to develop diabetes. The groups were normal and diabetic controls, as well as treatment groups that received 1%, 3%, 5%, or 7% onion peel extract (OPE). From day 0 to day 56, the 3% OPE group had the greatest reduction in blood sugar levels, going from 289 mg/dL to 205 mg/dL, respectively, among all. This final blood sugar level was significantly lower than in the 1% OPE (234 mg/dL) and 7% OP (230 mg/dL) groups [172].

UTILIZATION OF FRUIT AND VEGETABLE WASTE IN THE PRODUCTION OF FOOD PRODUCTS

Utilization of fruit and vegetable waste is a challenge due to poor consumer acceptance of its primary form and the collection of huge quantities of waste for processing. The process is even more complicated as the waste collection and segregation require much energy and manpower. The chance of microbial contamination increases spoilage and leads to the risk of developing foodborne illness if not properly processed. Utilization of this waste not only helps generate a secondary income for the company but also increases the wide production of nutraceuticals [180]. Most by-products are nutritionally superior and can be excellent low-cost sources of protein and other bioactive compounds [181]. There are different methods for utilizing fruit and vegetable waste to produce functional foods or to incorporate peel/pomace or seed powder into a product as a functional ingredient.

Herbal infusions and drinks

Herbal teas are one of the most important types of tea made from different ingredients that may contain therapeutic properties. It contains antioxidants, polyphenols, and so many flavonoids [202]. Herbal tea is commonly referred to as any beverage plant that doesn't belong to the *Camellia* genus. Tea prepared with dehydrated avocado peel showed high antioxidant activity, and it also had good sensory acceptability [182]. In a study conducted by Ubbor *et al*., herbal teas were developed from pure blends of moringa leaves, dried lemon peel powder, and a mixture of moringa leaves and lemon powder. It's been shown that the results of the proximate analysis were comparable with the control, but the vitamin C content and the phytochemical content showed a relatively high concentration [183].

Not only tea but also research done on developing herbal drinks based on fruit and vegetable waste has been carried out. An herbal extract called 'Tisane' has been developed using pomegranate seed powder and pomegranate peel powder in different ratios. The study showed that the blends of these powders had great antioxidant capacity and retained most of the flavonoids that were originally present in the raw materials [203]. Kombucha is a fermented drink prepared from a symbiotic culture of bacteria and yeast called 'SCOBY'. The ingredients of Kombucha involved are black tea, sugar, and fruit pulp [204]. Kombucha prepared from banana peel showed high antioxidant capacity and acted as a suitable ingredient [205]. Kombucha prepared from orange and pomegranate peel also showed good sensory and antioxidant properties [206].

Preparation of edible coatings

Edible coatings can enhance the sensory properties of the product and increase the microbial stability of the product by acting as a packaging material. Usually, polysaccharides and chitin are used as coated material. Apple pomace polyphenol is incorporated into standard coating material and was found to be very effective in increasing the shelf life of strawberries. It also showed that it has good antioxidant capacity [207]. In another study, they incorporated pomegranate peel powder with gelatin and found it to have increased water permeability and antioxidant properties [208]. An edible coating made from whey protein concentrate and apple pomace extract to extend the shelf life of fresh-cut apples. The coating was found to have good antioxidant properties and increased freshness of the product [209].

Functional ingredient in food

Fruit and vegetable pomace acts as a novel ingredient in bakery products to increase the functional properties, and they also increase the sensory properties. They increased the shelf of these products with the increased antioxidant contents in them. [210]. Raw and de-fatted flour from mango kernels used in bread as flour substitutes showed high levels of phenolic compounds [211]. Cake incorporated with apple pomace showed a good number of phenolic compounds and good functional properties [212]. Biscuits enriched with pearl millet flour and pomegranate peel showed high levels of total dietary fiber [213].

The sprouted pumpkin seeds showed an increase in phenolic content as compared to the raw ones. The amount of phenolic content from control to germinated ranges from 24.16 (control) and 215.01 mg GAE/100 g (germinated) to 57.14 (control) and 185.72 mg/100 g (germinated) [214].

Value-added products

Value addition is an effective methodology to increase the value of a product and a new possibility to increase the sustainability of a product. "USDA defines value addition as a change in the physical state or form of the product (such as milling wheat into flour or making strawberries into jam [215]). Food supplements, nutraceuticals, and oleoresins are examples of value-added products. Fruit and vegetable peels can act as a great source for producing value-added products.

Table 7. Studies depicting the valorization of fruit and vegetable waste into different products

S. No.	Ingredients used	Processing conditions	Benefit	Ref.
A	HERBAL INFUSIONS AND TEA			
1)	Avocado peel	Peels are chopped and dried in an oven at 60°C and dipped in hot water. It is then compared against Mate tea, Apple tea which was available in the market.	-Antioxidant activity was comparable with Mate tea (1954.24 a±87.92) -High level of phenolics (123.57a±4.64)	[182]

2)	Moringa leaves and lemon peel powder	3 Formulations – 100% moringa leaves, 100% lemon peel powder, Different ratios of Moringa leaves and lemon peel powder in the ratio 50:50, 30:70, and 60:40 respectively	-Tea with 100% lemon peel showed high carotenoid content (5.52µg/100g) -Tea with 100% moringa leaves showed high values of saponins and phytates 1.5 and 1.25mg/100g, respectively -Blend having 70: 30 also showed good alkaloid and tannin content, i.e, 1.29±0.01 and 11.50 ±0.01	[183]
3)	Mango leaf tea supplemented with moringa and ginger powder	3 Formulations – 100% mango leaves -A 60% mango leaf, 30% moringa leaf and 10% ginger - B 40 % mango leaf, 30% moringa leaf and 30% ginger -C Infusing 3g of tea powder into a tea bag and dipping it in hot water.	Showed a good number of glycosides. 1.89b ±0.1 1.86b ±0.15 and 1.08b ±0.2 for A, B and C respectively	[184]
4)	Herbal Tea prepared from orange peel	Orange peel was dried using different methods i.e. sun dried, oven dried, and air dried was ground and sieved. 2g peel powder added to 100ml	Catechin tannins are found to be present in all combinations	[185]
5)	Addition of Jamun seed powder in orange, ginger, and anola juice	Jamun seed powder extract at 5,10,15, and 20% of different concentrations with 10% anola fruit juice, 5% orange juice, and 2% ginger juice were	Among all the combinations, T3C7, ie, 15% JSE, 10% Anola Juice, 5% Orange juice, and 2% ginger juice, got the highest sensory acceptance	[186]
6)	Development of functional drinks from melon by-products	Melon seed powder and extract, melon peel extract, and powder were prepared separately. Different concentrations of this are mixed with 1L water, 13% sugar, 0.3-0.4 % citric acid 0.20% CMC	High phenolic and anti-oxidant capacity was observed for a 3% Melon peel extract-based drink (2.51 GAE/mg and 62.10 %)	[187]
B)	USES IN EDIBLE COATING			
1)	Edible films and coatings based on mango peel and seed kernel	Mango peel flour dissolved in citrate buffer, mixed thoroughly and then glycerol was added. Constantly agitated and and temperature lowered to 5°C. Films made by casting technique	Showed good polyphenol content of 14.7 GAE/mg and great protection to coated peaches	[20]
2)	Anti-microbial edible films from chitosan incorporated with guava leaf extract	Different ratios of vacuum filtered Guava leaf extract are added to a mixed solution of 2% chitosan and 2% acetic acid solution, stirred for 5h	Polyphenols in guava helped to increase the anti-microbial properties of chitosan.	[188]
3)	Potato Peel Extract based edible film	5g Potato peel powder is mixed with 93g of distilled water and 1.5g of glycerol. Poured on a labeled dish and dried	The phenolic component in Potato peel helped to reduce the oxidation and microbial activity (39 ± 0 mg of GAE for ethanolic extracts)	[189]
4)	Edible coatings Citrus limon peel extracts and *Ocimum tenuiflorum* leaf extracts	Limon peel and Tenuiflorum leaf extract were added to glacial acetic acid (100ml) and glycerol (0.75%) and coated on bananas.	Bananas with coating showed lowered weight loss but increased phenolic content as to non-coated ones. (4.9 % and 90.76%)	[190]

5)	Edible coatings Moringa leaf extract	2% moringa leaf extract + 0.5% chitosan extract and (CN 0.5%), M + CN 1%, M + CMC 0.5%, M+ CMC 1%) of chitosan concentrations. Fruit is dipped in the treatment solution	Moringa with 1% CMC extract lowered the ripening rate and also reduced the lipid peroxidation rate	[191]
C)	AS A WHOLE INGREDIENT			
1)	Mango peel powder	Washing, disinfection, blanching, drying (lyophilization, infra-red drying, oven drying, etc.), blending	Novel non-thermal methods retained the phenolic contents, and the peel powder works as a source to produce commercial pectin	[192]
2)	Pumpkin peel and seed powder	Parts were cleaned and dried in a hot air oven at 60ºC until constant weight and blending of the dried parts.	Peel powder showed good levels of antioxidant activities (DDPH - 13.00±0.08b mg AAE/100g)	[193]
3)	Guava leaf powder	Leaves were cleaned and dried in a hot air oven	Leaf extracts lowered post-prandial blood glucose levels in diabetic rats	[194]
4)	Jamun Seed Powder	Seed powder at a dose of 5g twice daily was given before meal was given to patients having Type 2 Diabetes and the control group was those who type 2 diabetes patients who got placebo powder.	Fasting plasma glucose reduced from 143 mg/dl to 131mg/dl	[195]
5)	Pomegranate peel powder	Peels and arils are cut into small pieces and dried at 38°C for 48h in a dryer. And is added to fruit salad at different concentrations (2.5: 2.5% & 5:5%)	The microbial colony was less as compared to the control one log reduction ie 4CFU/g for 5:5% and control 5 CFU/g in 1 week.	[196]
D)	AS AN INGREDIENT IN BAKING			
1)	Avocado seed powder in cupcakes	Seed powder is added to cupcakes at different concentrations like 0,5, 30 & 50 %	The total phenol content of cupcakes increased with increasing seed powder concentrations (5% -2.5, 3-30%, and 4 for 50%)	[197]
2)	Mango seed kernel on muffins	Dried mango seeds are separated from the stone, the kernels removed, and dried in an oven at 60ºC for 5 h, grinding and adding the powder to the muffins in different ratios ie 0%, 10%, 20%, 30%, and 40%	30% mango kernel increased the sensory qualities. It also increased the ash content from control -1.56 to1.82%	[198]
3)	Pomegranate seed powder in gluten-free bread	Pomegranate seed powder was added to bread ingredients in different ratios ie. 2.5%, 5.0%, 7.0%, and 10%, and baked at 230ºC for 20 min.	The total phenolic content of bread increased 2.8 times as that of control when 10% PSP was added (0.88 to 2.47 Mg/g)	[199]
4)	Watermelon rind flower in wheat flour cookies	Rinds are dried and milled by an attrition mill, sieved, and added to cookie flour. The combination ratio of wheat flour in the ratio of 100:0% (sample A [control]), 97.5:2.5% (sample B), 95:5% (sample C), and 92.5:7.5% (sample D).	The ratio 97.5: 2.5% was more accepted. Showed a significant increase in vitamin C content as of control 2.72 to 7.23 mg/g	[200]
5)	Potato peel in fabricated potato snack	15g potato flour and peel of combined weight is maintained using different formulations. Spices and oil are added and baked.	The developed snack had a good amount of fiber content (9.82%)	[201]

A study of the production of single-cell protein from peels of orange, pineapple, and banana and wastes from garlic and sugar cane was conducted by Ahmed et al. using fungi under liquid fermentation. And it's been found that the substrates are suitable for producing SCP using *A. niger* [216]. Dietary fiber extracted from mango peel has great hydration capacities and antioxidant capacities due to the presence of phenolic compounds in the peel [217]. Soluble dietary fiber from orange peel showed a good extraction rate with an increase in temperature. The soluble dietary fiber content of orange peel is approximately 5%, and when the extraction temperature is increased to 135°C, the extracted fiber content reaches 24.28 percent. An approximate five-fold increase in extraction recovery was observed with raised temperature [218].

DISCUSSION

The current study gives an overview of the anti-diabetic activity of fruit and vegetable waste highlighting the presence of bioactive compounds such as polyphenols, flavonoids, carotenoids, and other phytochemicals. Through various mechanisms like the inhibition of carbohydrate-digesting enzymes, which include α-amylase and α-glucosidase, improvement in insulin sensitivity, regulation of oxidative stress, and upregulation of glucose transporters such as GLUT4, these compounds display their hypoglycemic activities.

Various fruit and vegetable by-products, including mango peel, pomegranate seeds, guava leaves, and orange peel, have shown promising anti-diabetic effects *in vitro* and *in vivo* models. For example, the extract from pomegranate peel has shown tremendous potential in inhibiting α-glucosidase which was like drug-like potency of pharmaceutical drug acarbose ($p=0.0295$) [107], whereas the onion peel extracts polyphenols significantly decreased the blood glucose levels from 289 mg/dL on day 0 to 205 mg/dL on day 56, in diabetic rats [172]. However, there are some gaps in this research. Even though various bioactive compounds have been identified, the molecular mechanisms through which they exert anti-diabetic activity require more biochemical and genetic research.

Secondly, most studies rely on *in-vitro* and animal models, with limited human clinical trials available to validate their efficacy and safety. Most studies are conducted on *in vitro* and animal models with very few human clinical trials that can confirm their efficiency and safety. Finally, although natural products are generally considered safe, long-term toxicity studies are necessary to evaluate their potential risks at higher doses. Several issues must be resolved to take full advantage of fruit and vegetable waste for diabetes management.

Consumer perception is another key hurdle, since the idea of incorporating waste-derived materials in nutraceuticals may be met with suspicion and opposition due to safety and hygiene concerns. Regulatory clearances are also a barrier because the items must undergo extensive testing and validation before they can be launched. Scalability, processing, and storage of massive amounts of fruit and vegetable waste are further logistical problems. Stability difficulties also arise with bioactive substances. Most phytochemicals deteriorate due to heat, light, and oxygen, necessitating improved formulation procedures to increase the shelf life.

Pharmaceutical applications include the potential for bioactive molecules to be developed as supplementary therapy to standard diabetic medications. Future research should focus on improving extraction and processing technologies, such as supercritical fluid extraction and enzyme-assisted extraction, to increase active ingredients, yield, and bioavailability. Rigorous clinical trials are required to establish dose recommendations and determine long-term safety. Encapsulation and delivery technologies, such as nanoencapsulation, should be investigated to improve the stability and bioavailability of these drugs. Furthermore, incorporating fruit and vegetable waste into functional food production chains has the potential to speed up large-scale integration. Finally, approaches to customized nutrition will adapt diabetic interventions based on genetic diversity.

In conclusion, fruit and vegetable waste is a valuable yet underutilized resource in the battle against diabetes. There has been significant progress in clarifying its bioactive potential; nevertheless, there is still an urgent need for more research, regulatory clearances, and smart commercialization activities to put this knowledge into practical, consumer-friendly health solutions.

CONCLUSION

The fruit and vegetable processing industry generates a substantial amount of waste, including peels, seeds, pulp, and discarded pieces that are rich in vitamins, minerals, and bioactive compounds. Many bioactive compounds, such as quercetin, fiber, naringin, peptides, and fatty acids, have demonstrated hypoglycemic potential. In-vitro and in-vivo studies indicate that supplementation with fruit and vegetable waste can exert anti-diabetic effects through various metabolic, enzymatic, and molecular mechanisms. These include enhanced insulin production from β-cells, suppression of apoptosis, pancreatic cell regeneration, improved peripheral glucose uptake, controlled glucose release, and activation of antioxidant enzymes like catalase and glutathione peroxidase. Additionally, reduced activity of glucose-metabolizing enzymes such as α-amylase, upregulation of PPARγ and PPARα, and enhanced transcription of Nrf2 have been proposed as contributing factors.

Along with these promising findings, further research is needed to fully elucidate the mechanisms of action and optimize extraction techniques to enhance the bioavailability and effectiveness of these bioactive compounds. Innovations such as nano-encapsulation, green extraction methods, and AI-driven personalized nutrition strategies could address existing research gaps. Furthermore, large-scale human clinical trials and regulatory support will be critical for the commercial development of functional foods, nutraceuticals, and pharmaceutical applications. By integrating scientific advancements with sustainable waste utilization practices, fruit and vegetable by-products can be effectively transformed into valuable therapeutic resources for diabetes management.

Statements and Declaration

- *Author contribution- VT- Study conception and design, written, edited, and supervised the manuscript. NV, RS, JK, KA, TP, and AM- collection of data and drafting the manuscript. AK, VS, and PP have edited and improvised the final draft. All authors reviewed the manuscript and approved the final version of the manuscript.*
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Revolutionizing waste management: transforming sewage sludge into eco-friendly biochar for sustainable soil enrichment

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Urban sewage treatment plants have contributed more sewage due to the movement of people to earn money towards cities in recent years. Biochar from high-temperature sewage sludge has lower nitrogen but higher phosphorus, potassium, and less water-soluble nitrogen. It helps soil by slowly giving out nutrients. When pyrolysis temperatures rise, nitrogen decreases while phosphorus and potassium increase. Likewise, it is made at higher temperatures and shows less water-soluble nitrogen but more water-soluble phosphorus and potassium. Biochar production slows when temperatures elevate, and the best results show at 700 °C - higher alkalinity, better pore structure, lower dissolved salts, and better nutrients, but nitrogen levels are still low. The trace nutrient levels in biochar are less than in sewage sludge, but heavy metals increase with pyrolysis. Yet, it has lower leaching toxicity than sewage sludge and acts as a more stable soil enhancer, significantly improving the soil's nutrients.

Keywords: Sewage, solid waste, biochar, anaerobic digestion, pyrolysis

Abbreviations: MSW-Municipal solid waste; GDP- Gross domestic product; AC-Activated carbon; IC-Inorganic contaminant; OC-Organic contaminant; SS-Sewage sludge

INTRODUCTION

Sewage, the primary solid waste produced by urban sewage treatment plants, has steadily risen over the past few decades, along with global GDP and urbanization. The absence of oxygen during the pyrolysis of biomass results in biochar, a carbon-rich solid [1]. Biochar feedstock could be sourced from various biomasses, including all types of agriculture, garden waste, biodegradable and municipal solid waste. Biochar has primarily been treated as an adsorbent for both organic and inorganic waste and as a catalyst for soil conditioning/amendment [2]. Applying sewage sludge to farmland has great potential because it boosts soil fertility and increases organic carbon storage [3]. Landfilling, incineration, and spreading it on fields are the most typical ways to get rid of sewage sludge. Toxic leachate and soil scarcity have hampered landfill and land application options, while incineration's high operating costs and hazardous gas emissions have caped the practice [4]. One promising alternative is pyrolysis, which not only destroys the microbes and different organisms and parasites in sewage sludge but also generates valuable bioenergy through the thermochemical accumulation of bio-degradable waste in the absence of oxygen (bio-oil and biogas) [4, 5]. Biochar, the solid residue that's left over, has great potential to boost soil quality by supplying nutrients and microbial biomass [6]. Adding biochar from sewage sludge to agricultural soil can increase crop yields by boosting soil aeration, cation exchange capacity, and nutrient supplementation [7]. The pyrolysis of wastewater and agri waste yielded biochar that exhibited improved characteristics, including heightened stability, a moderate pH level, a substantial concentration of accessible phosphorus, and reduced metal toxicity. India's raw sewage generation was calculated to be 7.34 kg/capita/year, or about 144 kg/million liter of sewage per day on a dry basis. Complete sewage treatment would produce 4.01 million tons of dry sludge [8].

Table 1 presents a selection of data collected by researchers about the -pyrolysis of wastewater and agri waste [4, 9, 10]. The production of biochar with improved stability was achieved by co-pyrolyzing bamboo sawdust. Furthermore, adding rice husk during co-pyrolysis resulted in higher metal stability within the biochar, particularly when the process was performed at 700 °C. The observation made by a researcher indicates an increase in the carbon (C) concentration of biochar when sewage sludge is subjected to co-pyrolysis with biodegradable additives such as reed straw, brewers' leftover grain, and sawdust. In contrast, the obtained biochar

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exhibited a decline in pH, amount of ash, electrical conductivity, H/C proportion, and O/C proportion [9]. Significant attention has been dedicated to examining the behavior of phosphorus (P) and different heavy metals in sewage slurry and biomass co-pyrolysis. In several research papers and reviews, researchers discovered that transforming non-apatite inorganic phosphorus into apatite phosphorus can potentially be accomplished through co-pyrolysis. This process involves adequate mixing of elements such as magnesium (Mg), chlorine (Cl), potassium (K), calcium (Ca), that are present in cotton stems with phosphorus [10, 11]. Based on the findings of certain researchers, it has been observed that introducing bamboo shavings to sewage sludge reduces the hazard of heavy metals present in the resultant biochar. This reduction can be attributed to the conversion of the active states of these heavy metals into a potentially active form and a reliable condition [12]. However, it should be noted that not all biomass wastes can be attributed to the sewage treatment method. Utilizing wastewater and different types of agri waste, which yield biochar synthesis, would result in a notable escalation in transportation expenses. Organic materials, macro and phytonutrients, essential minerals, pathogenic organisms, and micro-pollutants comprise the biomass residue known as sewage slurry, a byproduct of water treatment [13, 14]. Using physical, chemical, and biological processes, constructed wetlands (CWs) can purify polluted water [15]. Recently, there has been an observable increase in the application of artificial wetlands as a commonly accepted approach for treating effluent derived from treatment plants. The reason for this is the possibility of treated water from treatment plants not adhering to set environmental quality standards for surface water. To achieve the intended degree of treatment efficacy, properly disposing of the wetland plants regularly generated during water purification was crucial. Therefore, co-pyrolysis combined with a wastewater filtration system can be viable for concurrently disposing of wetland plants and sewage slurry. The current body of research lacks exploration of the potential application of wetland plants and sewage wastewater for the manufacturing of biochar, as well as the behavior of phosphorus and different heavy metals during the pyrolysis process.

This research deals with co-pyrolyzed sewage slurry and a common wetland plant (*Phragmites australis*) at various temperatures and mixing ratios. The goals were: (1) to learn more about composite biochar, (2) to learn how phosphorus is transformed during co-pyrolysis, and (3) to learn more about the heavy metal's speciation in the resulting biochars. Most studies have concentrated on the thermochemical features of pyrolysis [19, 20] and the heating-and-cooling cycle's role in phosphorus recovery [21, 22]. Phosphorus migration and transformation have been the subject of relatively few studies [23].

Table 1. Biochar characteristics of different materials at elevated temperatures.

Biochar characteristics of bamboo [16]								
Temperature	Yield	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
350	52.1	-	68.4	4.5	0.33	26.7	0.07	0.39
450	34.3	-	70.9	0.33	0.25	24.91	0.06	0.35
550	31.1	-	73.4	0.63	0.25	22.38	0.05	0.3
Biochar characteristics of agri biochar [17]								
Temperature	Yield	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
300	48.5	--	62.1	4.51	0.88	24.2	0.86	0.29
400	38.5	--	4.04	4.04	0.95	16.4	0.66	0.17
500	34.4	--	2.84	2.89	0.84	12.4	0.45	0.13
Biochar characteristics of sewage sludge (SS) [18]								
Temperature	Moisture	Retention rate	Percentage					
			C (w/w)	H	N	O	H/C	O/C
350	2.6	--	45	4.2	4.9	7.3	--	--
400	0	--	42.1	3.2	4.6	5.3	--	--
550	--	--	40.5	2	5.7	0.7	--	--

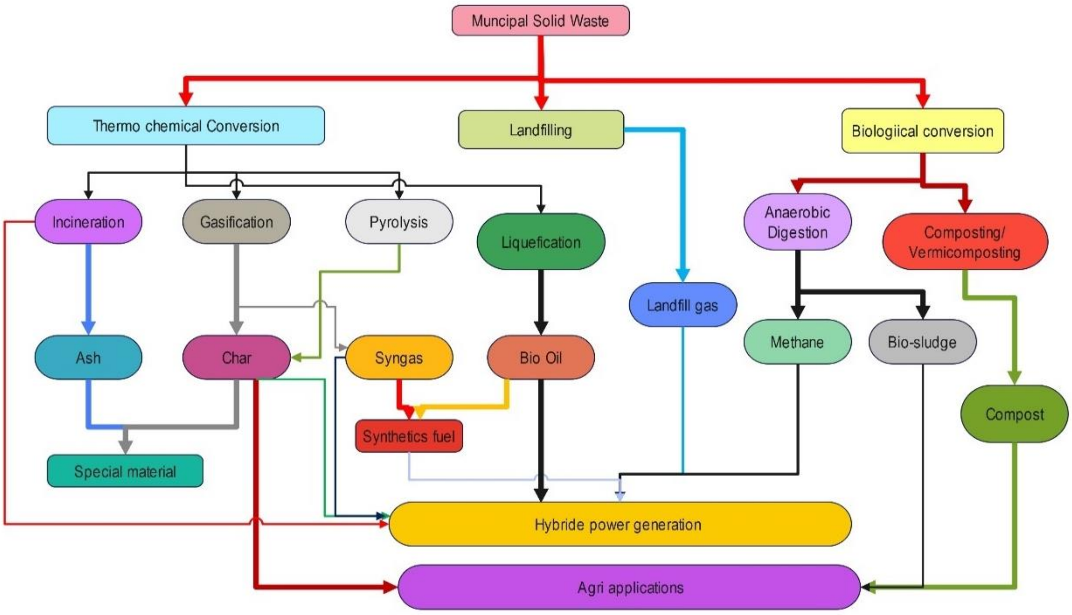

Figure 1. MSW method of waste to energy

POTENTIAL FOR RECOVERING ENERGY FROM SEWAGE SLUDGE.

Potential factors for energy regaining by the incineration and anaerobic digestion of municipal sewage sludge are provided. It has been calculated that between 500 and 1070 kWh/ton of dry sludge can be recovered through sewage sludge incineration. Anaerobic digestion of the wastewater slurry was found to have a potential energy generation range of 300-609 kWh/ton of dry sludge. A study conducted in Greece supports these results [24]. Their research shows that the energy produced by incineration is around 1399–1698 kWh/ton total amount of dry sludge matter, while the energy produced by anaerobic digestion is approximately 1398–1449 kWh/ton. Anaerobic digestion in the present study yielded biogas with CH_4 concentrations of 58-65% in ASP effluent sludge, 55-67% in SBR effluent sludge, 50-60% in UASB effluent sludge, 55-73% in MBBR effluent sludge, and 36-53% in WSP effluent sludge, as shown in Figures 1 and 2.

SEWAGE SLUDGE

Various types of sludge are generated at distinct phases of wastewater treatment plants.

1. *Primary sludge*: The byproduct generated during the initial treatment phase of wastewater, whereby solid materials such as heavy particles, grease, and oils are separated from the raw sewage through filtering, removal of dust and lumps, backing, precipitation, and deposit. This sludge typically contains a solids content ranging from 1.9% to 9.8%, with the remaining composition being predominantly water, accounting for more than 89.9% of its total volume [25].

2. *Secondary sludge*: The byproduct of biological treatment, in which microorganisms decompose the organic matter in wastewater (activated sludge) [26]. Depending on the specific natural treatment method, the solids concentration can be anywhere from 0.79% to 3.29%, with water making up the rest, C (49-55 %), oxygen (24-25%), nitrogen (9.8-15.1 %), hydrogen (5.8-10 %), phosphorus (1.9-2.9 %), and sulfur (0.5-1.5 %) make up the organic component of activated sludge [27].

When nutrients must be removed from the effluent before it is released into the ecological system or all kinds of water sources, tertiary sludge (nitrogen and phosphorous) is produced in the final stage of sewage treatment [28].

To lessen the biodegradable loading for the successive treatment method, sewage treatment plants often use a chemical process that includes dosing with the appropriate coagulant upstream of the elementary deposit. This results in the accumulation of chemical sludge. Phosphorus is often precipitated from treated wastewater at some wastewater treatment plants by adding compounds like alumina or iron salts. This methodology is also reflected in a chemically treated method. Separating the slurry, which is generated as chemical sludge, is impossible because it is frequently combined with secondary sludge [29, 30]. Future waste management issues include sewage sludge disposal and reuse [25]. Global sludge production is at an all-time high and is estimated to keep moving in the upcoming years [26]. Significant sewage waste is generated yearly in European countries, more than 10 million tons (dry/dewatered quantity). Sludge production is highest in Germany, the UK, and other European countries. Compared to Spain and Italy, they produce more than five lakh-ton dry matter annually. An additional 75% of Europe's sewage sludge is thought to originate from just five countries. Sewage waste is a growing environmental concern due to issues surrounding its accumulation, utilization, and disposal [31, 32].

The storage of sewage waste at ground level might pose ecological hazards due to its ability to undergo fermentation and the existence of many harmful compounds, both bio- and non-biodegradable matter. These substances include microbes and hazardous metals [32, 33]. Leaching production and CO_2 emission are directly affected by sewage sludge landfilling. Large amounts of waste necessitate environmentally responsible management of sewage sludge, and its management and disposal are among the trickiest issues facing wastewater treatment facilities, so any solution must be well-received [34, 35]. Developing countries face several challenges in efficiently managing waste, primarily due to insufficient regulations, the absence of a systematic approach for choosing appropriate slurry management systems, and the substantial financial burden associated with upgrading outdated sewage treatment facilities [36]. Sewage sludge is classified as a hazardous waste in numerous nations owing to its substantial organic content, presence of chemical contaminants (including heavy metals, pesticides, and toxic organic compounds), abundance of solid waste, and potential for harboring pathogenic bacteria, viruses, and other disease-causing agents [37]. Even though some sludge is reused in the treatment process to improve efficiency, a significant amount of wastewater slurry still needs to be resolved and properly managed. Compaction, stabilization, conditioning, dewatering, hygienization, and drying are all components of sewage sludge treatment. However, not all these steps must be taken in every sewage treatment plant [38]. Implementing sludge treatment techniques has resulted in increased infrastructure development and associated expenditures for supplemental treatment.

Additionally, the imposition of strict requirements about wastewater treatment before discharge has contributed to an escalation in the expenses associated with sludge disposal. Environmental concerns, such as unpleasant odours or the escalation of waste volume, can be mitigated using appropriate sludge treatment and disposal techniques. Moreover, the energy harnessed from these procedures can be effectively utilized in other beneficial applications. The proper remedy, controlled disposal, and appropriate management of sludge are widely recognized as crucial due to the significant environmental consequences that can arise from improper sludge disposal. These consequences encompass risks to public health and the potential contamination of ecological and aquatic life sources. Conventional techniques of sewage sludge management have become obsolete due to the coexistence of infective agents, medicinal compounds, all types of hazardous metal and biodegradable pollutants, and limited space availability. As environmental regulations become more stringent, old methods of sludge disposal are being phased out in favor of more modern approaches. The European Union has mandated the replacement of traditional sludge storage techniques with more environmentally friendly waste stabilization and recycling methods. The removal of the solids and the subsequent reduction in odour concerns caused by sludges are two examples of how resource recovery contributes to all three of sustainability's pillars (economy, environment, society). Thanks to the recent implementation of various state-of-the-art technologies, sludge recycling rates have increased, and the number of toxic substances in this biodegradable waste has decreased. Choosing a sewage sludge managing mode or technique that has the least negative impact on the environment in the short and long term is essential. By applying these cutting-edge processes, potentially dangerous wastes can be processed and used in agricultural settings, different industrial sectors, and thermal and electrical energy production [39].

REUSING AND REPROCESSING WASTEWATER SLUDGE

The goals of current sludge treatment technologies are to lessen the mass and volume of the waste, kill any harmful microorganisms present, eliminate any unpleasant odors, and reduce the number of volatile solids present so that they can be safely disposed of.

PYROLYSIS

The final sewage sludge management method significantly impacts the number and variety of technological processes required for sludge treatment. The physical and chemical properties of sludge are altered during treatment, which can affect the final product's quality and viability [36]. Some of the most common methods for getting rid of sewage sludge are:

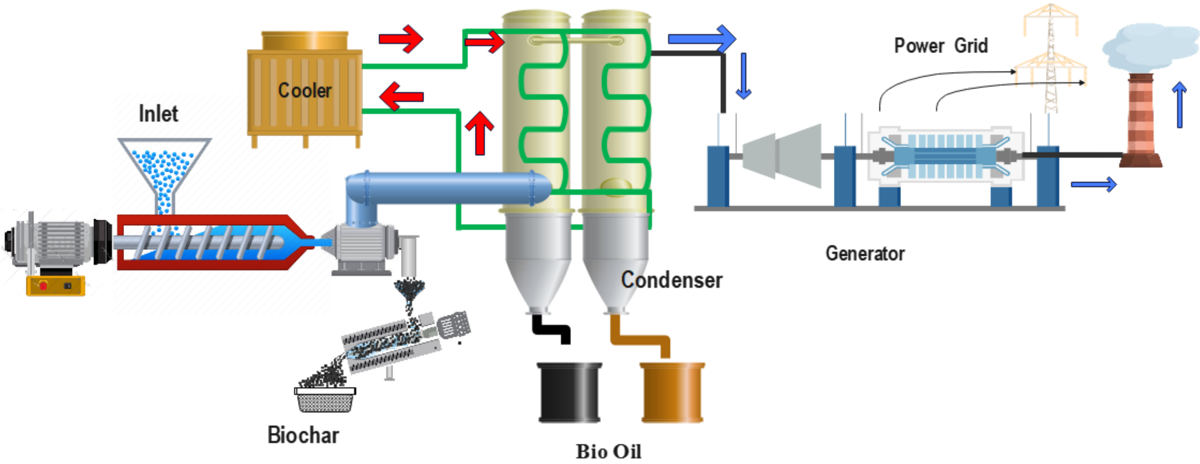

Figure 2. Process of biochar generation and other practical utilization

- Organic recycling has garnered significant interest due to the possible utilization of sewage sludge as a fertilizer. Various approaches have been explored, including applying this sewage waste in agriculture, which helps rebuild degraded soils, composting slurry for fertilizer manufacture, and mechanical and biological treatment methods.
- Several thermal processing methods, including all types of energy generation and co-incineration in concrete factories and the energy generation sector, can utilize sludge for energy and material recycling. These processes facilitate the conversion of sludge into fuel and other valuable minerals.

Due to the stabilization and reduction of the hazardous metal movement and the accessibility of biodegradable pollutants and pathogenic agents, sewage sludge treatment technologies have intensified and diversified over the past decade. Because optimal sludge treatment modifies sludge properties and ultimately affects product quality, it can have wide-ranging effects on the environment, the economy, and society. A diverse range of treatment methods exists, encompassing anaerobic digestion, composting, alkaline material stabilization, chemical ingredient stabilization, thermal processing, Pyrolysis, combustion, and more. When formulating a strategy for recycling sewage sludge, it is imperative to consider both financial implications and environmental consequences [44, 45].

The method of thermal accumulation of biodegradable compounds in the absence of O_2, occurring within the range of temperature between 250 to 900 ºC, is commonly known as "pyrolysis." This could be a step toward allowing modern biomass pyrolysis techniques for global carbon capture, creating biofuels, Biochar, syngas, and other valuable products. An alternative to incineration that can mitigate these massive waste volumes is the production of Biochar from agricultural byproducts. Compared to alternative biomass feedstocks, Biochar performs better in its catalytic action, surface area, absorbency, and physicochemical strength. Char and bio-oil may be identified as solid and liquid byproducts, respectively, and CO_2, hydrogen, CO, and syngas can be classified as gaseous byproducts, explicitly falling under the category of C_1-C_2 hydrocarbons. Kilns and bubbling fluidized beds are a subset of reactor types that can produce Biochar, among other alternatives. The quantity of Biochar generated by the pyrolysis is contingent upon the specific characteristics and makeup of the biomass utilized. The yields, pore volumes, and surface areas of chars are primarily influenced by holding time concerning temperature. The products resulting from the pyrolysis process can be classified into three distinct groups: syngas, bio-oil, and solid residue. This will possess diverse applications within the energy and chemical sectors [39].

Combustible aliphatic volatile materials are prevented from escaping the structure during biochar production at low temperatures. Once heated, the volatile components of biochar can be used as fuel. Nevertheless, at elevated temperatures (such as those over 500 °C), the volatiles within the biochar undergo evaporation, resulting in the retention of solely the carbon framework.

ANAEROBIC DIGESTION

The anaerobic digestion process is often employed in certain types of sophisticated wastewater treatment facilities, which convert this sewage sludge into valuable materials such as biogas, methane hydrogen, or value-added products (as shown in Figure 2). Applying the technique decreases the levels of organic carbon and the C/N ratio in the sludge, hence impeding the proliferation of pathogenic fauna. Utilizing methane-rich biogas generated via fermentation holds potential as a fuel source for gas turbines, enabling energy recovery. This practice not only aids in revitalizing eroded soils but also assists farmers.

Table 2. Different soil parameters concerning sewage sludge/slurry (SS) [7]

Parameters	Gravel characteristics	SS
Sand (%)	76.4	–
Silt (%)	13.9	–
Clay (%)	5.7	–
pH	8.1	7.01
EC (dS m $^{-1}$)	0.55	11.64
Organic carbon (%)	0.37	24
Nitrogen (%)	0.05	1.23
Carbon nitrogen ratio	6.92	19.01
Total phosphorus (%)	0.18	0.5
Total potassium (%)	0.02	0.93
NH4+ N (mg kg $^{-1}$)	5.9	680.16
NO3− N (mg kg $^{-1}$)	42.1	260
Metal content (mg kg^{-1})	Gravel characteristics	SS
Zn	31.2	530
Cu	20.9	329
Cd	--	12.01
Cr	2.5	270
Ni	2.7	121
Pb	27.4	250
Fe	3509	14021

* The dry weight determines the value of sewage sludge and soil.

The combustibility of high-temperature biochar surpasses that of low-temperature biochar due to its absence of volatiles and pores. The fireproof nature of high-temperature biochar can be attributed to the robustness of the C-C covalent bonds. Biochar produced through pyrolysis at temperatures over 500 °C exhibits notable fire-resistant characteristics because of the creation of robust C-C covalent bonds and the absence of volatile substances. Figure 3 illustrates the mechanics of the pyrolysis reaction. Influences such as reaction temperature, residence time, and pressure distinguish two broad categories of pyrolysis: fast and slow.

RESULTS AND DISCUSSION

Biochar's sensitivity to temperature

An increase in pyrolysis temperature led to a decrease in the nitrogen content of the Biochar produced from sewage sand. According to the data presented in Table 3, it can be noted that when the pyrolysis process is performed at a temperature of 400 ºC, over 50% of the nitrogen content is depleted. Conversely, at a lower temperature of 300 ºC, 96.92% of the nitrogen remains intact inside the sewage slurry biochar. The volatilization of nitrogen in sewage slurry biochar when subjected to elevated temperatures has been previously hypothesized. Furthermore, the syngas exhibited detectable levels of nitrogen gas (N_2), ammonia (NH_3), and hydrogen cyanide (HCN), suggesting that a complete conversion of nitrogen in the sewage sludge to tar-nitrogen did not occur. Due to the extensive binding of N to various organic molecules, particularly in the form of protein-N, the extraction of N from sewage sludge poses a challenging task. Biochar's RR (retention rate), defined as the percentage by which its element content exceeds that of the sewage sludge sample, ranged from 0% to 100%. Since biochar had a lower RR, fewer elements had been removed. The RR was determined using

$$RR = \frac{C_{\mathrm{biochar},i}}{C_{\mathrm{feed},i}} Y_{\mathrm{biochar}} \qquad (1)$$

Equation (1), where C_{biochar}, $\boldsymbol{i}$ element content represents $\boldsymbol{i}$ in the biochar, C_{feed}, $\boldsymbol{i}$ showed how much element $\boldsymbol{i}$ is present in the sewage sludge, Y_{biochar} represents biochar production results [41].

The sewage slurry sample and the biochar generated at 300 °C were acidic, but the biochar generated within the temperature range of 400-700 °C exhibited alkalinity. One plausible explanation is that pyrolysis induces the accumulation of organic acids and carbonates. Higher pyrolysis temperatures also increase the biochar's alkaline organic anion content [42].

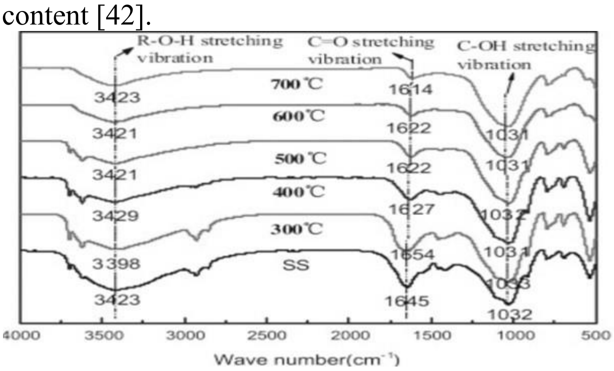

Figure 3. Thermally induced changes in the FTIR spectra of a sludge sample and biochar [30]

Table 3. Biochar made at different temperatures has varying nutrient content [30].

Temperature	RR (Retention Rate)	NPK and other heavy metal composition						
		Cu(mg L^{-1})	N(mg kg^{-1})	Pb(mg L^{-1})	P(mg kg−1)	Zn(mg L−1)	K(mg kg^{-1})	Ni(mg L^{-1})
300	83--96	5.23	61200	3.52	38800	12.04	7470	1.83
400	53.32--96.92	2.71	37900	3.81	42700	5.57	8990	2.31
500	24.44--94.71	2.2	18500	3. 75	44700	5.34	10100	1.94
600	18.62--92.2	2.25	14600	3.55	45100	5.67	13300	2.06
700	11.25--97.5	2.07	9100	3.38	49200	5.63	16600	2.15

Figure 3 shows that the FTIR spectra of the sewage slurry sample and biochar support the previous conclusion. The presence of carbonyl and hydroxyl peaks observed at. 1.6×10^{-7} cm^{-1} and 3.3×10^{-3} –3.4×10^{-3} cm^{-1} were weaker in the sewage slurry sample than in the biochar generated at the temperature of 700 °C [43].

EVALUATION OF POTENTIAL THREATS TO THE ECOSYSTEM

Due to its inherent internal structure, biochar possesses agronomic utility and can serve as a soil conditioning agent. Biochar can boost several soil features, including biological and physical aspects. These improvements include the augmentation of soil nutrient levels and the enhancement of water retention capacity. Consequently, biochar mitigates supplement leaching and facilitates plant nutrient accessibility, increasing crop output. Protecting the natural world requires carefully considering the dosage of sewage sludge for agricultural purposes. There are dangers to living things from incorporating a circular economy that uses sludge containing micropollutants. Soil quality in areas where sewage sludge and its byproducts have been used in agriculture can be impacted. Pharmaceuticals were also examined for their potential impact on microorganisms in the environment. Treatment of soil with sewage sludge can expose bacteria to antibiotics, which could increase the prevalence of antibiotic-resistant strains of bacteria. This is supported by research showing that antibiotics inhibit microbial growth in the short term. Despite prolonged drug exposure, bacterial activity and biomass eventually return to their pre-test levels. Sewage sludge contains a mixture of antibiotics and bacteria resistant to those antibiotics. Since antibiotic resistance is a growing problem, many worry that spreading sludge on farmland will help fuel its growth. Biochar's ability to retain fertilizing elements depends on the raw materials used and the temperature and length of the pyrolysis process (N, P, K). Biochar's impact on yields is moderately dose- and application-rate-dependent. Plant growth necessitates the presence of a diverse array of micro- and macronutrients, encompassing carbon, hydrogen, oxygen, nitrogen, potassium, magnesium, phosphorus, sulfur, boron, chlorine, copper, iron, manganese, molybdenum, zinc, cobalt, silicon, and salt [44].

SEWAGE SLUDGE BIOCHAR AND ITS POTENTIAL HAZARDS

It is advisable to conduct a comprehensive ecotoxicological assessment before implementing biosolids in soil, as treated sewage sludge may comprise hazardous organic compounds and heavy metals that could compromise the integrity of the soil and water. An adequate soil ecotoxicological evaluation, as outlined by ISO soil quality guidelines, considers the loam's ability to serve as an environment for organisms and their ability to immobilize contaminants, thereby preventing groundwater adulteration [39].

Chemical analysis alone cannot be relied upon to identify all potential hazards of applying biochar from sewage sludge to soil as a fertilizer. Due to its widespread application in agricultural settings, it is crucial to determine biochar's toxicity to various organisms and populations. Biochar's direct impact on lifeforms can result from its content of organic or inorganic pollutants, which can have beneficial and detrimental outcomes depending on the organism we are talking about, as shown in Figure 4. To achieve low toxicity levels, pyrolysis temperatures above 600 °C are advised; however, not all biochars are suitable for agricultural purposes. Because of its low nutrient content and high porosity, Biochar made through the rapid pyrolysis method is recommended for restoring degraded soil.

Large-scale agricultural uses are possible for biochar is made at lower temperatures (500 °C) and contains more nutrients [45]. Not every ground loam has shown dramatic improvement, and not every crop responds similarly to the biochar as an alteration to the soil is also worth noting.

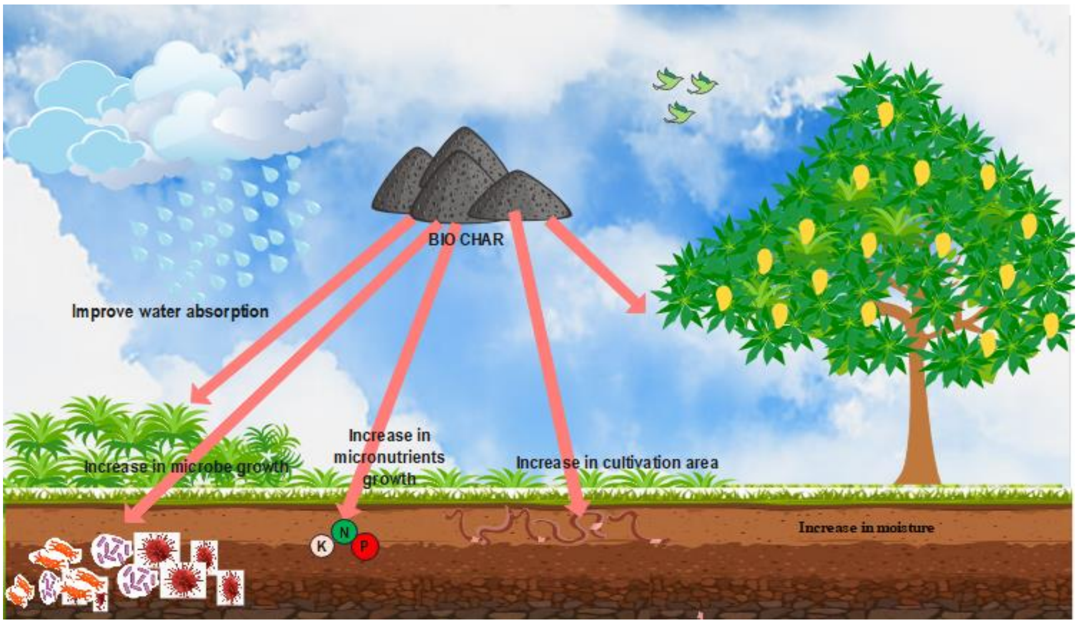

Figure 4. Effect of biochar on soil and agriculture

Biochar has a high capacity for sorption, which means it can absorb nutrients while decreasing their bioavailability and deactivating agrochemicals like pesticides and herbicides. Some plant modifications, such as shifts in root characteristics, may be determined by adding biochar, for instance, in agricultural fields with crops and weeds (depth, length, shape). In general, the phytotoxicity of biochar predominates and will alter depending on the treatment cycle and doses; this is because some plant groups are susceptible to specific chemical elements (P/B/Cu/Na/Zn/Mn/Cl). More importantly, biological tests provide the best evidence for the presence or absence of a toxic effect on organisms by allowing the investigation of interactions between various contaminants [46].

FUTURE PROSPECTS

Due to increasing global populations, a global imperative exists to explore more effective strategies for recycling and repurposing organic waste. Researchers are actively working to alleviate the escalating environmental consequences associated with the proliferation of global organic waste. One potential method for recycling the nutrients included in organic waste is incorporating them into the soil as a form of amendment. The mitigation or complete removal of harmful constituents in organic waste can be achieved through appropriate treatment measures before utilization. Several approaches can be employed to accomplish this objective, including composting, anaerobic digestion, or heat treatment. These procedures facilitate the decomposition of organic waste, converting said waste into valuable resources such as compost that is rich in nutrients or biogas, which can generate electricity.

Furthermore, implementing stringent legislation and disseminating educational initiatives to promote proper waste management techniques can effectively reduce the environmental repercussions of organic waste. The environmental impact of waste volumes is a matter of concern. Nevertheless, it is worth noting that organic waste has the potential to be recycled and utilized as a source of crop fertilization, provided that appropriate conditions are met. To achieve a final product that minimizes its environmental footprint and avoids excessive production expenses, it is imperative to ascertain the most efficient approach for managing organic waste, considering economic and ecological factors. Furthermore, the utilization of organic waste in the future can serve several purposes, including the rehabilitation and recovery of soils that have been contaminated. Using organic waste as a soil amendment has positively affected soil structure and fertility. Additionally, the transformation of organic waste into biogas offers potential benefits such as the reduction of greenhouse gas emissions and the decrease in reliance on fossil fuels. From a waste management perspective, it is crucial to evaluate the effectiveness of various methods for managing organic waste and to ascertain their possible impacts on the environment, soil quality, plant life, and other relevant factors. Comparative studies on organic waste use might illuminate alternative viewpoints about the long-term ramifications and interplay between biodegradable waste and chemicals employed as soil enhancers.

CONCLUSIONS

The study demonstrated that the nitrogen content of wastewater biochar decreases while phosphorus and potassium levels increase with rising pyrolysis temperatures. Sewage sludge biochar produced at peak temperatures effectively reduces water-soluble nitrogen while enhancing water-soluble phosphorus and potassium content, with the optimal synthesis occurring at 700 °C. At this temperature, biochar exhibited higher alkalinity, improved pore structure, reduced dissolved salts, and enhanced nutrient composition, excluding nitrogen. While the pyrolysis process increased heavy metal concentrations in the biochar, its leaching toxicity remained lower than that of sewage sludge, making biochar a more reliable soil amendment. Future research could explore alternative biomass sources, investigate co-pyrolysis with diverse additives, and optimize biochar properties for use in extreme environmental conditions. These efforts could further enhance biochar's applicability in sustainable waste management and soil enrichment. Alternative sources of biomass and optimization strategies may be considered in future studies so that biochar is applicable in extreme environmental conditions.

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Phytochemical screening and antibacterial efficacy of curry leaves in water purification and fertilizer use

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The phytochemical components and antibacterial effects of the leaf extract of *Murraya koenigii* and the water purification capacity was investigated in the present study. Treated and untreated water samples were studied for physio-chemical characteristics including hardness, TDS, nitrate, BOD and COD and bacteriological analysis using MPN method. Water and ethanol were used as solvents for curry leaf extract preparation which was further utilized for antibacterial and qualitative phytochemical assays. The *in vitro* antibacterial activity assay was performed by the agar well diffusion method. The results showed that both the aqueous and ethanolic leaf extracts had significant antibacterial activity in terms of zone of inhibition against *Escherichia coli*. The ethanolic extract showed a maximum reduction in MPN count of 56.25%. The phytochemical analysis of leaf extract showed the presence of bioactive agents like tannins, flavonoids, terpenoids, phenolic compounds and absence of glycosides, saponins, anthraquinones.

The aim of this study is to investigate the antibacterial properties, phytochemical composition, and water purification potential of curry leaf powder. Phytochemicals found in plants are bioactive compounds that have been shown to offer numerous health benefits, such as reducing the risk of cancer and strokes, as well as exhibiting antimicrobial effects. This work is unique in that it explores both the medicinal and environmental applications of curry leaves, specifically in the context of water purification. By examining the antibacterial and water treatment abilities of curry leaf powder, this study seeks to provide new insights into the versatile uses of curry leaves, with implications for both health and sustainability.

Keywords: agar well diffusion, antibacterial activity, chemical oxygen demand, leaves extract, most probable number, phytochemical components, water purification

INTRODUCTION

Different plant parts are rich in a wide variety of secondary metabolites such as tannins, terpenoids, alkaloids, flavonoids, glycosides which have been found to have antimicrobial properties. The studies about the effect of leaf extracts against different types of bacteria and for sustainable water purification are still one of the most important fields of research [1-2]. The extracts thus obtained may be used as medicinal agents normally expected to contain phytochemicals. Curry leaves are a part of small deciduous aromatic shrub scientifically named *Murraya koenigii* belonging to the family *Rutaceae* commonly considered as natural medicinal plant. Curry leaves have a blood pressure lowering effect, antibacterial activity, antifungal activity, antiprotozoal activity, laxative effect, anti-diarrhoeal activity, wound healing action, anti-cancer activity, antidiabetic activity, anti- inflammatory action, antioxidant, cholesterol lowering effect, antiulcer activity and anti-tumor activity [3-4]. Curry leaf extract showed abroad spectrum of very significant antibacterial activities by producing a clear zone of inhibition against *Staphylococcus, Streptococcus* and *Proteus* [5]. The present study was carried out to evaluate the antibacterial and phytochemical activity, as well as water purification efficacy of curry leaf powder. Phytochemicals are naturally bioactive components found in plants which may reduce cancer, strokes, hinder the aging process and have antimicrobial properties [6-7].

MATERIAL AND METHODS

Collection of plant material and extract preparation

Mature leaves of *Murraya koenigii*, commonly known as curry leaves, were harvested from a botanical garden. After collection, the leaves were sorted and cleaned with tap water, followed by rinsing with distilled water. Subsequently, they were dried in an oven at the optimal temperature and then ground into a powder using a mixer and grinder. This curry leaf powder was utilized to prepare various extracts. For the extraction process, 10 g of the dried leaf powder was placed in a 250 ml conical flask, and 100 ml of water and ethanol were added separately.

The flasks were tightly sealed with polyethylene sheets and vigorously shaken on a shaker for 48 h.

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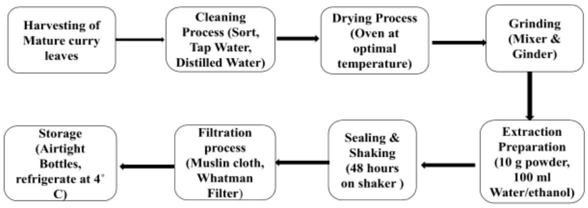
After extraction, both the water and the ethanol extracts were initially filtered through muslin cloth and then through Whatman No.1 filter paper. The resulting filtrates were stored in airtight sample bottles in a refrigerator at 4ºC until further use [4-5].

LITERATURE

Flow Diagram for Curry Leaf Extraction Process



Some studies on curry leaf extract (*Murraya koenigii* L.) highlights the presence of several bioactive compounds including alkaloids, flavonoids, saponins, polyphenols, and tannins. The alkaloid content was found to be 23.73%, as indicated by a positive test that resulted in a white precipitate. Flavonoids were present at a lower concentration of 1.24%, with a pink color formation confirming their presence. Saponins were detected at 8.74%, with foam formation within approximately one min serving as the positive indicator. The polyphenol content was 4.4%, identified by a greenish-black color during testing, while tannins were present at 5.2%, confirmed by a greenish-orange color. UV-Vis spectrophotometry was used to measure the absorbance at various wavelengths, with the levels of flavonoids, polyphenols, and tannins correlating with higher absorbance values at increasing concentrations. These findings suggest that curry leaf extract is rich in bioactive compounds, making it a potential ingredient for both animal feed and medicinal applications [8]. The methanolic extract of *T. cordifolia* stem was most effective against *Staphylococcus aureus*, with *Escherichia coli* being the least sensitive. Amoxicillin was the most potent antibiotic, followed by others like ampicillin and chloramphenicol. A synergistic effect was noted between amoxicillin and *Murraya koenigii* leaf extract, showing maximum inhibition against *Staphylococcus aureus*. Increasing the extract concentration reduced microbial growth. *Murraya* leaves contain bioactive compounds such as steroids, saponins, flavonoids, and alkaloids, which contribute to its antimicrobial properties [9]. Some researchers evaluated the drying behavior and kinetics of curry leaf and pulp, comparing different drying methods. It finds that CHD (conductive hydro drying), particularly at 40°C, is the most efficient for drying time, proximate composition, and antioxidant activity, with the best color retention. CHD at 80°C and freeze drying (FD) excel in preserving phytochemicals and achieving low water activity, essential for longer shelf life**.** FD and CHD at 80°C are also most effective for moisture removal and improving flow properties. The research highlights that while TD (tray drying) is energy-efficient for pulp, CHD offers a better balance of time-saving and quality preservation, making it ideal for maintaining the nutritional and medicinal properties of curry leaves. Overall, CHD is superior for optimizing the drying process to enhance both health and culinary benefits of curry leaf [10]. The health benefits and applications of *Murraya koenigii* (curry leaves), emphasizing their nutritional composition and functional properties. The study reveals that *M. koenigii* leaf powder is a valuable source of fiber, low in fat, and rich in phenolic compounds, making it an effective natural antioxidant. The difference in phenolic and flavonoid content offers insights for future research into their specific health effects. Using advanced techniques like HPLC, SEM, FTIR, and GC-MS, the study provides a comprehensive analysis of its composition and potential uses. These findings lay a strong foundation for developing functional foods, supplements, or therapeutic agents based on the nutritional and bioactive properties of curry leaves, with promising implications for global health and well-being [11].

Culture media and inoculum preparation

Pure culture isolates of *E. coli* were cultivated in nutrient agar broth by inoculating a loopful of culture into sterile nutrient broth, followed by incubation at 37°C for 48 h. From these broth cultures, a loopful was extracted and spread onto sterile nutrient agar plates using a sterile cotton swab to produce a dense, uniform lawn culture. The nutrient agar and broth were prepared individually in distilled water and sterilized by autoclaving at 120°C for 15 min under a pressure of 15 lb. Bacterial cultures of *E. coli* were separately introduced into the nutrient broth and subjected to shaking conditions for 24 h.

Comparison between the present work and published works

Plant leaf	Phyto-chemical components	Antibacterial target	Antibacterial effect	Ref.
Murraya koenigii (Curry leaves)	Alkaloids, Glycosides, Tannins, Saponins, Flavonoids, Steroids	*E. coli*, Coliforms (Water sample)	Significant reduction in coliform count (56.25%) in treated water samples	Present work
Murraya koenigii (Curry leaves)	Alkaloids, Flavonoids, Glycosides, Saponins, Tannins	*Staphylococcus aureus*, *Streptococcus*, *Proteus*	Broad-spectrum antibacterial activity, clear inhibition zones	[5]
Murraya koenigii (Curry leaves)	Alkaloids, Glycosides, Tannins, Flavonoids, Steroids	*E. coli*, *Klebsiella pneumoniae*	Antibacterial activity against *E. coli* and *Klebsiella pneumoniae*	[4]
Murraya koenigii (Curry leaves)	Alkaloids, Flavonoids, Tannins	*E. coli*, *Salmonella*	Significant antibacterial effects	[1]
Murraya koenigii (Curry leaves)	Alkaloids, Flavonoids, Glycosides, Tannins	*E. coli*, *Staphylococcus aureus*, *Bacillus subtilis*	Antibacterial activity against multiple strains	[3]

Collection and analysis of water sample

A sample of pond water was gathered and preserved in pre-cleaned plastic containers. It was then subjected to both physio-chemical and bacteriological analysis using standard protocols, both prior to and following treatment with curry leaf extract. Various parameters including total hardness, nitrate levels, fluoride content, total dissolved solids (TDS), and chemical oxygen demand (COD) were measured in the water samples.

Treatment of effluent

A sample of pond water was treated with 10 ml of alcoholic curry leaf extract and left to incubate for a period of 48 h. Following incubation, the sample was filtered and subjected to analysis. Total dissolved solids (TDS) were determined using the oven drying method, hardness was assessed through EBT-EDTA titration, nitrate and fluoride levels were measured using an Aqua water testing kit, and chemical oxygen demand (COD) was quantified *via* the ferroin-FAS titrimetric method [12].

Most probable number (MPN) test

It is a method used to estimate the viable microorganisms in a sample by means of replicate lactose broth, both single strength and double strength tubes prepared in ten-fold dilution. It is a most commonly used applied test for quality testing of water to ensure whether the water is safe or not in terms of bacteria present in it. A group of bacteria commonly referred to as faecal coliforms act as indicator of faecal contamination of water.

Phytochemical screening of the extract

A known volume of alcoholic curry leaf extract was subjected to the phytochemical tests [13] for alkaloids, glycosides, tannins, flavonoids, saponins, terpenoids and phenolic compounds.

Test for alkaloids: Filtrates were treated with Wagner's reagent (iodine in potassium iodide) Formation of brown/reddish precipitate indicates the presence of alkaloids.

Test for glycosides: The extracts were hydrolyzed with HCl solutions and neutralized with Na_2SO_4 solutions. A few drops of Fehling solution A and B were added. Red precipitate indicates the presence of glycoside.

Test for tannins ($FeCl_3$ solution test): 10% alcoholic ferric chloride solution was added to 2 ml extract. The formation of green color indicated the positive result.

Test for flavonoids: About 0.2 g of the extracts were shaken with 5 ml of distilled water and then a few drops of 10% lead acetate solution was added. A yellow or dirty white precipitate shows the presence of flavonoids.

Test for saponins: 5 ml of hot distilled water was mixed with 1 ml of extract solution and shaken vigorously for two min. The test tube was left for a while and then was checked for the presence or absence of frothing formation as an indication of presence of saponins.

Test for terpenoids: To 200 mg of the dry crude extract, 2 ml of chloroform and 3 ml of concentrated sulfuric acid were added. Formation of a reddish-brown color is an indication of the presence of terpenoids.

Test for phenolic compounds: 1 ml of the methanol extract was treated with 10% ethanolic ferric chloride. Change in color from blue-green to dark blue is an indication of the presence of phenolic compounds.

Antibacterial activity assay by agar well diffusion

The antibacterial activity of the curry leaf extract was assessed against pre-prepared 20 ml of sterilized Müller-Hinton agar plates. These plates were inoculated with 100 µl of fresh *E. coli* culture, which was evenly spread across the surface using a sterile swap spreader to ensure uniform microbial growth. Following inoculation, heat-sterilized cork borers with a diameter of 10 mm were employed to create wells in the agar medium. Subsequently, 50 µL of the curry leaf extract was loaded into the wells and tested against the inoculated organism. Diluted curry leaf extract was poured into the wells. The plates were then placed in an incubator at 37°C for 24 h and subsequently examined for clear zones of inhibition, which were measured. Sterile water was used as a control in this experiment.

Similarly, for another set of experiments, bacterial inoculum was uniformly spread onto sterile Petri plates and allowed to solidify. Following this, four wells were created in each plate using a cork borer with a diameter of 10 mm. Different concentrations (100%, 10%, and 5%) of ethanol extracts from selected plant sources were added to three respective wells, while one well was filled with 70% ethyl alcohol. The Petri plates were then incubated for 18-24 h and observed for bacterial growth. The zone of inhibition surrounding bacterial growth was measured in mm.

RESULTS AND DISCUSSION

Aqueous test of water sample

Table 1. Water quality parameters after treatment with ethanolic extract

S. No	Parameter (mg/l)	Before treatment	After treatment	% Removal
1.	TDS	578	380	34
2.	Total hardness	300	90	70
3.	Fluorides	2.5	0.5	90
4.	Nitrate	200	50	75
5.	COD	124	100	19

Treatment with the curry leaf extract resulted in a significant reduction in the hardness (300 to 90 mg/l), fluorides (2.5 to 0.5 mg/l), nitrate (200 to 50 mg/l) of the water sample at a concentration of 100 mg/l, which was in accordance with previous literature (Table 1). Treatment with curry leaf extracts presented moderate reductions in the TDS (578 to 380 mg/L) and COD (124 to 100 mg/l) of the pond water samples [14-15]. These findings strongly validate the high coagulation potential of the curry leaf extract in purification of water [16].

Chemical oxygen demand (COD) analysis

Chemical oxygen demand (COD) is a measure of the capacity of water to consume oxygen during the decomposition of organic matter and the oxidation of inorganic chemicals. The higher the value of COD, the lower is the dissolved oxygen in water. An aliquot of the sample was digested for 2 h at 150°C in the presence of dichromate and sulfuric acid. The resulting solution was titrated to a colored endpoint with ferroin indicator.

Equations for COD:

$$\text{COD} = \frac{(a-b)\times N\times 8\times 1000}{Volume\ of\ Sample\ (mL)}$$

Result of water sample without treatment:

$$\text{COD} = \frac{(8.1-5)\times 0.1\times 1000\times 8}{20} = 124\text{ mg/l}$$

The total chemical oxygen demand in untreated water sample was 124 mg/l.

Result of water sample after treatment

$$\text{COD} = \frac{(8.1-5.6)\times 0.1\times 1000\times 8}{20} = 100\text{ mg/l}$$

The chemical oxygen demand in the water sample after treatment with curry leaves extract was 100 mg/l.

Phytochemical analysis of curry leaf ethanolic extract

A small portion of ethanolic extract was subjected to the phytochemical testing for alkaloids, glycosides, tannins, flavonoids, saponins, terpenoids, phenolic compounds and anthraquinones (Table 2).

Table 2. Phytochemical analysis test results

S. no	Phytochemical test	Results
1.	Alkaloids	-
2.	Glycosides	-
3.	Tannins	+
4.	Flavonoids	+
5.	Saponins	-
6.	Terpenoids	+
7.	Phenolic compound	+
8.	Anthraquinones	-

[(+) means present, (-) means absent]

Presence of different phytochemicals in leaves of *M. koenigii* Linn., is shown in Table 2. The results are in confirmation to [4, 6].

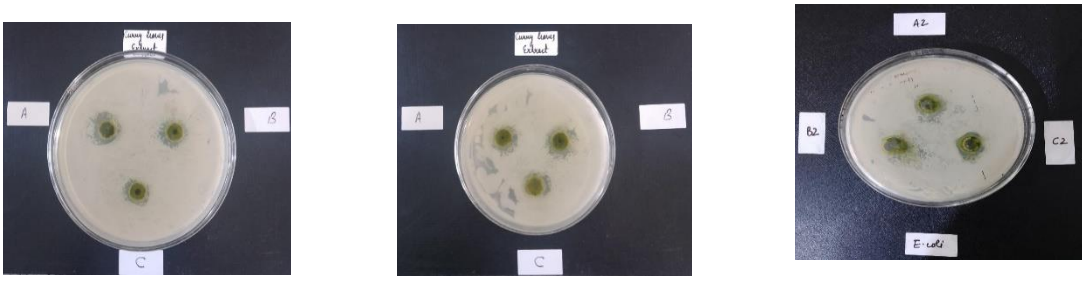
Antimicrobial activity (mm) of M. koenigii leaves extracts against test organisms

Antimicrobial test for the ethanolic and aqueous leaves extract was carried out against *E. coli* on the already prepared 20 ml of sterilized Muller-Hinton agar plates which were inoculated and incubated at 37^0C for 24 h. A heat-sterilized 10 mm cork borer was then used to make wells in the already inoculated medium and the plant sample to be tested against each test organism [17]. The sterile petri plates were filled with sterilized nutritional agar medium (20 ml) and allowed to harden. The *E. coli* broth culture was swabbed on an agar plate using a sterile bud. The wells (5 mm in diameter) were drilled into the agar with a sterile borer. Curry leaves extract was aseptically placed into each well and incubated at 37°C for 24 h. A measurement of the inhibitory zone was made (Table 3). Antibacterial activity was measured with ruler using the diameter of the inhibition zone which was measured in millimetres [18]. It was shown that the bigger the zone, the higher is the antibacterial activity but the lack of zone of inhibition does not necessarily mean absence of activity. A zone is generally shown by antimicrobial agents which kill the microbes present on as well as around the treated area [13,19]. From Table 3 it is observed that ethanolic extract is more effective for varying concentrations against *E. coli* culture as compared to the aqueous extract.

Table 3. Antimicrobial activity results for both extracts

Bacteria	Concentration	Aqueous extract	Ethanolic extract
Escherichia coli (*E. coli*)	100 ppm	5 mm	15 mm
	50 ppm	9 mm	12 mm
	25 ppm	5 mm	12 mm

Aqueous extract result



100 ppm 50 ppm 25 ppm

Fig. 1. Zones of inhibition by aqueous curry leaf extract for 100 ppm, 50 ppm and 25 ppm.

Ethanolic extract result

100 ppm 50 ppm 25 ppm

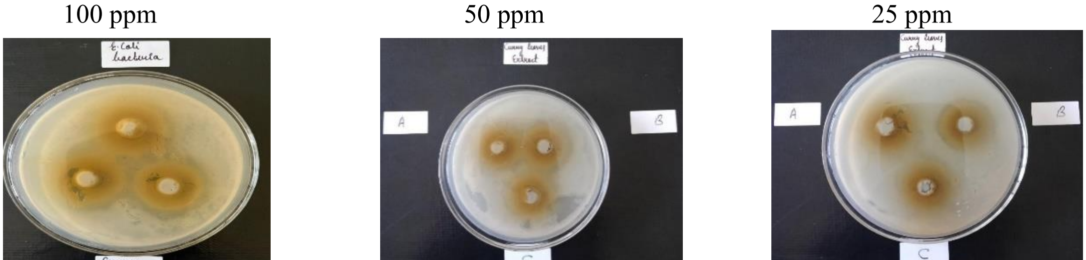


Fig. 2. Zones of inhibition by ethanolic leaf extract for 100 ppm, 50 ppm, 25 ppm.

Total coliform using the most probable number (MPN) method

The most probable number (MPN) method is a statistical method used to estimate the viable numbers of coliform bacteria in a water sample by inoculating lactose broth in 10-fold dilutions and is based on the principle of extinction dilution [20]. The presumptive test involves inoculating multiple tubes of liquid growth medium with different volumes of the sample being tested. Dispense the double strength medium in 6 tubes (10 ml in each tube) and single strength medium in 3 tubes (10 ml in each tube) and add Durham tube in an inverted position. The test tubes were then incubated at 37^0C for 24-48 h. The test involves observing the media color change and/or formation of gas bubbles in the tubes from the confirmed test.

The number of tubes showing gas production were counted and the figure was compared to a table developed by American Public Health Association (Table 4). The number was the MPN of coliform per 100 ml of the water sample [17, 21].

Table 4. Most probable number (MPN) results

S.no	Pond water with ethanolic extract	Untreated water sample	Treated water sample	MPN count of untreated water sample	MPN count of treated water sample	% Reduction in MPN count
1.	10ml	3	2	16	7	56.25
2.	1ml	2	1			
3.	0.1ml	1	1			

MAJOR CHALLENGES

The study on *Murraya koenigii* (curry leaves) extracts shows its potential for antibacterial activity and water purification. However, several challenges need to be addressed. These include variations in phytochemical composition due to factors like location and extraction methods, which can affect consistency. Additionally, the extraction process may be inefficient, leading to high costs and low yields. The exact mechanisms behind the antimicrobial and water-purifying effects are not fully understood, requiring further investigation. Scaling up production for commercial use presents logistical and financial difficulties, and the safety of the extract needs thorough evaluation. Regulatory approval is another challenge, along with the need to assess its effectiveness against a broader range of pathogens. Overcoming these challenges will be essential for the widespread use of curry leaf extract in different applications.

CONCLUSIONS

From the present research it follows that the curry leaves extract was successful in increasing the purification of water by reduction in various parameters. There was a significant reduction (56.25%) of coliform count in treated water sample with curry leaves extract [22] as seen from Table 4. The phytochemical analysis revealed the presence of bioactive compounds which are responsible for the *in vitro* antimicrobial action of the ethanolic extract of *Murraya koenigii* on *E. coli* strain. The results showed that extracts obtained from the leaves of the plant *Murraya koenigii* are rich sources of potent phytochemicals and have inhibitory effects on the tested microbes. From previous studies and the current work, it is clear that the plant is a rich source of alkaloids, glycosides, tannins, saponins, flavonoids and steroids. These bioactive complex phytochemicals can be used for the development of potent drugs, medicines or antimicrobial agents that can be used for various purposes for human welfare upon further extensive and systematic studies.

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Extraction and isolation of stevioside and rebaudiana A from *Stevia Bertoni* leaves

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Stevia rebaudiana Bertoni leaves are a natural source of diterpenic glycosides and various bioactive compounds. Over the past two decades, this plant has garnered substantial scientific and industrial interest as a potential nutritional alternative to sugar. Notably, stevia contains glycosides, particularly stevioside (ST) and rebaudioside A (Reb-A), which are of significant interest for their applications in the production of sweeteners, nutraceuticals, and functional foods. This study systematically examines the influence of key extraction parameters, including plant material size, solvent type, solid-to-liquid (S/L) ratio, and agitation, on the extraction efficiency of ST and Reb A. The optimized extraction methodology developed in this study yielded 42.07 % of the total extract from stevia dry leaves. These findings provide valuable insights for enhancing the efficiency of the extraction and isolation processes, facilitating their potential scale-up for industrial applications.

Keywords: Stevia, stevioside, rebaudiana-A, extraction, isolation, purification.

INTRODUCTION

Stevia Rebaudiana Bertoni, a sweet hub from South America, is being cultivated around the world and used as a low-calorific natural sweetener in food and beverage industries as it is 200-300 times sweeter than sugar [1]. Its sweetness is mainly due to two steviol glycosides, namely stevioside (ST) and rebaudiana A (Reb A) [2]. There are various conventional or green extraction methods reported to extract ST and Reb A from stevia leaves [3-7]. In a recent publication, different green methods such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), and supercritical fluid extraction (SFE) were used to extract ST and Reb A from stevia leaves [8]. In green extraction technology, a solvent such as water, methanol, isopropyl alcohol, or glycerol was used to yield the key components in the extract solution [4, 6, 9-11]. In recent publications, researchers have also used a binary solution of different alcohols for better extraction yield [3, 5, 6, 12-14]. The highest steviol glycoside extracted in the extract phase reported for green extraction is 26.91 g/100g stevia leaves using pressurized liquid extraction using 70% ethanol as a solvent at process conditions of L/S = 30 mlg^{-1}, 60 min, 125 ºC and 10.0 MPa [15]. Most of the green extraction methods used for extraction of ST and Reb A reported in literature haven't used any further unit operation to get steviol glycoside in crystal form which is essential, as it is used as a natural sweetener in the food industry. Most of the authors of research work related to green extraction methods haven't included any isolation or purification steps to get the product in the crystal form. However, many researchers have used the conventional extraction method followed by various isolation steps to get steviol glycoside in the crystal form [16-20]. Moreover, all the green extraction methods require high initial capital costs and can't be operated continuously and hence are difficult to be scaled up at industrial level [21].

After extraction of steviol glycosides from stevia a crude extract was obtained which was foul-smelling, bitter-tasting, and dark brown, unable to be used directly in food products. Therefore, successive purification is necessary for developing a product of commercial quality (90% purity and up). Purification of stevioside often involves processes such as inorganic salt treatment, ion exchange separation, columns, solvent liquid extraction, ion exchange, ultra-membranes, nanofiltration, crystallization and fractional distillation [22-28]. There are few publications involving conventional extraction and modern purification steps which were based on size difference (membrane separation), charges (ion exchange), solubility (crystallization)

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and polarity (chromatography) available in the literature. [16, 19, 20, 29-33]. In a recent publication, 4.15 g of dry extract of steviol glycoside was obtained from 10.5 g initially present in 100 g of stevia leaves which have 39.52 % overall efficiency [33]. The extraction and isolation of pure steviol glycosides, as reported in the literature, are often labor-intensive, costly, and energy-demanding. Certain isolation methods for steviol glycosides generate harmful residues and bitter alkaloids, which can negatively impact the quality and taste of the sweet glycosides [20, 34]. Despite the significant advancement in extraction and purification, the production of pure steviol glycosides that are scalable, is still complicated [19]. Thus, there was a need to have a combination of extraction and isolation steps to get ST and Reb A from stevia leaves which are scalable at an industrial scale. In this work, the combination of extraction and isolation steps was developed to get the ST and Reb A in crystal form.

MATERIALS AND METHODS

Materials

Stevia leaves which wre a raw material for the process were purchased from local farmers in Gujarat, India. Leaves were dried in shade for two days and moisture content was kept close to zero before being grounded to 400-500 µm. The standard HPLC grade ST (85 %) and Reb-A (98%) were purchased from TCI Chemical, India. The HPLC-grade solvents such as water, butanol, methanol and isopropyl alcohol have been purchased from Alpha Chemika, India.

Effect of different solvents on extraction

A 5 g sample of dried grounded stevia leaves was taken in a 100 mL beaker with solvent as per the required solid-to-liquid ratio (1:10, 1:15, 1:20 and 1:25.). It was kept for maceration for 24 h. After 24 hours the sample was filtered by vacuum filtration. After experimenting with extraction using different solvents, the 2 mL sample was taken and sent for HPLC analysis.

ST and Reb A content in stevia leaves

The content of ST and Reb A in stevia leaves was determined by the reflux extraction method. The stevia powder of 50 g was extracted with 750 mL of water using the reflux extraction method for 8 h. After extraction, the mixture was cooled, and filtered by vacuum and 5 mL of the sample was analyzed by HPLC analysis.

Effect of agitation on extraction

The extraction was performed in a glass beaker of 1 L capacity filled with 750 mL of water as a solvent. An overhead stirrer was used at 100 rpm. The temperature was controlled through an automatic PID temperature-controlled water bath (15 L) for extraction and kept at 80 ºC. 50 g of dried stevia powder with a size of 400-500 µm was added to the beaker. The extraction was performed for 4 h and the mixture was cooled and filtered using vacuum filtration unit. A sample of 2 mL was taken for HPLC analysis. The procedure above was repeated at different speeds (100 rpm, 200 rpm, 300 rpm, & 400 rpm) to study the effect of agitation on extraction.

Extraction technology

A powdered sample of 130 g was used for extraction with 1950 mL of water as a solvent at 80 ºC for 4 h. The aqueous extract was cooled, filtered under vacuum (600-620 mm Hg) and further processed by electrocoagulation to remove chlorophylls which give a green color to the extract. In this step, a direct current (15 V, 0.8-1.2 A) was passed for 1 h *via* two pairs of aluminium plates as electrodes and 15 g NaCl was added as an electrolyte. The resulting mixture was again vacuum filtered and the process of electrocoagulation was repeated once more to remove all chlorophyll. The resulting solution was passed through 7.36 g of activated charcoal. Further, cation and anion resins were used to remove dissolved ions like Na, K, Ca Mg, and P from the solution. After this operation to filter the solution celite was used as a filter aid, which was found more effective to be used for filtration. The extract was preconcentrated by vacuum evaporation. For crystallization, butanol was used as an anti-solvent to obtain crystals. After each process step, samples were taken and sent for HPLC analysis. A material balance was performed in each stage. The extraction recovery of the extraction technology was calculated using the following equation:

$$\%Yield\ (Extraction\ Recovery) = \frac{content\ of\ ST\ and\ Reb\ A\ in\ crystal\ in\ gram}{content\ of\ ST\ and\ Reb\ A\ stevia\ dried\ leaves\ in\ gram} \times 100. \quad (1)$$

HPLC method

The chromatographic method was carried out on a C18 (2) (length: 250 mm; inner diameter: 4.6 mm, particle size: 5 µm) column without temperature control with a UV-Vis detector set to a wavelength of 210 nm. The mobile phase was a 32:68 (v/v) mixture of acetonitrile: water and 10 mmol/L sodium phosphate buffer (pH 2.6) at a flow rate of 1 mL/min.

The sample injection volume was 20 µL and HPLC analysis was performed [35].

RESULTS AND DISCUSSION

Effect of different solvents on extraction

Many popular solvents such as isopropyl alcohol, methanol, water and butanol were used for extracting ST and Reb A from stevia leaves in this study. The extraction was carried out at room temperature and the duration of extraction was 24 h. The % extraction recovery of ST and Reb A from stevia leaves using different solvents at different S/L ratios is shown in Fig. 1. For the lower S/L ratio, less amount of solvent for extraction was observed. It dissolved lesser phytochemicals from the plant material. With increasing S/L, the concentration gradient for the diffusion of solute from leaves to solvent increases and hence liquid extraction efficiency increases. The results, summarized in Table 1, demonstrate that methanol achieved the highest extraction recovery across different solid-to-liquid ratios, highlighting its superior solvent efficiency. However, methanol is costlier, more volatile compound than water. Since methanol has a boiling point of 64.7 ºC, Extraction cannot be operated beyond 60 ºC for methanol due to its low boiling point. Since ST and Reb A can remain stable up to 90 ºC for a large pH range[36], water can be used to extract more phytochemicals from the plant material at higher temperatures as rising in the temperature, the diffusivity of solute was increased in solvent for extraction.

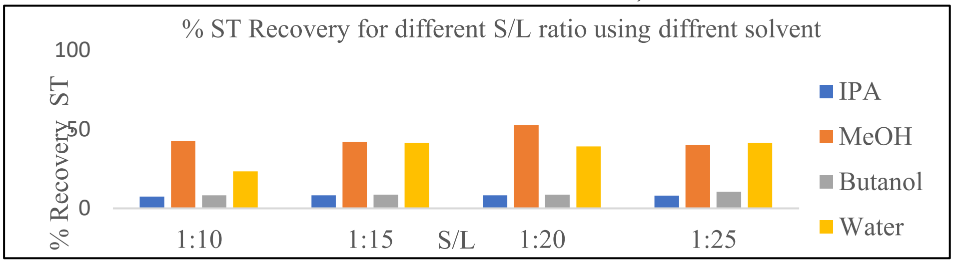


Figure 1. Extraction of ST using (A) IPA (B) n-butanol, (C) water (D) meOH

Table 1. Best S/L ratio for extracting ST and Reb A using the maceration method

Solvent	Best S:L ratio	% Reb A recovery	% ST recovery
IPA	1:15	5.61 %	8.32 %
n-butanol	1:25	7.29 %	10.47 %
Water	1:15	47.05%	41.27 %
Methanol	1:20	56.23 %	52.68 %

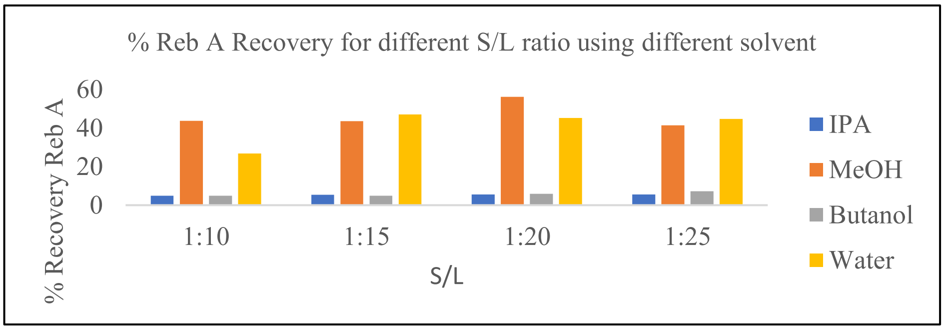


Figure 2. Extraction of Reb A using (A) IPA, (B) n-butanol, (C) water (D) MeOH

Effect of size of particle size on extraction

In this study, extraction experiments were carried out on different sieve sizes of the stevia leaves powder (120 µm,200 µm, 332 µm, 404 µm, 812.5 µm) and also for whole leaves while other extraction parameters remained the same (S/L=15, Temperature = 70 ºC, Time =3 h). In this work, the effect of different size of stevia leaves on the recovery extraction of ST and Reb A were studied using water as a solvent. Fig. 3 shows the effects of different particle sizes on extraction recovery. The result shows that the extraction yield sharply increases until the 200 µm size. Particle size below extraction recovery remains almost constant. The extraction recovery was not increased beyond 200 µm size. This suggests the internal mass transfer remains the rate-limiting step until the size of 200 µm. By reducing the size of the particle, the surface area can be increased Which reduces the diffusion path for mass transfer resulting in increased extraction. It also helps to rupture cells of the leaves and hence increases the efficiency of extraction. Fig. 3 also suggests that the extraction of unwanted phytochemical increases if size of the stevia leaves decreases. Similar results were found in the literature [37].

Effect of agitation on extraction

In this work, to study the effect of agitation on extraction, the extraction of stevioside and Reb A from stevia leaves to powder using water at the agitation of 300 RPM and without agitation, was performed and compared. During the extraction, in the absence of agitation, the settling of the stevia powder was observed during the experiment. The comparison of recovery of extraction for 300 RPM and without agitation is given in Fig. 4. From Fig. 4, it can be observed that the extraction recovery for 300 RPM is higher than extraction without agitation. During the extraction, the solute transfer was done in three steps. (1) washing (2) internal diffusion (3) external diffusion. In internal diffusion, solvent reaches through the pores of the plant material, dissolved the solute and diffused out near the solid surface.

However, during the external diffusion, solute was transferred from the surface of the solid to the bulk of the solvent. The experiment at 300 RPM was conducted to ensure the turbulent region outside the solid material ($N_{Re} > 10{,}000$). This agitation effect has created no resistance to external diffusion. Hence, the overall extraction efficiency has increased. However, extraction rates seem to remain highest at 300 rpm. Beyond 300 rpm, in this work, internal diffusion seems to be the controlling step.

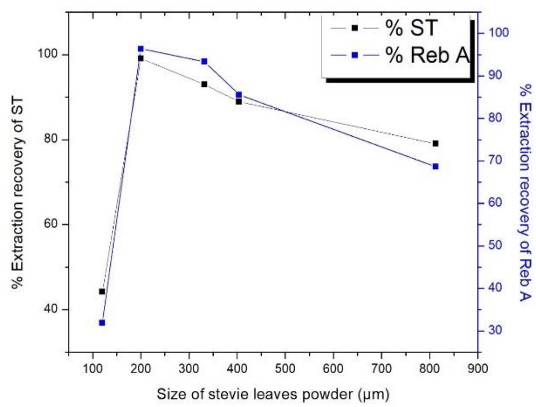


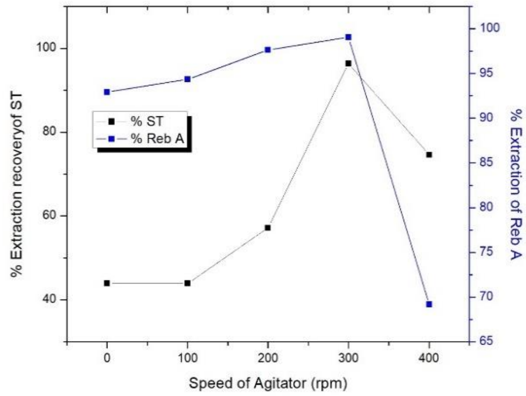
Figure 3. Effect of size of stevia leaves powder on the extraction of ST and Reb A at 80 ºC

Effect of S/L ratio on extraction

For different S/L ratios, extraction kinetics studies were conducted to observe the effect of the

Figure 4. Effect of agitation speed on extraction at 80 ºC and S/L =15

duration of extraction. From Fig. 4, it can be



observed that the best extraction recovery can be achieved by using S/L =15. At a lower S/L ratio, For S/L= 10 , all solvent evaporated during extraction studies and the extraction experiment was stopped at around 2 h.

Purification of extract

The extraction technology for extraction and isolation of ST and Reb A from stevia leaves was developed. This schematic diagram of the methodology is given in Fig. 5. The detailed compound material balance of ST and Reb A at each stage is given in Table 2. The extraction technology developed in our previous work has been used for the material balance of ST and Reb A[38]. In this extraction technology, a study has been carried out to find the importance of each unit operation step in this technology. Before the extraction step, the content of the ST and Reb A in stevia leaves was determined using the reflux extraction method as per the previous discussion. The extraction step recovered 86 % of ST and 92.50 % of Reb A from the stevia leaves. In the extract impurities such as pigments, chlorophylls were also present. For isolation and purification of ST and Reb A electrocoagulation, adsorption by activated charcoal, cation, anion, and vacuum evaporation were used. In isolation and purification steps, 60.47 % of ST and 24.66 % Reb A were recovered.

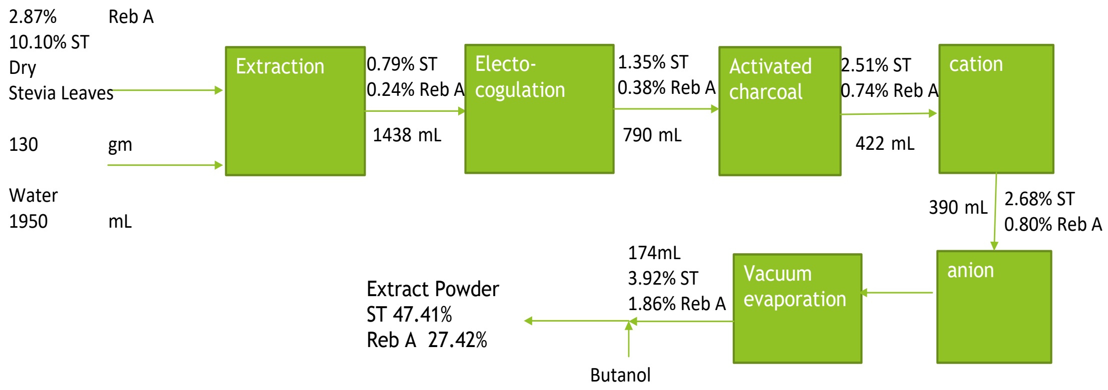


Figure 5. Extraction and isolation of ST and Reb A from stevia leaves (prepared in this work)

Table 2. Material balance of ST and Reb A from 130 stevia leaves to powder and 1950 mL of water

Sr. No	Unit operation	Input ST (g)	Output ST (g)	Input Reb A (g)	Output Reb A (g)	Conc. of ST	Conc. of Reb A
1	Extraction	13.13	11.36	3.73	3.45	0.79%	0.24%
2	Electro-coagulation	11.36	10.66	3.45	3.00	1.35%	0.38%
3	Activated charcoal	10.66	10.59	3.00	3.12	2.51%	0.74%
4	Cation	10.59	10.45	3.12	3.12	2.68%	0.80%
5	Anion	10.45	9.69	3.12	2.93	2.91%	0.88%
6	Vacuum Evaporation	9.69	6.82	2.93	3.24	3.92%	1.86%
7	Extract power	6.82	4.49	3.24	2.60	47.41%	27.42%

Table 3. Yield/ Extraction recovery of ST and Reb A using extraction and isolation method

S. No	Compound	In 130 g leaves (g)	In extract powder (g)	Yield of the purifiction
1	ST	13.13	4.49	34.23%
2	Reb A	3.73	2.60	69.67%
3	Total extract (mixture of ST and Reb A)	16.86	7.09	42.07%

Table 4. Summery of recent studies of UAE

Power	Time	Temp	Tip dia	Solvent	Result	Optimi-zation	Ref.
360 W	18 min	30 ^{0}C	20 mm	Isopropyl alcohol (60%)	35.61 mg/ 100 g (Reb A)	NA	[13]
330 W	1 min	50 °C	Ultrasonic bath	Water	14.12 mg/g (Reb A) 39.09 mg/g (ST)	NA	[10]
400 W	10 min	81.2 ˚C.	22 mm	Water	36.92 mg/g (Reb A) 96.48 mg/g (ST)	NA	[39]
480 W	18 min	30 ^{0}C	20 mm	Isopropyl alcohol (60%)	371 mg/ g (Reb A)	NA	[6]
360 W	6 min	30 ^{0}C	20 mm	EtOH (30 %)	338.5 mg/g (Reb A)	NA	[6]
360 W	6 min	30 ^{0}C	20 mm	Water	327.9 mg/g (Reb A)	NA	[6]

Table 5. Recent summery of MAE

Power	Time	Temp	Solid to liquid ratio	Solvent	Result	Optimi-zation	Ref
80 W	1 min	50 ^{0}C	100 mg/ 10 ml	Methanol :water (80 :20)	ST: 8.64 mg/g Reb A: 2.34 mg/g	NA	[9, 40]

200 W	120 sec	30 ^{0}C	1 g/10 ml	Water	ST: 76.58 mg/100 g	NA	[4]
3.30 W/gm	1 min	50 ^{0}C	1 g/100 ml	Water	ST: 46.48 mg/g, (Reb A): 17.03 mg/gm	NA	[10]
400 W	45 min	90 ^{0}C	1:10 g/ml	Ethanol	Reb A:4.21 mg/g , ST:17mg/g	RSM	[41]
160 W	4 min	50 ^{0}C	25 g/ 250 ml	75 % ethanol	ST:19.58 mg/g Reb-A 15.3 mg/g	ANN is better than RSM	[5]

Table 6. Summary of recent studies on SCF of ST and Reb A from stevia

Pressure	Temp	Solvent	Recovery	Remarks	Ref
211 bar	80 ^{0}C	17.4 % ethanol	ST: 36.66 mg/g Reb A: 17.79 mg/g	RSM (BBD)	[42]
225 bar	45 ^{0}C	40 % ethanol	ST: 98.56 mg/g Reb A: 65.07 mg/g	ANN is better than RSM (CCD)	[43]

The total extract (mixture of ST and Reb A) of 7.09 g in crystal form was recovered using this extraction technology. The yield of ST and Reb A was 34.23 % and 69.67 %, respectively and it is given in Table 3. The extraction method discussed in this paper were compared with literature and prsented in Tables 4-6. In this extraction work, the content of the ST and Reb A in the dry stevia leaves were 16.9 g and 5.02 g, respectively. The % of recovery of ST and Reb A from the stevia leaves was 97.40 % and 98.80 %, respectively.

Domestic farms supplied stevia leaves for under $2 per kg, and the main solvent used in the extraction process was water. This technology employs a recoverable organic solvent, which further increases cost effectiveness. The production cost for one gram of Steviol glycoside (ST and Reb A) crystals is about $0.10, which makes it the cheapest method. There is a possibility of selling the extract at $13 per gram.There is also a wide market for these extracts as they can be used in cosmetic manufacturing. The low set up costs are also due to an inability to use novel extraction techniques, as the process of purification in stamping does not involve any complex technologies. Furthermore, the combination of purification steps practiced makes this technology easily adaptable to high production volumes.

CONCLUSION

Stevia Rebaudiana Bertoni becomes an attractive natural sweetener in today's world because of its health benefits. To extract stevioside and Reb A from stevia leaves, the latter should be dried and ground before the extraction which can enhance the extraction yield. Moreover, from this study, water can be used instead of methanol because of its cost and lower hazard to the environment. In extraction, stevia leaves in powder form should be used to enhance extraction efficiency. In this work, crystals of 5.45 g of extract powder of steviol glycoside were obtained from 12.96 g initially present in the 100 g of stevia leaves which shows that our extraction methodology has 42 % extraction efficiency. In the work, various parameters such as duration, size of the leaves, solid-to-solvent ratio and temperature are reported that can affect the yield of the extraction steps. Thus, estimating the optimum conditions for extraction the overall yield of the entire extraction can be enhanced and the isolation methodology to get the product in crystal form.

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Effect of various nano-particles and surface treatments on the mechanical properties of jute basalt fiber reinforced epoxy-based composites: a review

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Depletion of fossil fuels, global warming, carbon footprints on the environment are the major issues leading to the requirement for sustainable materials. Researchers are endeavoring to develop the green polymer composites for various structural and non-structural applications. Lots of research studies are going on for the surface improvement of natural fibers with the help of various surface treatments. For further improvement in the mechanical properties, nano particles are also used as reinforcements in the polymer composites made by natural fiber reinforcement. Still a lot of research is further required which replace synthetic composites with green polymer composites due to their biodegradability and sustainability concerns. This review aims to give more insight into the adoption and effect of methods used for surface treatment and the use of nano particles on the mechanical properties of jute/ composites made using epoxy with basalt reinforcement.

Keywords: nanoparticles, natural fibers, polymer composites, mechanical properties, jute fiber, basalt fiber, surface treatment

INTRODUCTION

A composite material has characteristics that are significantly different from those of its constituent materials when it is formed using multiple materials having varied physical as well as chemical characteristics The first uses of composites date back to 1500 B.C. when the Egyptians and Mesopotamians made use of straw and mud in the construction of houses and buildings. These composites have stood the test of time, with continual improvements and advancements to enhance their strength and usability. Over the years, new technologies and techniques have been developed to make these traditional materials more durable and sustainable. Straw and mud composites offer a natural and eco-friendly alternative to modern building materials. They are readily available, inexpensive, and have excellent insulating properties. Additionally, they have a low carbon footprint, making them a popular choice for environmentally conscious construction projects [1]. Over the years, traditional materials like steel, concrete, and timber have been widely used for various construction and development purposes. However, as society has become more aware of the importance of sustainability, there has been a shift towards utilizing composite materials in different applications. Composites offer numerous benefits, such as being lightweight, strong, and corrosion-resistant, making them ideal for a wide range of uses. The introduction of natural fiber-reinforced polymer composite materials has come as a timely solution to the need for more sustainable and environmentally friendly alternatives. With their high mechanical properties, natural fibers show great promise in potentially replacing conventional composites. Developmental efforts are under process to explore the possibilities of obtaining polymer composites by reinforcing with natural fibers that are not only effective but also eco-friendly.

Natural fibers are derived from various sources such as jute, flax, kenaf, banana, many more, each with its unique characteristics. These fibers are of biological origin, emphasizing their biodegradability and renewability, making them a preferred choice in today's environmentally conscious world. Moreover, natural fibers offer high specific strength and modulus, processing flexibility, low self-weight, cost-effectiveness, and significant resistance to corrosion and fatigue. The development and utilization of natural fiber-reinforced polymer composites represent a significant step towards sustainable materials that

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do not compromise on performance. As research in this field progresses, innovative applications of natural fibers are expected in various industries, contributing to a greener and more sustainable future [2]

Strong reinforcing fibers held together with cost-effective, tough, environmentally durable resin systems showed immense potential. Being lightweight made it exceptional reinforcement for already deteriorating conventional structures. Increased durability, controllable thermal properties, tailored performance were among other benefits [3]. High moisture absorption, high anisotropy, poor compatibility with traditional resins, and lower homogeneity than glass and carbon fibers are a few disadvantages [4].

The strength of composites depends highly on the adhesion between fiber and polymer matrix. Fiber surface treatments are performed to shield the fibers from mechanical harm and to increase fiber-matrix adhesion. Different kinds of surface treatment have different effects on the properties of fiber [5]. [6] discussed the issue of poor compatibility of natural fibers hydrophobic polymer matrices and the solution, i.e., greener surface treatments using different alternatives such as plasma treatment, use of enzymes, use of fungi, coating natural fibers with nanocellulose. To improve the interfacial strength and bonding between natural fibers and the matrix material, [7] applied surface treatment techniques such as alkalization and mercerization. According to this study, if a fiber has good matrix compatibility, its mechanical characteristics will improve as needed for various applications. Figure 1 represents the classification of various natural fibers [7].

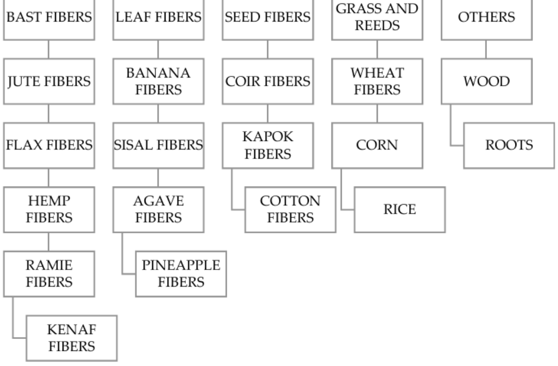

Figure 1. Classification of various natural fibers [7]

Composites made of a polymer matrix with functional nanoparticles added as fillers have been popular for a few years. A variety of nanoparticles such as silicon carbide, silica, calcium carbonate, zinc, alumina, carbon black nanoparticles, etc. are being used for reinforcements in the fabrication of composite materials [8]. Nanoparticles can enhance and even change the properties of composites (including optical, dielectric, electronic, magnetic, and mechanical) [9]. [8] Used basalt nanoparticles on basalt epoxy composites. Compared to traditional basalt fiber epoxy-reinforced composites, these composites demonstrated better mechanical characteristics. This is explained by the fact that there is an enhanced force of friction between the matrix and nanoparticles, which causes a higher mechanical interlock of the composite system. To create nanocomposites that can withstand hard environments and reduce the danger of fire accidents, [10] treated basalt/epoxy composite tubes, neat epoxy, and filament-wound E-glass/epoxy tubes with silica nanoparticles. The addition of silica nanoparticles (less than or comparable to 1.5 wt %) to the neat epoxy and FRP composites resulted in an improvement in the flexural and thermal properties [11]. Treated coir-basalt-innegra fibers reinforced bio-synthetic epoxy composites with coir micro-particles and titanium carbide (TiC) nanofillers. The best results for flexural strength (4.43 times pure bio epoxy composites) were found when synthetic epoxy composites were treated with 5% micro-fiber of coir and 5% nanoparticles of TiC.

In recent times, basalt and jute fibers have emerged as key players in the world of natural fibers. Basalt fiber has become a popular choice due to its ability to create cost-effective hybrid materials with impressive qualities. Its exceptional heat resistance, capable of withstanding temperatures up to 600°C with minimal weight loss, makes it a sought-after material for various applications. Additionally, basalt fiber boasts sophisticated mechanical properties, further enhancing its appeal in industries looking for durable and reliable materials. By harnessing the potential of basalt fiber, manufacturers can develop innovative products that meet the demands of modern technology and construction. As sustainability and efficiency have become increasingly important, the versatility and performance of basalt fiber make it a promising contender in the natural fiber market [12] Jute is a natural fiber with properties similar to basalt fiber, making it a popular choice for various applications. Not only is jute cost-effective and strong, but it is also biodegradable and sustainable, making it an environment-friendly option. Additionally, jute can absorb more energy, making it a material, trustworthy for different purposes. One of the advantages of jute is its abundance in nature, ensuring a steady supply for industries. Furthermore, jute burns cleanly and releases no carbon dioxide, further adding to its eco-friendly profile. Overall, the unique properties of jute make it a versatile and practical choice for a wide range of products and industries, contributing to a more sustainable and greener future [13]. But jute has a major drawback, i.e. low impact strength as compared to other counterparts.

Composites are widely recognized for their versatility and strength, making them vital components in various industries in today's world. The increasing demand for composites underscores the importance of exploring continuous advancements in this field. This comprehensive study delves deep into the intricate fundamentals of composite materials, with a particular emphasis on natural fiber composites like basalt and jute fibers. These natural fibers, with their exceptional properties and eco-friendly characteristics, have generated significant interest from researchers. The current research meticulously scrutinizes the unique properties of basalt and jute fibers individually, while also delving into the enormous potential of combining them to create jute basalt composites. By closely examining the chemical and mechanical properties of these fibers, the researchers aim to gain insights into how these materials can be effectively applied in a wide array of applications. Moreover, the study underscores the critical role of surface modification in increasing the complete performance of composites. Various methodologies for surface modification are thoroughly discussed, including the incorporation of nanoparticles to further elevate the properties of composites to new heights. Through an exploration of diverse nanomaterials and their potential applications, the researchers aspire to push the boundaries of composite technology, unlocking innovative possibilities. Furthermore, the research elaborates on the different methodologies employed in composite development and envisions potential advancements on the horizon. By continuously striving for innovation and staying abreast of emerging trends, researchers are opening doors to new avenues for polymer composites, ensuring their sustained growth and evolution in our rapidly changing world.

Based upon the source, natural fibers can be categorized as animals such as wool from sheep, camel, goat, rabbit, horse, and angora, and plants such as seed fiber cotton, kapok, akon, rice & husk, bast fiber as flax, hemp, jute, ramie & husk, leaf fiber as sisal, plam, manila, carua & abaca, hard fiber as agave, banana & coir, bamboo, wheat, rice, grass & corn and mineral as asbestos, basalt & mineral wool [14-15].

Jute fiber

- *Origin of jute fiber.* When it comes to the industrial and engineering applications of textiles, jute (*Corchorus capsularis* L. and *C. olitorius* L.; *Malvaceae* s. l.) may be the most versatile natural fiber crop [16]. There are 40 to 100 species of Corchorus, which can be found in warm climates on every continent as well as many tropical and subtropical areas [17]. The juvenile fibers can be easily identified between the starch sheath and the wood if a transverse piece of a young internode of Corchorus is cut off. While the fibers in jute are created as a secondary growth from the cambium itself, the flax fibers start as a part of the original stem structure in the cambium, formed straight from the primary tissue. While none of the bast cells created by the cambium thicken in flax, some do in jute, and these result in the jute fibers [18].

Jute fiber, renowned for its illustrious past, reaching back to ancient civilizations, has been predominantly cultivated in the fertile Ganga-Brahmaputra delta of the Indian subcontinent. The transformative establishment of jute mills in the bustling city of Kolkata, a pivotal moment during the mid-1800s, marked a turning point in the jute farming industry, propelling it towards remarkable commercial success. The industry witnessed an unprecedented surge in demand for jute sacks when the Netherlands commissioned substantial quantities for the transportation of coffee beans to the flourishing East Indian Plantations in 1838. The intrinsic essence of jute fibers journey resonates with the essence of innovation, adaptation, and sustainability, underscoring its enduring relevance in a rapidly evolving industrial landscape [19] But as early as 1575, references to jute sacking bags can be found in regional literary works [17].

- *Microstructure of jute fiber.* Jute stands out as a remarkably versatile multicellular fiber, highly revered across numerous industries for its unparalleled strength and utility. This exceptional attribute is intricately woven into the very essence of jute, deriving from the meticulous construction of the cylindrical sheath that envelopes it. The process of imbuing jute with such formidable characteristics involves a remarkable convergence of individual fibers, aptly known as reed within commercial circles. These fibers seamlessly interlock to form a robust three-dimensional network within the jute plant's stem, a process that underscores their pivotal role within the plant's ecosystem. Despite constituting only, a modest fraction—typically ranging between 4-6%—of the entire plant, these fibers hold immense significance, showcasing the plant's remarkable ability to produce these resilient strands. Stretching impressively between 1.5 to 3 m in length when bundled together, the reed fibers eloquently display the plant's inherent capacity to generate such enduring materials. After undergoing the meticulous retting process, these distinct reed segments emerge prominently, offering a stark contrast to the plant's woody components and thereby revealing the unique and unmistakable characteristics of jute fibers. The cross-section and microstructure of jute fiber comprises of the lumen, micro-fibrils, cell wall, primary wall and secondary wall, etc. [20].

- *Extraction of jute fiber.* Extraction of jute can be done using two major methods microbial retting and chemical retting [21].

Jute retting mechanism. The process of fermentation in plants is not only captivating but also incredibly complex, unfolding with a series of intricate steps that showcase nature's ingenuity. Starting with the plant's absorption of water and subsequent swelling, the stage is set as it eventually bursts open, unveiling a treasure trove of sugars, glucosides, and nitrogenous compounds. This pivotal moment heralds the arrival of microorganisms, eager denizens residing in both the plant and the water, ready to partake in a feast of nutrients. These microscopic organisms, with their insatiable appetite, embark on a transformative journey where they meticulously break down the plant's rich organic tapestry. Proteins, hemicelluloses, pectin, and sugars succumb to the enzymatic prowess of these tiny conquerors, unraveling into simpler compounds that fuel the microcosmic ecosystem within. As the symphony of fermentation progresses, the sugars gracefully bow out first, leading the way for the degradation of pectin, hemicelluloses, and nitrogenous substances to follow suit. Ultimately, the grand finale of fermentation in plants unfolds as a harmonious natural process, a vital cog in the machinery of ecosystem balance. A cycle where organic matter finds renewal, microorganisms find sustenance, and the intricate dance of life continues unabated [21].

Microbial retting. The primary obstacle to retting jute with high-quality fiber production is the availability of high-quality retting water. Retting requires a significant amount of fresh water. Taking this into account, numerous innovative retting techniques were created that used much less water than the conventional retting technique. These newly developed enhanced retting techniques work in tandem with microbial formulation [22]

Chemical retting. Chemical retting is a process used to extract fiber from jute ribbons by dissolving the cementing substance with specific chemicals. This method results in stiffer and slightly coarser fibers with a rougher feel compared to microbial retting. The gravimetric fineness values of fibers from both processes are similar, but after drying, the fibers require hand rubbing to reduce stiffness. Additionally, a cationic softener can be used on up to 0.2% of the fiber's weight to further soften the strands. Ammonium oxalate and sodium sulphate have been identified as suitable chemicals for this process. While chemical retting allows for controlled fiber extraction without altering the fiber's characteristics, it is costly and impractical for field use by cultivators. Despite these drawbacks, the fiber's quality remains unaffected by the process [21].

- *Chemical composition of jute fiber.* Jute, a type of bast fiber, is primarily composed of cellulose, lignin, and hemicellulose, all extracted from the bark of the jute plant. Cellulose makes up most of the jute fiber at 58-63%, providing strength and durability. Lignin, comprising 12-15%, adds rigidity and helps bind the cellulose units together. Hemicellulose, at 20-24%, also contributes to the structure and strength of the fiber. Additionally, jute contains small amounts of lipids, pectin, aqueous extract, and other substances. This unique combination of chemical components gives jute its desirable properties, making it a valuable resource for various applications in industries such as textiles, packaging, and construction [23]. Table 1 shows the mechanical properties of jute fibers.

Mechanical properties of jute fiber

Table 1. Mechanical properties of jute fiber [24-25]

Property	Value
Mean elastic modulus	30GPa
Fiber Strength	2455MPa
Interface strength	83MPa
Young's modulus	10-30GPa
Tensile strength	393-800MPa
Elongation	1.5-1.8 %
Density	1.46(g/cm^3)

Basalt fiber

Basalt rock, formed from solidified magma at temperatures between 1500-1700 ^{o}C, is the key ingredient used to produce basalt fiber. This fiber, known for its exceptional heat resistance, stability, and vibration properties, is considered an environmentally friendly product. The process involves extracting basalt rock, composed of frozen lava, and finely separating it into fibers known as basalt fibers. These fibers are predominantly made up of plagioclase and pyroxene, which together account for 80% of its composition. The use of basalt fiber in various industries has been on the rise due to its unique properties and environmentally friendly nature [26-27].

- *Extraction of basalt fiber.* Extraction of basalt fiber includes grinding, washing, melting, drawing, winding processes employed with suitable equipment. Figure 2 represents the plant layout of basalt fiber production [28].

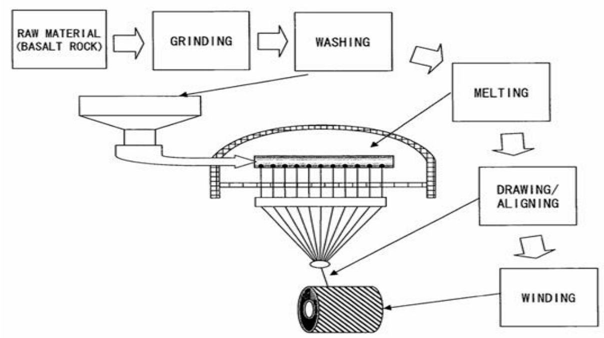

Figure 2. Plant layout of basalt fiber production (open access) [28]

- *Chemical composition and mechanical characteristics of basalt fiber.* Basalt fiber is rich in the oxides of Mg, Ca, Al, Si and having high percentage of SiO_2 and Al_2O_3 33.3% of basalt is a copious mineral. Table 2 below represents the compositions in detail [29]. The mechanical characteristics of basalt fiber are represented in Table 3.

Table 2. Chemical composition of basalt fiber [29]

K_2O	1.46%	Cr_2O_3	0.06%	Na_2O	3.34%
TiO_2	1.38%	SiO_2	52.8%	CaO	8.59%
P_2O_5	0.28%	Al_2O_3	17.5%	MgO	4.63%
MnO	0.16%	Fe_2O_3	10.3%		

Table 3. Mechanical characteristics of basalt fiber [30-31]

Property	Value
Elongation at break	3.15%
Tensile strength	4.84GPa
Density	2.65g/cm^3
Maximum service temperature	650°C
Elastic modulus	89 Pa

- *Nanoparticles in polymer composites (jute & basalt).* The addition of nano particles as reinforcing agents in the polymer composites gives better electrical, optical, and mechanical properties [32].

Nano materials are classified based upon following parameters:

a) Carbon based such as fullerenes, graphene, carbon black, carbon tube, carbon fiber; organic such as ferritin, micelles, liposomes, dendrimer.
b) Inorganic such as metal based, metal oxide, lipid based, ceramic, semiconductor.
c) Based on number of dimensions classified such as 0, 1, 1, pore dimension such as microporous, mesoporous and macro-porous.
d) Based on origin such as artificial and natural based on potential toxicity CMAR, bio persistent granular & fiber like [33].

Uses of nanoparticles in various polymer composites

Functionalized nanoparticle-loaded nano-composites have emerged as a highly promising technology in terms of property improvements. These materials are garnering considerable attention in scientific circles due to their unique ability to enhance various properties even at low particle concentrations. This remarkable characteristic has made them a popular subject of study, leading to an influx of research articles detailing their applications and benefits. These materials have proven their mettle in a wide array of power-related processes, exhibiting exceptional performance metrics that point towards a transformative impact on various industries [34]. The automotive, aerospace, marine, and construction industries are becoming increasingly interested in fiber-reinforced polymer composite materials (FRPs) because of their exceptional mechanical qualities, adaptability, and exceptional resistance to fatigue and corrosion [35].

Table 4 represents various nanoparticles used as reinforcement particles to enhance the properties of polymer composites: [36] evaluated the effects different nano particles on mechanical properties, flammability and thermal degradation of polyester/jute fiber composite. The graphical abstract representing the methodology of composite fabrication along with the results are depicted in Figure 3 [36].

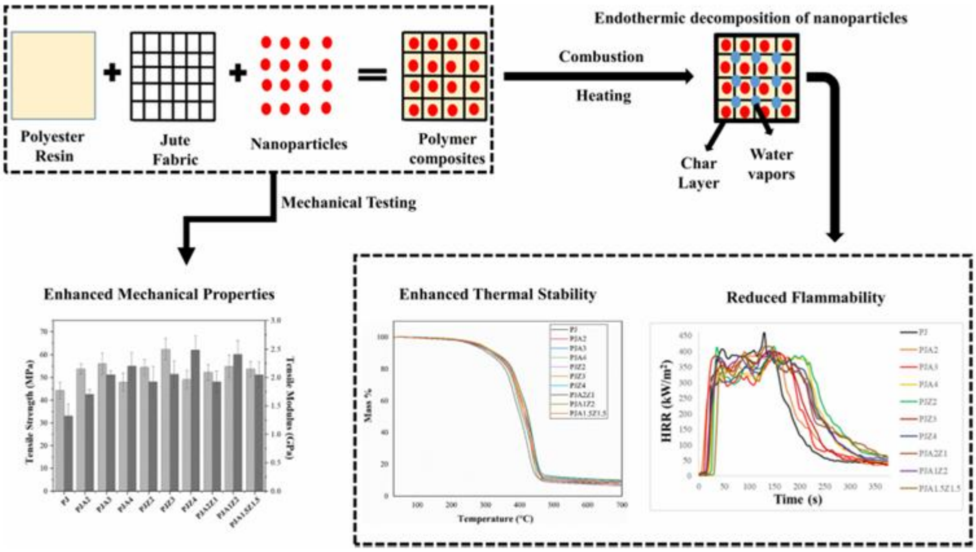

Figure 3. Graphical abstract representing the effects of various nanoparticles on different properties of polymer composites (open access) [36]

Table 4. Effects of various nanoparticles on mechanical properties of polymer composites

Nano-particles	Concentration	Composite materials	Conclusion	Reference
$Al(OH)_3$, $Zr(OH)_4$	2%, 3% and 4%	Polyester/jute composite	The results demonstrated that adding three weight percent of either kind of nanoparticles significantly improved the polyester/jute composite's tensile, flexural, and impact characteristics.	[36]
SiO_2	5%	Basalt/ epoxy	When compared to a pure epoxy coating, the SiO_2 epoxy nanoparticle composite coating significantly increased the tensile strength of the fibers of basalt. Additionally, the coating gave the fibers of basalt a promising interfacial property in the resin matrix composite reinforced by the basalt fibers.	[37]
ZrO_2	10%, 15%, 20%	Polyether-etherketone / carbon fiber	In a composite with 70% PEEK, 20% carbon fiber and 10% ZrO_2, maximum tensile strength and young's modulus was observed.	[38]
Graphene	0%, 1%, 3%, 5%	Carbon fiber	Maximum performance was observed at the optimal value of 3 weight percent GnPs, where improvements in modulus and flexural strength of 16.8% and 16.2%, respectively, were attained.	[39]
SiO_2	0%, 5%, 10%, 15%	Jute/polyester	10% silica powder, 10% jute and 80% polyester showed increased mechanical properties.	[40]
ZnO_2	0.5%, 1%, 3%, 5%	Jute/ epoxy	Of all these specimens, the compound that is 3weight% ZnO_2-filled has the best qualities. In the short-beam shear test, adding ZnO_2 to the composites increased the compressive property by 43%.	[41]
Silica and clay	0%, 1%, 2%, 3%	Rice straw/ polypropylene	Addition of up to two weight percent of nano clay increased the flexural and tensile moduli. Nevertheless, noted qualities reduced after this point. Reduced interfacial adhesion between the matrix polymer and filler is typically caused by high concentrations (3 weight percent) of nanoparticles in composites, which restricts their potential uses.	[42]

SURFACE MODIFICATION OF FIBER

In recent years, researchers have shifted towards using natural fibers instead of synthetic ones due to their advantages such as lower density, easy availability, and cost-effectiveness. However, natural fibers do have certain limitations when used in composites, including poor compatibility and drawbacks. To address these challenges, various surface modification techniques have been developed. These techniques play a crucial role in enhancing the performance and durability of natural fiber composites. By modifying the natural fibers' surface, researchers have shown the improvement in their compatibility with other materials, enhance their mechanical properties, and increase their environmental resistance factors. This advancement in surface modification techniques has allowed for the broader and more efficient use of natural fibers in various industries, contributing to the sustainable development of materials and reducing the reliance on synthetic fibers [43].

Alkali treatment

Treating the surface of natural fibers is an essential practice that significantly enhances their ability to bond with the polymer matrix in composite materials. Among the array of treatments available, alkali treatment, which involves the use of sodium hydroxide (NaOH), stands out as a highly effective and economical option. This specific treatment method operates by effectively eliminating lignin, pectin, hemicellulose, and oils present on the fibers, thereby greatly improving their affinity to the matrix through interactions with cellulose molecules. The successful outcome of the alkali treatment process hinges on several key factors, which include the concentration of sodium hydroxide, the duration of the treatment, and the temperature at which it is carried out.

In essence, the alkali treatment utilizing sodium hydroxide should be viewed as a fundamental step in the enhancement of natural fibers for composite materials. By ridding the fibers of impurities and enhancing their bonding capability with the polymer matrix, this treatment methodology not only ensures superior mechanical characteristics but also contributes to an overall elevation in the quality and performance of the composite material as a whole.

Cell - OH + NaOH ⇒ Cell- O^- Na^++H_2O+ surface impurities (Mohanty *et al.,* 2001) (1)

Benzene treatment

The process of treating raw fiber with a solution containing sodium hydroxide (NaOH) and O-hydroxy benzene diazonium represents a significant advancement in the enhancement of mechanical characteristics when equated to leaving the fiber untreated. By immersing the raw fiber into the NaOH solution first and then subsequently applying the diazonium solution, a remarkable transformation takes place within the fiber structure, leading to a notable increase in its strength and durability. This method involves subjecting the fiber to a precise sequence of treatments that optimize its physical characteristics for industrial applications that demand superior mechanical properties.

The processed jute fiber, once dried, demonstrates exceptional enhancements in its mechanical attributes, making it a desirable material for a wide range of industrial applications that require high tensile strength and durability. The successful completion of this treatment process underscores the pivotal role of chemical interventions in heightening the intrinsic qualities of raw fiber, thereby unlocking its full potential for various industrial uses. This sophisticated treatment method underscores the importance of leveraging chemical processes to elevate the functional properties of raw fiber, paving the way for broader applications across multiple industries that rely on robust and resilient materials [44].

Glycine treatment

The process of applying aqueous glycine onto untreated fiber strands serves as a crucial preliminary step in assessing and understanding the characteristics of the fibers thoroughly. Researchers engage in subjecting these untreated fiber strands to varying concentrations of glycine for a duration of 1.5 h at a temperature of 100 ºC, enabling them to closely observe and analyse the interaction dynamics between the fibers and the glycine solution. Moreover, by conducting tests on the samples using four different pH values and maintaining a consistent mass to liquid ratio of 1:20, researchers gain a comprehensive and in-depth insight into how the fibers behave under diverse environmental conditions.

Post-treatment, once the samples have undergone the glycine application process, they are meticulously dried in an oven at a constant temperature of 50 degrees for a duration of five hours. This significant observation underscores the essential role that both pH levels and glycine concentrations play in influencing the efficacy and outcomes of the glycine treatment on the fiber strands, offering valuable insights for further research and development in this area [45]. Figure 4 represents the various treatments of the jute fibers [45].

Silane treatment

The cellulosic fibers, renowned for their inherent qualities in the natural realm, were subject to an intricate treatment process characterized by the meticulous application of a 3% concentration of a specific silane in an ethanol/water solution with an 80/20 v/v ratio. This elaborate treatment plan, impeccably carried out over a carefully monitored two-hour timeframe, played a pivotal role in priming the fibers for subsequent transformations. Post the initial treatment, a methodical filtration procedure was implemented, followed by a period of natural air-drying spanning two days under standard room temperature settings.

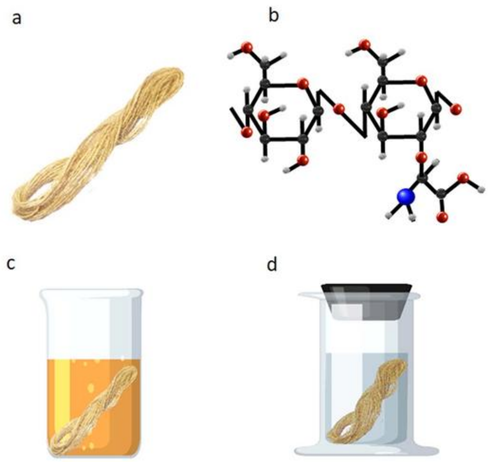

Figure 4. a) Untreated jute yarns, b) chemical interaction of jute fiber with glycine, c) alkali treatment of jute yarn, d) glycine treatment of jute fiber (open access) [45]

This detailed and comprehensive treatment plan underscored a profound commitment to elevating the characteristics of the cellulosic fibers and harnessing their full potential for a diverse array of uses [46-49].

Alkali bleaching

The study extensively delved into the impact of hydrogen peroxide bleaching and alkali treatment on the tensile properties of short jute fiber composites, revealing valuable insights that contribute significantly to the field. Experimental procedures involved the meticulous mixing of different weights of treated and untreated jute fibers with the PLA matrix, highlighting the meticulous approach undertaken in the research [50-54]. Notably, the composite materials treated with a combination of 10% NaOH and hydrogen peroxide bleaching exhibited remarkable enhancements, with the tensile strength surging by 7.5% and the modulus soaring by an impressive 40% compared to the untreated counterparts [1], underscoring the efficacy of the treatment methods employed.

Moreover, beyond the scope of treatments, the structure and chemical composition of jute fibers are affected by various environmental factors such as climate, age, and digestion, underscoring the intricate dynamics that shape their properties. It is fascinating to note that these fibers primarily consist of 60% cellulose, accompanied by 12% lignin, in addition to pectin, moisture, and ash content, painting a comprehensive picture of their composition. Remarkably, jute fibers exhibit exceptional resilience, capable of withstanding air temperatures of up to 100°C without undergoing degradation, further highlighting their robust nature and suitability for diverse applications [55]

Furthermore, the pivotal role played by alkali bleaching in augmenting the quality and performance of jute fibers for various applications, especially in the realm of composite materials, cannot be overstated. Through the intricate process of alkali bleaching, the fiber surface undergoes a transformative refinement, thereby ridding it of undesirable components and enhancing its overall utility, making it an indispensable step in optimizing the properties of jute fibers for numerous industrial applications. This meticulous treatment method not only enhances the physical properties of the fibers but also improvises durability and applicability in a wide array of scenarios, underscoring the importance of such treatments in the realm of materials science and engineering [56-60].

Plasma and alkali-plasma treatment

Plasma treatment and alkali-plasma treatment represent cutting-edge methodologies utilized in altering the surface characteristics of natural fibers such as jute, aimed at improving the bonding interface with the matrix material. One notable investigation by [61] delved into the realm of jute fiber/high-density polyethylene (HDPE) composites, with a primary focus on enhancing the inherent properties of jute fabrics through meticulous surface modification via oxygen plasma treatment. In their comprehensive study, a combination of low-frequency (LF) and radiofrequency (RF) plasma systems was seamlessly employed, with the plasma power meticulously fine-tuned to 30, 60, and 90 W for a duration of 15 minutes. An in-depth analysis utilizing X-ray photoelectron spectroscopy (XPS) served as a pivotal tool in evaluating the transformative effects on the functional groups treated with oxygen plasma residing on the surface of jute fibers. Subsequently, composite materials were meticulously developed by blending 20% jute with 80% polylactic acid (PLA) through the intricacies of the injection molding process. A comparative evaluation brought into light that the mechanical properties of plasma-treated jute/PLA composites showcased a remarkable uptick in performance metrics when compared to their untreated or alkali-treated counterparts. Particularly, the plasma-treated jute/PLA composite displayed substantial enhancements, which included an impressive 28% surge in tensile strength, a notable 17% augmentation in Young's modulus, and a commendable 20% amplification in flexural strength. These findings underscore the profound positive influence of plasma treatment methodologies on the overall mechanical prowess and structural integrity of jute/PLA composites, thus establishing a solid foundation for the utilization of plasma treatment techniques in revolutionizing the landscape of composite material engineering [62].

Permanganate treatment

In the process involving the utilization of permanganate, a potent chemical compound characterized by the presence of the permanganate group denoted by the chemical formula MnO4, alkaline-treated jute fibers undergo immersion in a neatly concocted solution that comprises 50% permanganate acetone, which is then meticulously carried out for a specific time duration. Subsequently, to eliminate any residual solvent and moisture, the treated fibers are subjected to a thorough drying process meticulously maintained at a temperature of 40°C for a set time span of 5 hours [63-65]. This method of treatment with permanganate effectively diminishes the innate hydrophilic properties of the jute fibers, leading to a tangible decrease in the overall water content contained within the Jute fiber reinforced polymer composite (JFRPs), as precisely highlighted by a study reference [66]. Consequently, as a direct result of this particular treatment process, the moisture content inherently present in the fibers is entirely eradicated, consequently facilitating a notable enhancement in the material's strength characteristics, thus further validating the efficacy of the permanganate treatment as a viable approach in manipulating and fortifying the properties of jute fibers within composite materials [

Hydroxybenzene diazonium salt treatment

Typically, treatments of jute fiber are conducted to modify the surface properties, with one such treatment involving the use of benzene diazonium salts. Specifically, the jute fibers undergo a series of steps to enhance their characteristics. First, the fibers are immersed in a 5% NaOH solution for 10 minutes while placed in an ice bath to ensure proper penetration and absorption. Following this initial treatment, a cooled solution of o-hydroxy benzene diazonium chloride is added and stirred for 10 minutes, facilitating a chemical interaction that alters the fiber's surface properties. To remove any residual substances, the fibers are then washed sequentially with soap solution and water before being dried thoroughly. The process is repeated with p-hydroxy benzene diazonium chloride and m-hydroxy benzene diazonium chloride under both alkaline and acidic conditions, presenting a comprehensive examination of the treatment effects [49]

The outcomes of these treatments have revealed significant differences in the physical properties of the jute fibers. Notably, the treated jute fibers exhibited a decrease in tensile strength, tenacity, and moisture absorption compared to their untreated counterparts. This observation suggests that the modification process impacts the fiber's structural integrity and absorption capabilities, potentially influencing its performance in various applications. Further analysis of the treated fibers revealed distinct variations based on the type of hydroxy benzene diazonium salt used. Among the treatments with ortho, meta, and para hydroxy benzene diazonium salts, the most promising results were obtained with o-hydroxy benzene diazonium salts, showcasing the highest tensile strength and tenacity. In comparison, the fibers treated with m-hydroxy benzene diazonium salts demonstrated slightly lower performance, while those treated with p-hydroxy benzene diazonium salts exhibited the least improvement in mechanical properties. These findings highlight the importance of chemical treatments in tailoring the properties of jute fibers for specific applications, showcasing the potential for enhancing their performance through strategic modifications [47].

Silane and alkali-silane treatment

Silane treatment using reactive silane molecules holds a pivotal role in augmenting the bond between fibers and polymers within composite materials. Specifically, alkali-silane treatment enhances the reactivity with the fiber surface, which ultimately leads to a superior bonding mechanism. Both types of silane treatments contribute significantly to the enhancement of interfacial adhesion, subsequently fortifying the overall performance, durability, and strength of the composite material [50]. This heightened bond between fibers and the polymer matrix not only elevates the mechanical properties but also reinforces the material's ability to withstand environmental stresses, making it an indispensable technique in the fabrication of composite materials. Silane molecules possess distinct ends that collaborate to construct a bridge between the water-attracting segments of the jute fiber and the water-repellent components of the polymer matrix. When natural fibers undergo silane treatment, the molecules react with the fiber's surface, forming stronger bonds. This reaction occurs through the hydrolysis of silane molecules, resulting in the formation of silanol groups that bond with the hydroxyl groups present on the fiber surface, establishing either covalent or hydrogen bonds. Various types of silanes, such as alkyl, amino, methacryl, and glycidoxy, are commonly utilized to enhance the strength of fibers and increase their resistance to water, especially when a robust bond exists between the silane and the matrix [60].

DEVELOPMENT OF JUTE/ BASALT COMPOSITES

Jute and basalt epoxy-reinforced composites are at the forefront of material science, offering a fascinating avenue for creating high-performance materials with exceptional properties. The combination of these fibers with epoxy resin has led to the development of composites that strike a perfect balance between mechanical strength and sustainability. These composites are not only strong but also lightweight, showcasing impressive strength-to-weight ratios that make them highly desirable for a range of applications. Moreover, the production of bio-composites using traditional manufacturing methods has paved the way for environmentally friendly materials that can be utilized across various industries. Techniques such as moulding, resin transfer, compression moulding, extrusion, injection moulding, hand lay-up, spray lay-up, filament winding, and pultrusion have been employed to create these bio-composites, demonstrating the versatility and adaptability of these materials. In conclusion, the development of reinforced composites represents a significant advancement in the quest for sustainable and high-performance materials. With their unique properties and environmentally friendly nature, jute and basalt epoxy composites are poised to revolutionize industries and offer innovative solutions to complex challenges [51]. Figure 5. depicts the view of compression moulding machine. Table 5 presents methods used and mechanical properties of developed polymer composites.

Figure 5. Compression moulding machine

Table 5. Various methods used and mechanical properties of developed polymer composites.

Matrix	Reinforcement	Process	Outcomes	Ref.
Epoxy	Jute epoxy (treated with 20% NaOH)	Compression moulding technique	It was reported that comparative to raw jute has poor mechanical characteristics than jute treated with sodium hydroxide, later tested tensile strength of 97 MPa and flexural strength of 80 MPa.	[50]
Epoxy	Jute/basalt reinforced hybrid epoxy composites	Laminates of hybrid composite are prepared by hand lay-up method	The findings suggest that hybridizing jute fiber with basalt fiber led to enhancements in the tensile strength, bending resistance, in-plane shear strength, and bearing capacity of the composite.	[52]
Epoxy	Jute/basalt hybrid epoxy composites	Vacuum-assisted resin infusion	The findings revealed that jute/basalt hybrid laminates displayed superior impact energy absorption and flexural properties compared to those composed solely of jute fibers. Additionally, they exhibited greater resistance to aging over time. The results also indicated that jute/basalt hybrid laminates, particularly those with a sandwich-like configuration, demonstrated enhanced aging tolerance when compared to hybrid laminates with an intercalated configuration.	[53]

Polyester	Jute/glass fiber reinforced polyester	Pultrusion	The research examined production of hybrid composite using polyester, jute, and glass fibers interacts with water. It was discovered that integrating glass fibers into the composite increased its ability to resist water absorption and exposure to moisture led to a significant decline in the flexural and tensile properties of the hybrid composites due to water absorption.	[54]
PLA (Poly-lactic acid)	Polylactide green reinforced with jute fiber.	Injection moulding	The findings suggest that enhancing the Young's modulus and tensile strength of the prepared composites is achievable by employing thoroughly compounded pellets during the injection moulding process. Figure 6 depicts the behavior of composites fabricated at different temperatures on the tensile fractured specimens.	[55-56]
PBS (Poly-butylene succinate)	Basalt fiber reinforced with PBS	Injection moulding method	The flexural and tensile characteristics of the PBS matrix show improvement due to the synergistic strength provided by an increasing quantity of basalt fibers, resulting in increased tensile strength from 31 to 46 MPa and flexural strength from 18 to 71 MPa.	[57]
Epoxy	Epoxy of basalt composed of (0.5–2 wt%) tourmaline micro/nano particles	Vacuum-assisted resin transfer moulding technique	The tensile and flexural strength increased by 16%, while the tensile and flexural modulus showed increases of 27% and 153%, respectively.	[58]
PLA (Polylactic acid)	Basalt fiber/ polylactic acid composite	Hot press (compression moulding) and (APGD) atmospheric pressure glow discharge for surface modification of basalt fiber through plasma polymerizatio n	The findings indicated that the composite exhibited a 45% increase in strength and an 18% increase in modulus compared to untreated one. The most effective plasma polymerization treatment for basalt fibers was observed to occur at a plasma exposure time of 4.5 min.	[59-60]

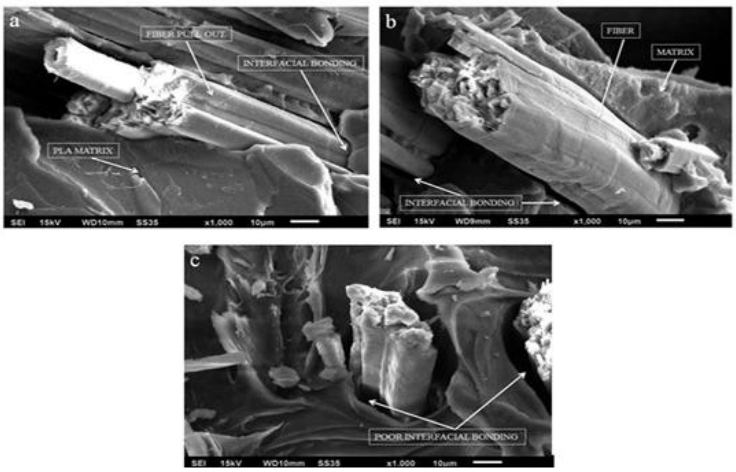

Figure 6. SEM micrographs of fractured tensile specimens of polymer composites fabricated at different temperatures (open access) [47]

MECHANICAL PROPERTIES OF JUTE/BASALT FIBER COMPOSITES

In this part of the review, different researches done on jute/basalt composites are discussed. [61] focused their work on reinforcing basalt and jute fabrics into a general-purpose poly ester matrix using the compression moulding process, poly ester-based polymer composites are created. Study showcases varied stacking sequence in reinforced composites with poly-ester resin, basalt fiber and jute fiber. The findings showed that in both the flexural and tensile tests, the pure basalt fiber combination maintained higher values. However, basalt fiber performs somewhat worse in impact tests than composite reinforced with jute fiber. [62] utilized Jute and basalt as reinforcements to get the benefits of both jute and basalt fiber. The composites made of jute and epoxy were created. Additionally, jute and basalt fiber hybrid composites were created. A variation in the percentage of the natural filler (walnut shell) material was also examined in the generated composites. The walnut shell was utilized as filler in different proportions: 0%, 5%, 10%, and 15% of epoxy resin. The use of walnut shell fillers increased the produced hybrid composites' tensile and flexural strength. Because of better impact energy absorption, the impact strength of the created composites rose as the filler concentration increased. [63] using compression moulding processes, and created basalt/jute fiber-reinforced hybrid polymer composites with a variable fraction of fiber. Basalt fiber was added to the composites at rates of around 10%, 20%, and up to 90%, while the amount of jute fiber was decreased from 90%, 80%, to 10% in accordance. Jute fiber incorporation resulted in improved tensile and flexural strength for 90% basalt and 10% jute fiber hybrid composites. Out of all the specimens made using polyester matrix, the composite material with 50% basalt and 50% jute exhibits the highest impact strength according to the impact test. Tables 6 and 7 represent the mechanical properties of jute and basalt fibers, respectively.

The influence of fiber volume fraction and curing temperature was evaluated on the mechanical properties of Jute/PLA fabricated composites [48] These effects are represented in Figure 7 at different temperatures. The tensile tests were correlated with the SEM micrographs (Figure 8) and it was concluded that the weak fiber matrix bonding resulted in less tensile strength at 50% fiber volume fraction.

There are changes for the better, through the uses of surface treatment and nanoparticles on natural fiber composites, mainly jute and basalt composites.

These enhance various mechanical and chemical properties making it useful for manufacturing products with different needs [75-78].

CONCLUSION

Basalt and jute fibers get along well with one another, and various surface treatments—such as silane, alkali, etc. produce various benefits. Likewise, this holds true for nanoparticles. Different surface treatments and nanoparticles might be employed for different needs. Just in the last few years various researches have been done in the sector of natural fiber composites, a lot of which include surface treatments to improve the bonding, as well as nanoparticles in order to improve mechanical properties of these composites, and yet there is a vast number of possible variations and enhancements that can be applied in order to get more out of these composites. The easy availability and inexpensiveness of jute and basalt fibers make them ideal for all the researches. A lot of possible variations for improving the properties are possible, and we are just a few steps from finding these improvements.

Table 6. Mechanical properties of jute fiber

Properties	Jute fiber							
	[64]	[65]	[66]	[67]	[68]	[69]	[70]	[71]
Tensile strength (MPa)	393-773	450-550	-	290	393-773	400-800	393-773	393-773
Young's modulus (Gpa)	13-26.5	10-32	-	28	26.5	10-30	19.0-26.5	13-26.5
Elongation at break (%)	1.16-1.5	1.1-1.5	1.56	-	1.5-1.8	1.5-1.8	1.16-1.80	1.16-1.5

Table 7. Mechanical properties of basalt fiber

Properties	Basalt fiber		
	[72]	[73]	[74]
Tensile strength (MPa)	2900-3100	2800-4800	2200-2500
Young's modulus (GPa)	85-87	86-90	85-100
Ultimate elongation (%)	3.15	-	-

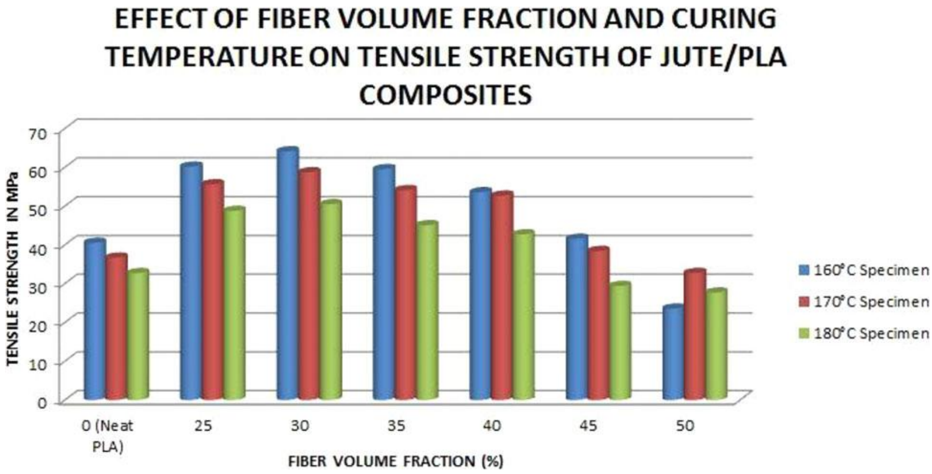

Figure 6. Effect of fiber volume fraction and curing temperature on tensile strength of Jute/PLA composites (open access) [78]

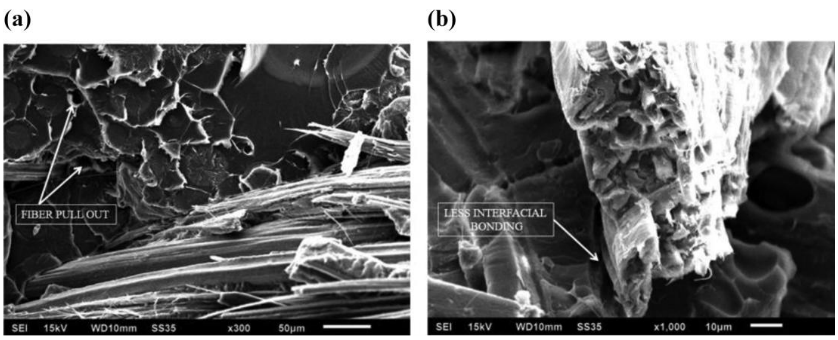

Figure 7. SEM images of tensile fractured specimen developed at 160_C with 50% fiber volume fraction (open access) [78] at a) x300 magnification and b) x1000 magnification.

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Synthesis and characterization of a slow-release fertilizer produced from coconut husk biochar

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Coconut biochar-based multi-nutrient fertilizer (CBMNF) was synthesized by first converting coconut husk to coconut biochar (CB) through pyrolysis. The essential nutrients like nitrogen, zinc, iron, manganese, copper, boron and molybdenum were impregnated onto the biochar matrix through adsorption to synthesize CBMNF. Nutrient levels increased significantly after adsorption, with carbon and nitrogen percentages rising from 56.86 and 0.147 % to 71.57 and 0.27 %, respectively. Additionally, micro-nutrients zinc, iron, manganese, copper, and boron in CB increased from 76, 343.21, 106, 30, and 52.29 mg kg^{-1} to 885, 1575, 328, 66, and 191.42 mg kg^{-1}, respectively, confirming successful nutrient impregnation into the biochar. This was further confirmed by shift in peak position observed in FTIR spectra and the reduction in pore size due to surface deposition of nutrients observed in SEM. TGA showed improved thermal stability of CBMNF in comparison to CB. Dissolution study in the soil further revealed its ability to gradually release essential macro and micronutrients, underscoring its slow-release capability. Hence, CBMNF may effectively replace or supplement traditional chemical fertilizers in agriculture.

Keywords: coconut husk, biochar, multi-nutrient-fertilizer, slow-release fertilizer, thermal stability, dissolution study

INTRODUCTION

Coconut is an essential perennial crop with multiple uses that supports life in vulnerable coastal and island habitats [1]. It is cultivated in around 80 countries, yielding a total global production of 69.8 billion nuts with Sri Lanka, Indonesia, Philippines, and India being the major producers [2].

Coconut husk contains 70 g of pith and 30 g of fiber [3] . Although coconuts are produced in vast quantities in different parts of the world and coconut husks is abundantly available, only about 28% of the coconut husks produced is used in coir industry. The rest is often discarded as a waste due to its lack of economic value. A sizable portion is found submerged in the fields as a cultural tradition, and the rest often burnt[4]. A better alternative is the conversion of agricultural wastes like coconut husks into valuable products by adopting modern technologies. Therefore, organic waste conversion via decomposition is crucial for Resource management and sustainable agriculture [5].

Biochar produced from waste materials like coconut husk by pyrolysis is a beneficial product with many useful characteristics [6]. Biochar application in soil has gained momentum because of economic and ecological benefits like improving soil remediation and increased carbon sequesteration [7]. It also improves soil fertility and soil health [8].

In contrast, the conventional chemical fertilizers, being soluble in water, are readily washed off and leached from soil. Approximately 40-70% of N, 80-90% of P, and 50-70% of K fertilizers are estimated to have been lost to the environment. The phenomenon not only seriously pollutes environment and threatens sustainable agriculture, it also results in significant economic loss to farmers. Furthermore, overuse of chemical fertilizers seriously deteriorates farming lands by reducing organic matter and salinizing the soil [9]. The awareness about slow-release fertilizers (SRFs), which are intentionally designed to address the shortcomings of conventional fertilizers, is now widespread. SRFs release nutrients more slowly than conventional fertilizers, extending their supply of nutrients without environmental problems.

Biochar with its unique characteristics, may be used as such or modified to develop slow-release-fertilizer. Techniques like impregnation, pelletization, and encapsulation were developed in the last decade to fabricate nutrient-loaded biochar [10-12]. In addition to reducing greenhouse gas emissions, they may modify pH of soil, increase soil permeability, decrease bulk density, sequester soil carbon and increase crop yields [13-15].

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Though studies on biochar derived from coconut husks exist in literature, the novelty of the present study is the enrichment of the prepared biochar with multi-nutrients, *viz*. nitrogen, zinc, copper, boron, iron, manganese & molybdenum, to synthesise a slow-release fertilizer. Since nutrient-enriched coconut husk biochar is derived from a widely available and inexpensive agro-waste, it effectively addresses the problem of waste management in agricultural land. Further, as the nutrients embedded in biochar are slowly released, it also addresses the problem of rapid release of nutrients and its consequent loss associated with conventional fertilizers.

MATERIALS AND METHODS

Preparation of coconut biochar

Coconut husk, the raw material used to synthesize coconut biochar (CB), was collected locally from Thrissur district, Kerala and subjected to pyrolysis at 330^{0}C over a 24 h duration. The biochar produced was crushed into extremely fine particles and then passed through a 2mm sieve to obtain uniform particle size. The final product was sealed in airtight plastic bags for future use.

Preparation and stability analysis of multi-nutrient mixture

Different analytical reagent (AR)-grade chemicals, including urea ($CO(NH_2)_2$), zinc sulfate ($ZnSO_4.H_2O$), boric acid (H_3BO_3), copper sulfate ($CuSO_4.5H_2O$), ferrous sulfate ($FeSO_4.7H_2O$), manganese sulfate ($MnSO_4.7H_2O$), and molybdenum trioxide (MoO_3), were purchased from Merck India Private Limited. These chemicals were blended to achieve the desired nutrient composition, that is, N (7.5%), Zn (6%), B (4%), Cu (0.02%), Fe (0.02%), Mn (0.25%) and Mo (0.01%) in the multi-nutrient mixture. The stability and quality of the prepared MNM were checked by regularly monitoring color, clumping tendency, solubility, pH and EC over a six-month period.

Synthesis of coconut biochar-based multi-nutrient fertilizer

The coconut biochar-based multi-nutrient fertilizer (CBMNF) was prepared by impregnating nutrients into the biochar. Ten g of biochar and 0.5 g of nutrient mix were added to 100 ml of water in a conical flask. This mixture was shaken on a rotary shaker for three h at room temperature. The substrate (CBMNF) was then filtered, oven-dried for 24 h at 105°C and later sealed in air tight plastic containers for further use.

Characterization of CB and CBMNF

- Physicochemical and electrical properties of CB. The pH, electrical conductivity (EC), moisture content, and ash percentage of the biochar were estimated using standard procedures [16, 17].
- Elemental composition & nutrient content. Analysis of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) was conducted utilizing a CHNS analyzer, specifically the Elementary Vario EL cube model. Additionally, the total nutrient content of zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B) was determined by first digesting the sample using a nitric-perchloric acid (9:4) digestion method [18] and then analyzing it using inductively coupled plasma–optical emission spectrometer (ICP-OES; Model: Optima® 8×00 series).
- Microstructural and chemical analyses. The biochar's surface morphology was examination utilizing a field emission scanning electron microscopy (SEM) tool, namely the Joel 6390LA/OXFORD XMX N SEM-EDAX system. Functional group analysis of the biochar was performed using Fourier transform infrared (FT-IR) spectroscopy, employing Perkin Elmer Spectrum IR instrument. For the identification of phases and determination of crystallinity, X-ray diffraction (XRD) was performed using the Aeris XRD diffractometer from Malvern Panalytical. To assess the thermal stability of the biochar, thermogravimetric analysis (TGA) was carried out utilizing the TGA-DTA Perkin Elmer STA6000 instrument.

Water retention (WR) of CBMNF

For the water retention (WR) study, pre-weighed cups were utilized. Cup A served as the control or blank and was filled with 50 g of sieved soil. Cup B contained 2 g of nanocomposite and 50 g of soil. Then, distilled water (30 mL) was added to both cups. After 24 h, the cups were reweighed (as WA_1 and WB_1). Subsequently, the cups were placed in a glass box, and their weights were measured daily for 30 days (referred to as WA_2 and WB_2) [19]. The water retention was determined using the following equation:

$$WR\ (\%) = \frac{W_A}{W_B} \times 100\text{------}(1)$$

Nutrient release study in soil

The experiment followed a completely randomized design (CRD). To evaluate the nutrient release from the substrate in soil, a PVC column measuring 30 cm in length a nd 10 cm in diameter was employed. The columns were filled with soil

(2.5 kg), soil + CBMNF (2.5 kg of soil and 62.5 g of CBMNF) and soil + nutrient mix (2.5 kg of soil and 6.25 g of nutrients), respectively. The soil was first saturated to attain field capacity and then left to stabilize for 3 days. Hundred mL of de-ionized water was added to the column every 24 h for 60 days. Leachate was collected at specific intervals of 1, 2, 3, 5, 10, 15, 30, 45, and 60 days and analyzed to determine the concentrations of N, Zn, Fe, Mn, Cu, B and Mo.

RESULTS AND DISCUSSION

Stability analysis of multi-nutrient mixture

No color change and caking of the mixture was observed on storage. It is readily soluble in de-ionized water and neither pH nor EC varied over time. Thus, the mixture has excellent stability and keeping quality and can be safely stored for at least six months.

Characterization of CB and CBMNF

The coconut biochar-based multi-nutrient fertilizer was synthesized by impregnating the nutrients onto the biochar. During this impregnation, all the nutrients, *viz*., N, Zn, Fe, Mn, Cu, B, and Mo, were adsorbed onto the biochar. The adsorption of nutrients onto biochar may be either physical or chemical or both. The extent to which nutrients are adsorbed on the biochar is influenced by various factors like covalent forces between the adsorptive biochar and nutrient, chelating reaction btween adsorbent & adsorbate, controlled ion exchange, etc. [20, 21].

- Physicochemical and electrical properties. The moisture content, ash content, pH and EC of CB and CBMNF are given in Table 1. The ash content, pH and EC of CBMNF were lower than those of BC while the moisture content was higher. CB & CBMNF are alkaline in aqueous solution, probably due to the presence of basic cations (Na, K, Ca & Mg) and their compounds like salts (chlorides), oxides, hydroxides, and carbonates [22-24]. During the synthesis of CBMNF, for adsorbing the multinutrients on to biochar, biochar & multinutrient mix are shaken together in an aqueous medium. This could have lead to the depletion of readily soluble salts, soluble alkaline cations, and fine ash resulting in lower pH values, EC values and reduced ash content in CBMNF [25, 26]. The pH & EC of CBMNF were lower than those of BC by 0.87 & 1.73 units, respectively. The ash content was lower by 56% while the moisture content was higher by 34%.

Table 1. Electrochemical properties of CB and CBMNF

Parameters	CB	CBMNF
Moisture (%)	10.42	15.8
Ash (%)	23.97	10.64
pH	9.48	8.61
EC (dS m^{-1})	3.46	1.73

- Elemental composition & nutrient content. The nutrient content of CB and CBMNF is given in Table 2. The three major constituents of biochar are carbon, hydrogen and nitrogen. This is unsurprising as biochar is mostly composed of cellulose, hemicelluloses and lignin polymers. The high carbon content of BC indicates the presence of organic plant residues like cellulose and lignin in BC [27, 28]. After conversion of CB to CBMNF, the carbon content increased by 25.8 % and nitrogen content by 15.8 %. This suggest successful incorporation of urea in CBMNF. The sulfur content increased by 83.7 %, possibly due to the incorporation of sulfate on to biochar. Additionally, micro-nutrients such as zinc, iron, manganese, copper, and boron are present in CB at 76, 343.21, 106, 30 and 52.29 mg kg^{-1} respectively. In CBMNF, these values are notably higher, with zinc at 885 mg kg^{-1}, iron at 1575 mg kg^{-1}, manganese at 328 mg kg^{-1}, copper at 66 mg kg^{-1}, and boron at 191.42 mg kg^{-1}. Comparing CBMNF to BC, an overall increase in nutrient content was observed, indicating that it has effectively adsorbed nutrients from solution.

Table 2. Elemental properties of CB and CBMNF

S. No.	Elements		CB	CBMNF
1	C	%	56.86	71.57
2	H		1.58	3.22
3	N		0.38	0.44
4	S		0.147	0.27
8	Zn	mg kg^{-1}	76	885
9	Fe		343.21	1575
10	Mn		106	328
11	Cu		30	66
12	B		52.29	191.42

- Microstructural and chemical analyses. The biochar's morphology from SEM micrographs at 10 µm and 2 µm magnification (Fig. 1a and b) shows that CB has a honeycomb-like appearance and a well-developed porous structure.

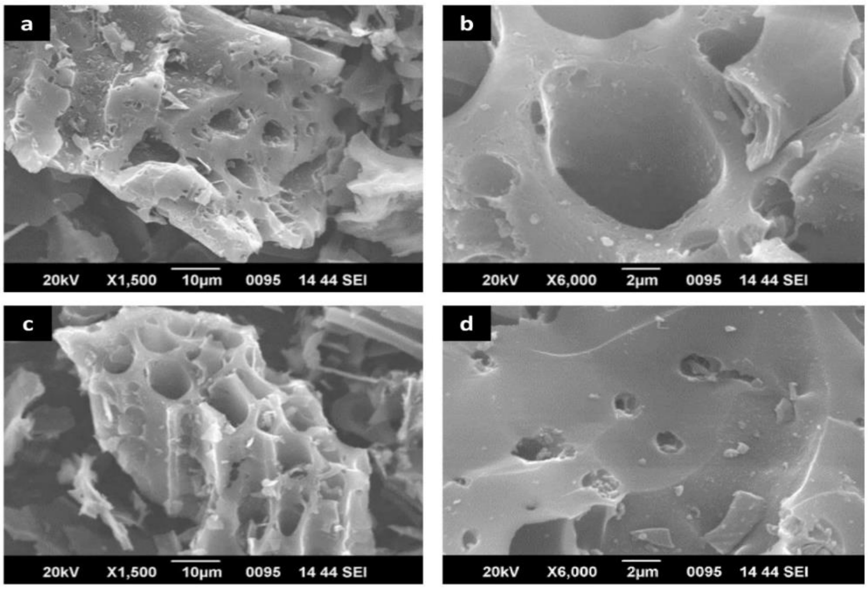


Fig. 1. SEM micrographs of coconut biochar (a) 10µm, (b) 2µm and CBMNF (c) 10 µm, (d) 2 µm

The porosity is due to the rapid volatilization of organic components from the plant matter during the pyrolysis phase and is beneficial for the attachment of metal ions [29]. The SEM micrographs depicting CBMNF are given in Fig. 1c and 1d. A comparison between CBNMF and CB revealed the variations in pore structures between these samples. The decrease in pore size of the CBMNF was due to the deposition of nutrients within the pores of biochar as suggested in previous studies [30]. This indicated successful deposition of nutrients onto the surface of CB thus converting it to CBMNF.

The FT-IR spectra of CB (Fig. 2a) exhibited peaks within the range of 750-1600 cm^{-1}. A weak broad low-intensity band was observed in the 3600-3400cm^{-1} region. This might be assigned to the hydroxyl group (OH) present on the biochar's surface. Polymeric alcohol, phenol and carboxylic acid groups, possibly originating from cellulose or hemicellulose and from adsorbed water molecule, may be responsible for this peak. The band due to N-H stretching of amines also appeared in this region [31-33]. A narrow band at 1565 cm^{-1} can be attributed to the C=C-C stretching vibrations of aromatic rings probably originating from lignin [34-36]. The weak absorption band at 1359 cm^{-1} might be due to OH bending in phenols possibly formed by the transformation of lignin [37]. A broad band appearing at 1100-1000 cm^{-1} could be associated with the C-O-C stretching of the ethers in lignin or the asymmetric stretching of Si-O-Si [38]. The peak at 874 cm^{-1} might be attributed to stretching vibration of C-H [39] and the peak at 806 cm^{-1} is likely attributed to the symmetrical stretching of Si-O-Si [40]. The peak at 755 cm^{-1} might be due to out-of-plane ring deformation or weak vibrational $-CH_2$ rocking [38].

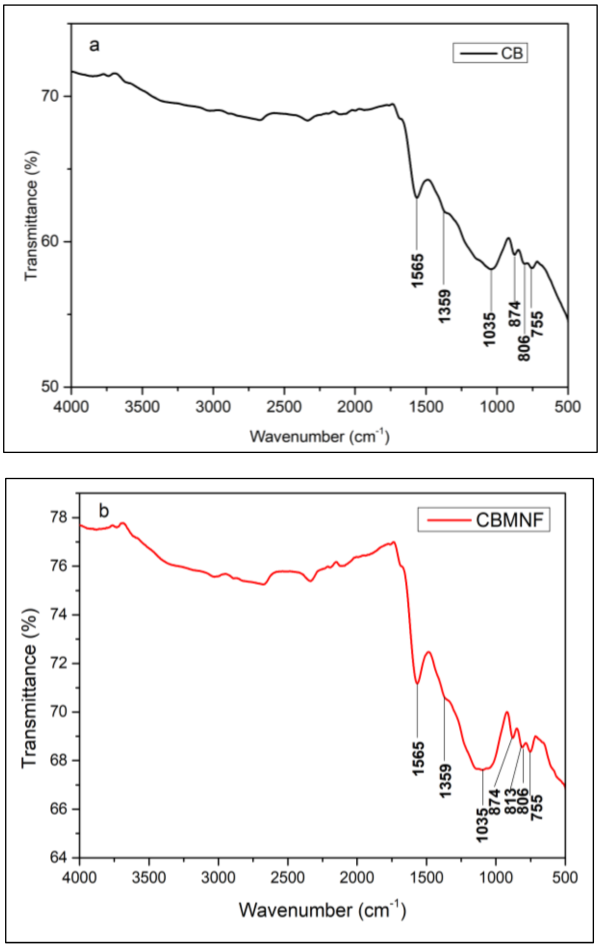


Fig. 2. FT-IR spectroscopy of (a) CB and (b) CBMNF

The FT-IR spectra of CBMNF was depicted in Fig. 2b. Similar to CB, CBMNF demonstrated a broad peak between 3600 – 3400 cm^{-1} , assigned to the hydroxyl groups (OH) originating from polymeric alcohol, phenol and carboxylic groups. It is also noted that changes in peak position and intensity served to distinguish nutrient-loaded biochar from regular biochar, indicating a subtle shift in peak location and varying peak intensities. This alteration in CBMNF spectra might attribute to the integration of nutrients into CB structure. Specifically, new peaks at 813 cm^{-1} were observed in CBMNF spectra, possibly indicating the presence of incorporated metal-ligand bonds, given that spectral bands within the 1000 to 700 cm^{-1} range are commonly associated with metal ligands such as M–O or M–O–H [37].

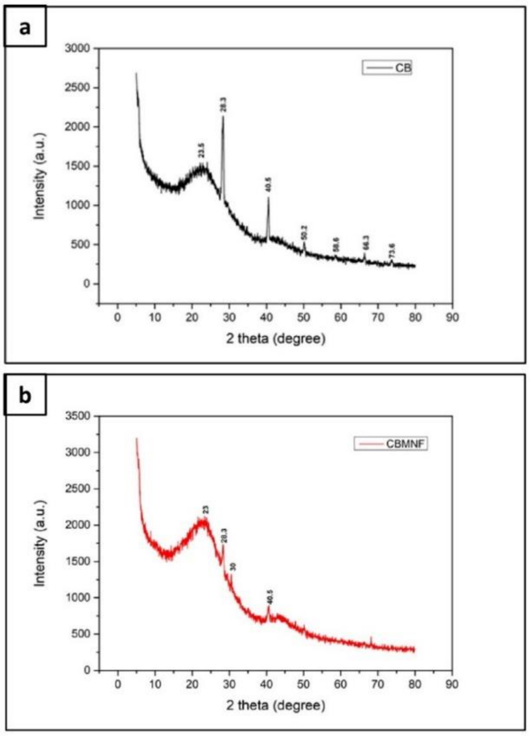


Fig. 3. XRD analysis of (a) CB and (b) CBMNF

The XRD pattern of CB is illustrated in Fig. 3a. The presence of crystalline inorganic fraction is suggested by the sharp peaks in the XRD patterns, while the diffused wide bands indicate the presence of short-range order in the biochar. The C (002) diffraction peak was identified as the one with a centre at around 2θ 23.5. Sharp peaks seen at 2θ values 28.3, 40.5, 50.2, 58.6, 66.3 and 73.6 could be assigned to KCl (sylvite-Ref. No. 00-041-1476) [41, 42].

In the XRD spectra of CBMNF (Fig. 3b), a prominent broad peak centered around 2θ value 23 was observed, showing greater intensity compared to CB. Additionally, the peaks associated with KCl at 2θ values of 28.3 and 40.5 exhibited reduced intensities. An additional peaks, observed at 2θ values 30 may be attributed to SiO_2.

The CB and CBMNF were assessed by TGA study, which examined how the material's physical and chemical characteristics changed as the temperature rose. The TGA and differential thermogravimetry (DTG) interlinked thermogram of CB (Fig. 4a) showed that about 10-12 % of mass was lost during the first phase (from the initial temperature to 100-120°C). This was due to the loss of moisture or free and non-structural water and other volatile matter from surface or pores of the material. The loss of mass in the second phase, from 121.9°C to 399.2°C, was attributed to the the oxidation of cellulosic materials by heat. The thermal oxidation of more resistant organic structures, such as lignin, and thermally generated carbonized/aromatic structures resulted in the third phase, where overlapping weight loss centred around 350°C is observed. This process may have involved the release of gases, such as CO_2, CO, and CH_4 [43, 44]. The recalcitrance index (R_{50}) value for CB was determined to be 0.467, slightly below 0.5. This suggests that the biochar is susceptible to degradation, and is not environmentally recalcitrant.

The TGA and DTG interlinked thermogram of CBMNF is given in Fig. 4b. In the thermogram of CBMNF, during the first phase, from 30°C to about 100°C, a 5 to 10 % reduction in weight was observed. This was attributed to moisture loss. Subsequently, when the temperature rose approximately to 350°C, the mass exhibited consistent stability, indicating the absence of free water molecules within the material. Between 300°C and 550°C, a significant mass reduction exceeding 50-60 % was observed, likely attributable to the decomposition of organic compounds. The final yield of CBMNF was determined to be in the range of 10-15 %. Beyond 550°C up to 750°C, there was no further change in mass, indicating that only the ash has remained. Also, the shifting of derivative thermo gravimetric (DTG) curve of CBMNF towards a wider range of temperatures depicted higher stability of the nutrient loaded biochar than the normal biochar. Upon adsorbing nutrient mix, an increase in R_{50} values to 0.543 was observed, indicating the improved stability of CBMNF.

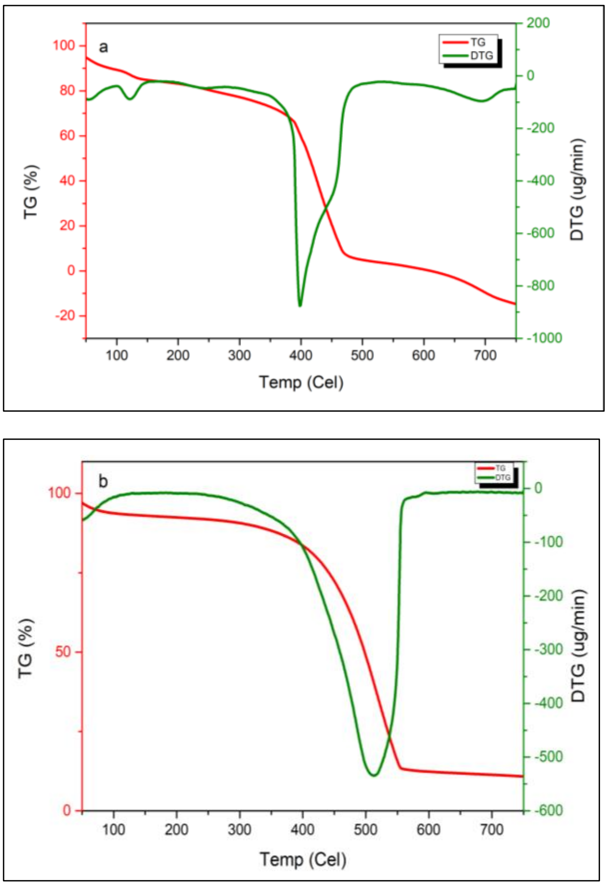


Fig. 4. TGA thermogram (green line) and DTG curve (blue line) of (a) CB and (b) CBMNF

Effect on soil water retention by addition of CBMNF

Soil enriched with CBNMF showed higher water retention than normal soil (Fig. 5), probably due to the decrease in the inter-particle pores. Addition of biochar improved the soil porosity allowing for higher water retention over an extended period [45].

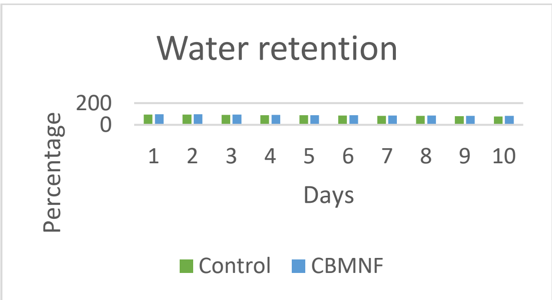
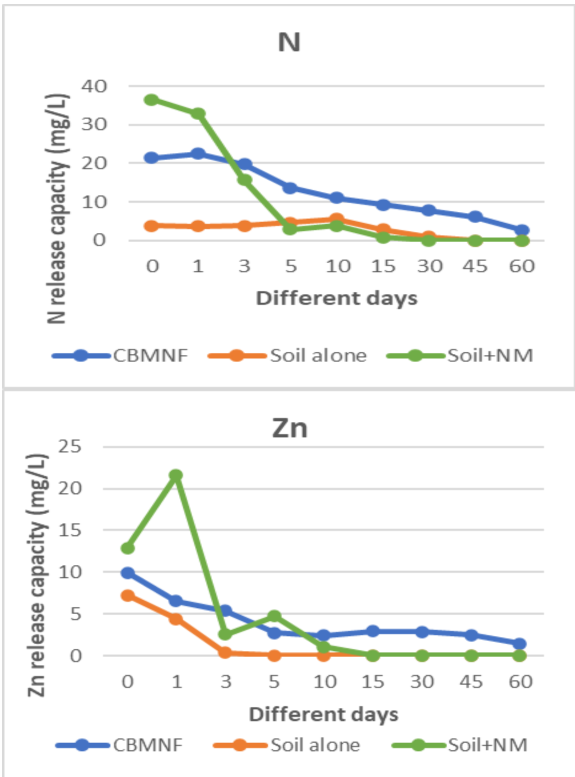


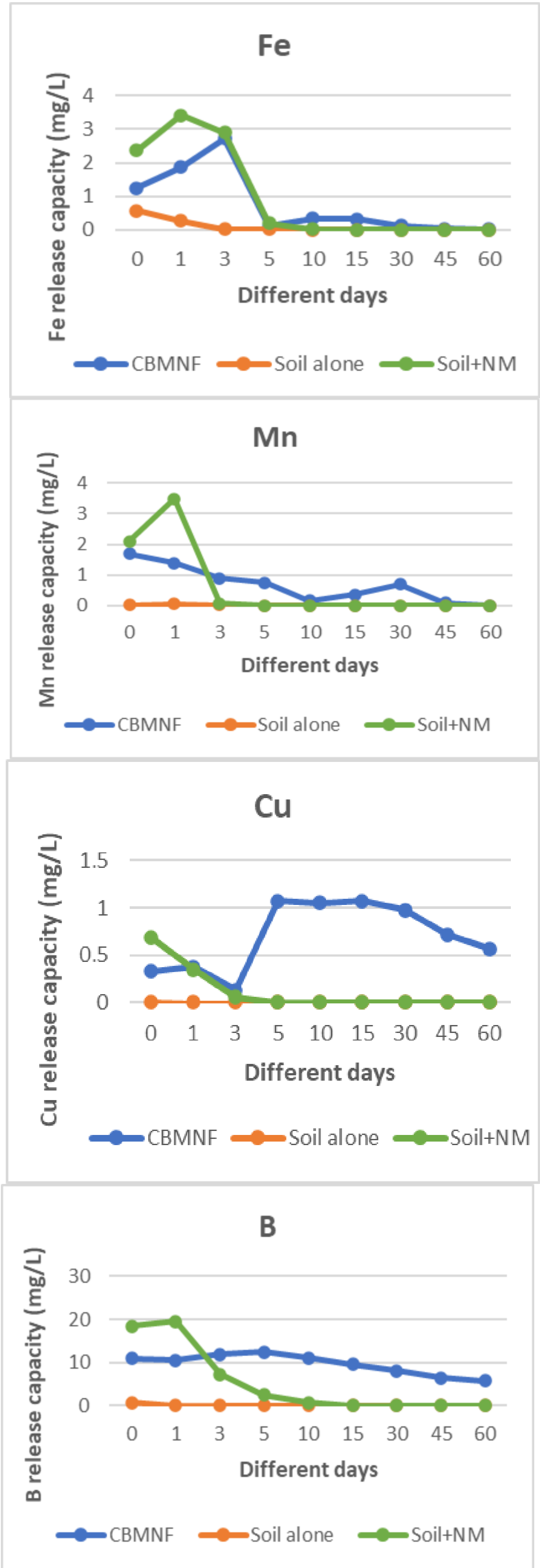
Fig. 5. Water retention by CBMNF

Slow release of nutrients in soil

The investigation analyzed the release patterns of essential nutrients, including N, Zn, Fe, Mn, Cu, B, and Mo, under various treatments. The results are shown in Fig. 6. The CBMNF treatment showed sustained NH_4^+-N release until the 60th day, with concentrations decreasing over time, while both soil-alone and soil+NM treatments ceased release by the 15th day. CBMNF also exhibited sustained Zn & Fe release throughout the experimental period, peaking on the first day and declining gradually thereafter, whereas soil-alone released these nutrients only up to the 5th day and soil+NM ceased release by the 10th day.

Continuous Mn release was observed under CBMNF treatment until the 60th day, while both soil-alone and soil+NM treatments ceased release by the third day. In the case of Cu, CBMNF showed continuous release, peaking from the 5th to 10th day, whereas soil-alone released Cu only on the first day, and soil+NM ceased release by the 3rd day. CBMNF sustained B release until the 60th day, while soil-alone and soil+NM treatments exhibited release for shorter durations Additionally, a steady decrease in release of Mo was observed over time under all treatments, with CBMNF showing the most prolonged release. The initial spike in nutrient leaching observed in the case of Zn, Mn & B may be attributed to the release of loosely held surface-loaded nutrients. The subsequent delayed nutrient release of nutrients over a sustained period probably originates from nutrients adsorbed in the pores of biochar. Mechanisms such as pore diffusion, ion interactions, and electrostatic forces influences nutrient adsorption and desorbtion on biochar. These findings underscore the potential of biochar-based slow-release fertilizers in extending nutrient availability over prolonged periods, offering insights for sustainable agricultural practices.





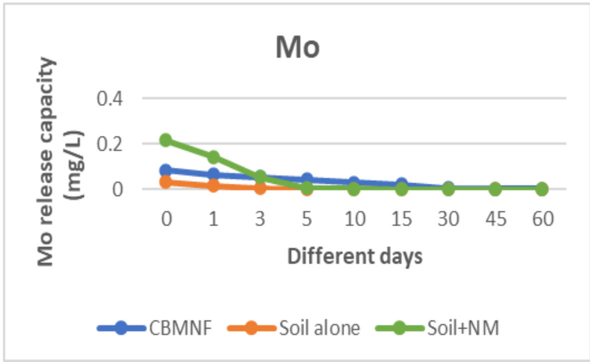


Fig. 6. Nutrient release patterns in soil

CONCLUSION

The coconut husk biochar has a honeycomb-like appearance with well developed porous structure as seen in the SEM images. The amorphous nature of biochar is confirmed by the diffuse broad bands observed in the XRD patterns. On incorporating the nutrients N, Zn, Fe, Mn, Cu, B and Mo into coconut husk biochar, the coconut biochar-based fertilizer (CBMNF) was synthesized. Comparison of FT-IR spectra of pristine biochar with that of CBMNF reveals a shift in the peak positions indicating changes in surface functional groups due to adsorbed nutrients. The deposition of nutrients within the pores of biochar is clearly visible in the SEM images of CBMNF. The XRD data of CBMNF were quite similar to those of CHB. A notable difference was the reduction in intensities of peaks assigned to inorganic entities like KCl, probably due to their loss during the impregnation process. TGA confirmed the higher stability of CBMNF than CHB. It also exhibited improved water retention. Additionally, studies on the nutrient release in soil revealed that CBMNF releases nutrients in a slow and sustained manner and acts as a slow-release fertilizer.

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Ethical approval: *Not applicable*

Informed consent: *Not applicable*

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Development of cashew nutshell-based composite material and heat-absorber panel: a comprehensive review

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This research focuses on developing a cashew nutshell (CNS) biochar-based composite panel to serve as a cost-effective and eco-friendly thermal energy storage alternative. Cashew nutshells, one of the most prevalent kinds of agricultural waste, can be subjected to controlled pyrolysis to obtain biochar. It is rich in thermal resilience, carbon content, and porosity, which are essentials for efficient heat absorption and retention. The purpose of the study is to compare the thermal efficiency of CNS-based panels with that of more conventional materials like metal and wood, to examine their construction, characterization, and performance assessment.

The proposed panel promotes sustainability and energy conservation *via* diverse applications, including industrial waste heat recovery, building thermal insulation, and solar thermal energy utilization. Construction and build processes have major impacts on ground, air, and water pollution. This research aims to combine waste reduction with clean energy development by providing a high-performance, inexpensive, and renewable thermal storage system. Additionally, this reearch will also explore phase change material integration to further enhance energy retention.

Keywords: Cashew nutshell (CNS), CNSL extraction, composite material, heat absorbing panel.

INTRODUCTION

The global demand for sustainable heat solutions has increased along with the increased interest in bio-based materials for heat absorption and retention. While traditional materials like metal and concrete provide high thermal conductivity, they can also pose environmental challenges, have high production costs, and lack of sustainability. In order to address these problems, this study explores the feasibility of cashew nutshell (CNS) biochar-derived composites as novel, sustainable alternatives in heat-absorbing panels. cashew nutshells (CNS) is a common and high lignocellulosic content agronomic waste product. Due to high phenolic resins in their structure, cashew nutshells have the potential to be used as materials for carbon-based thermal energy storage. Through regulated pyrolysis, CNS can be transformed into biochar with a high carbon content, high thermal stability, and improved porosity all essential characteristics for effective heat absorption and retention [1-3]. This project aims to investigate a systematic approach for developing a lightweight, long-lasting heat-absorbing panel for thermal energy storage and distribution for a variety of applications by incorporating CNS biochar into composite binders and composite reinforcement materials.

Although their hard shells need to be removed before processing, cashew nut seeds are high in fiber, healthy fats, and proteins [4]. 11,900 hectares of cashew farms were spread in Uttaradit, Chonburi, and Ubon Ratchathani in Thailand in 2019. The shell, which makes up 67–80% of the nut's weight, produces a substantial amount of biomass waste. Roasting produces shells that are semi-carbonized. Other processing techniques include frying, roasting, or mechanical cutting [5]. Applications in both industry and medicine can be found for cashew nutshell liquid (CNSL), a dark brown oil that is high in phenolic chemicals such as cardanol and anacardic acid. It is a natural substitute for manufactured phenols and makes up 30–35% of the shell's weight. Acetone has the highest CNSL output among extraction techniques, which also include solvent, heat, and mechanical procedures.

CASHEW NUTSHELL-BASED MATERIALS

Cement-based composites

Materials like cement composites are essential to the construction sector. However, the manufacture of cement uses a lot of energy and contributes significantly to CO_2 emissions. Researchers have

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studied CNS-derived supplemental cementitious materials (SCMs) handled at various temperatures, such as CNS ash (CNSA), uncalcined CNS, and CNS powder (CNSP), in an effort to address these problems.

For instance, Sakthivel and Suthaviji (2024) [6] have investigated the use of CNSA as a partial substitute for ordinary portland cement (OPC) and discovered that its pozzolanic activity improved long-term strength at an ideal CNSA concentration of 10 -30 %. Lima and Rossignolo (2010) [7] have investigated the physical and chemical characteristic of CNSA for application in cement suggesting that it has pozzolanic potential. Additionally, a critical assessment by Thirumurugan *et al.* (2018) [8] noted that, because of its oxide composition, CNSA shows promise as pozzolanic material and a possible SCM, enabling partial cement replacement in mortar and concrete applications. In mortar and concrete applications, CNSA shows promise as a pozzolanic material to partially replace cement.[9]. While a 20% substitution is appropriate for non-load-bearing applications and results in denser and stronger concrete, a 15% substitution is thought to be ideal for structural use. According to additional studies, up to 25% CNSA substitution improves overall strength, pore minimization, curing, and water absorption. On the other hand, because of its poor mechanical properties, uncalcined CNS cannot be used as a substitute for cement [10]. The effectiveness of CNS biomass is increased by calcining it, which permits a larger substitution ratio.

Generally, it is very crucial to achieve a high bearing capacity for soil stabilization. According to research, CNSA and lime together increase the strength of extremely expansive soils. For example, compressive strength rose dramatically when 5.5% of lime was substituted for 0.5% of CNSA. Only slight benefits were seen in lateritic soil when CNSA and glass industrial waste were added, according to another study. CNSA decreased the maximum dry density of the soil while increasing soil cohesiveness and decreasing the friction angle. The ideal CNSA % for soil stabilization, as well as its long-term impacts and cost-effectiveness in comparison to alternative stabilizers, require further investigation [9].

Biopolymers

Researchers are creating plant-based biopolymers to solve the environmental problems caused by non-biodegradable petrochemical polymers. Biodegradable plastics can be made using polyesters, proteins, lipids, and polysaccharides from renewable agricultural sources. Both cellulose and starch are important in this study, with starch showing promise as a non-toxic, biodegradable, and renewable substitute in the polymer sector. CNSc starch had double the solubility of maize starch, high crystallinity, and resin agglomeration, but it showed less swelling than polymeric resins despite having a high amylopectin concentration. Although its thermal processing should not go over 174°C, these properties make it a promising renewable material for the synthesis of polymers [10].

Along with starch, CNSc has been used to extract pure cellulose using a modified acid hydrolysis process that is followed by bleaching and alkali treatment. The application of CNSc in the synthesis of phenolic resin is another encouraging advancement. In the presence of particular catalysts, liquefaction of high-lignin biomass enables the partial replacement of formaldehyde with biomass, resulting in phenolic resins that are more ecologically friendly [11]. Due to its high lignocellulosic content, CNSc is a great feedstock for chemical transformation and liquefaction. A 2:1 phenol-to-CNSc ratio produced the most resin during the liquefaction process, which comprised heating ground CNSc and phenol with sulfuric acid. The oligomeric nature of the resin was confirmed by gel permeation chromatography, and the functional groups and chemical structure typical of phenolic compounds were validated by FTIR and NMR investigations. Although more study is required for thorough characterization, this breakthrough shows promise for CNS-derived resins. In conclusion, lignin, cellulose, and starch, all are crucial building blocks of biopolymer. With their biodegradability and lower environmental effect, starch-based biopolymers provide environmentally benign substitutes for petroleum-based plastics in products including packaging, cutlery, bags, and films [12].

Polymer matrix composites

Different types of CNS have been used as matrix ingredients, fillers, and reinforcements in composites for packaging, coatings, and structural materials [13]. As an illustration, consider the production of bio-thermoplastic films containing CNSc starch, walnut shell cellulose for reinforcing, and antioxidants from pomegranates for clever packaging uses. While decreasing moisture retention, higher CNSc starch concentration improved mechanical characteristics and oxygen transfer rates. The cellulose-reinforced film with pomegranate peel extract that performed the best showed promising properties for packaging. Composites have also been made using CNSP in polymeric matrices [14]. The characteristics of the composite were impacted by varying CNS concentrations when it was mixed with a recycled high-density polyethylene (rrHDPE) matrix. As the CNSP level rose, thermal examination revealed two stages of degradation with decreased crystallinity. The composite showed improved fluidity as a result of residual CNSL, although FTIR measurement revealed interface degradation. After processing, SEM pictures indicated voids, while mechanical testing demonstrated increased elongation at fracture and decreased elastic modulus [15].

Some researchers have investigated CNSA-based solutions to offset the detrimental effects of residual CNSL. In one investigation, an epoxy resin composite reinforced with sawdust, rice husk, and CNSA in different ratios was created. In addition to wood residues, ground CNSc has been added to particle boards. Because of the irregular particle geometry and residual CNSL caused by CNSc, strength and dimensional stability were adversely affected by the adhesive type and CNS/wood ratio [16]. But compared to pure wood boards, these boards showed less flammability, burning more slowly and extinguishing themselves more quickly. All things considered, CNS shows great promise as an economical and renewable component in composite materials, improving mechanical, physical, and chemical qualities while lowering prices for particular uses.

Supercapacitors

CNSAC's huge surface area, exceptional porosity, outstanding chemical stability, and improved electrical conductivity have all led to its use in electrochemical double-layer capacitors (EDLCs). It has been effectively created by carbonization in an inert atmosphere after chemical activation with different KOH ratios. A 3D honeycomb-like porous structure was discovered by SEM examination, which is very advantageous for ion transport and electrolyte storage. CNSAC is a preferred electrode material for supercapacitors because of its large surface area, which offers several interfaces for charge storage. Higher KOH activation ratios were shown to enhance pore size; however, this effect waned at an activation ratio of 1:2. As a potential substitute for supercapacitor applications, the CNSAC sample with a 2:1 activating agent ratio demonstrated greater capacitance (214 F/g), quicker charge transfer, and 98% capacitance retention after 1000 cycles [11].

Because of its large porosity and surface area, CNSAC exhibits good features for electrochemical applications overall. Strong promise for long-term performance in actual energy storage devices is indicated by its capacity to maintain high capacitance even after 1000 cycles. Nonetheless, a thorough assessment of supercapacitors that use CNSAC is required, with an emphasis on factors including cycle efficiency, energy density, power density, and long-term stability.

The findings of this study will offer fresh perspectives on high-performance, low-cost, and renewable thermal energy storage materials, enabling a more thorough use of agricultural waste in green energy applications. Future advancements, such as the use of phase change materials (PCMs) to boost energy retention capacities, will be based on the findings.

LITERATURE REVIEW

Throughout the world, the bushy, evergreen cashew tree (*Anacardium occidentale*) is found in tropical climates. The cashew's edible nut is its primary and most valuable product, even if cashew farming can yield a pseudo-fruit (cashew apple) that is used in the food industry. A beneficial product for a range of industrial uses that are garnering attention is cashew nutshell liquid, or CNSL, a phenolic liquid found inside cashew nuts that are encased in a shell with an internal honeycomb structure [17]. Large cashew producers in West Africa and Southeast Asia account for 90% of global cashew production. In any event, raw cashew nut production figures have increased gradually over time, from 1.6 million tons in 2003 to 2.13 in 2006-07 and 3.30 in 2015, as a result of growing demand for this item [18-20]. These figures, however, are usually thought to represent an underestimation of the true production. Consequently, the cashew industry generates an increasing amount of shell waste that needs to be properly valued. Burkina Faso accounts for around 2.3% of global production (75,000 metric tons) and has a planted surface area of 4 MHa, according to the African Cashew Initiative [21]. The bulk of production is meant for exports because smallholder farmers usually lack the specialized tools or equipment required for cashew nutshell processing or the recovery of CNSL as a valuable product [22]. Cashew nutshells are frequently disposed of (or temporarily stored for fire) at the field margins due to their toxicity [23]. If any of the CNSL is released and subsequently builds up or is absorbed into soil or water channels, this poses a serious environmental risk [24, 25]. In contrry, empty nutshells and CNSL may be valuable feedstocks for a variety of applications [26].

The high-energy byproduct of processing cashew nuts is their shell. It could replace fuelwood for thermal uses in a plant. As part of this approach, an effort has been undertaken to convert cashew nutshells into energy by gasification [27]. The physical attributes of the raw cashew nut were evaluated in connection with its moisture content. The average measurements of the three main axes (length, width, and thickness), mass ratio, equivalent diameter, and sphericity were measured at a moisture content of 46% d.b. Measurements were made of the 100 nut mass, porosity, bulk density, actual density, and coefficient of friction for moisture concentrations ranging from 15 to 05% d.b. It was found that raw cashew nuts' real density and 100 nut mass increased in tandem with their moisture content. The porosity and bulk density decreased linearly with increasing moisture content [28]. The successful synthesis of premium activated carbon from cashew nutshells, a frequently available agricultural waste product, represents a significant advancement in sustainable and eco-friendly material science. According to this study, it may have practical use in areas like gas storage and air purification, as well as perhaps in resolving environmental problems like greenhouse gas capture [29]. The physico-chemical properties of cashew nutshells show that they are suitable as raw materials for thermochemical energy recovery processes. However, their direct usage in these heat processes has detrimental effects on human health and the environment [30]. For the creation of many materials, including cellulose, lignin, and starch, CNS shows great promise. These factors make CNS a versatile and renewable resource that can be utilized in a variety of products, including activated carbon, adhesives, coatings, biopolymers, composites, cementitious materials, and rubber additives. This article reviews other applications for CNS. The potential uses are divided into three categories: material development, energy production, and substance absorption. The materials section discusses a number of applications where CNS is utilized as a raw material to produce cementitious materials, biopolymers, and other composites [31]. Various forms of CNS have been used as reinforcements, fillers, and matrix components in composites for structural materials, coatings, and packaging. For example, Harini *et al.* (2018) [32] synthesized a composite employing CNSc starch to make bio-thermoplastic sheets. Pomegranate antioxidants and antibacterial ingredients were mixed with walnut shell cellulose, which served as reinforcement, to create ingenious packaging. Better oxygen transfer rates and improved mechanical properties were the outcomes of increased CNSc starch concentrations in the composite, both of which are crucial packing qualities. The solubility of CNS starch films ranged from 40% to 48%, and higher concentrations of CNSc starch led to decreased moisture retention. Different CNS concentrations were investigated, and the composite properties were evaluated. The findings of tensile tests revealed a lower elastic modulus and greater elongation at fracture. The poor performance could have been caused by partial CNSL extraction, low resin absorption by the fiber, inadequate control of CNSP particle size, or void formation during processing. The author suggested that CNS-reinforced polymer composites might be suitable for less demanding applications, even if complete CNSL extraction is required for structural use [33]. Another example of CNS composites was provided by Mari and Villena (2016) [34], who combined pulverized CNSc with wood waste to create particle boards. The type of glue and the CNS/wood ratio had an impact on strength and dimensional stability. These two characteristics are adversely affected by CNSc replacement due to the uneven particle shape and residual CNSL. While boards lit more slowly and extinguished more rapidly than pure wood, they were less combustible and caused less damage to the wood board area. The results show that CNSc has budgetary benefits and is suitable for less demanding applications.

CNS has shown promise in several applications as an affordable and renewable component for composite materials, offering opportunities to reduce costs while enhancing mechanical, physical, and chemical properties [31]. Researchers have used epoxy polymer composites with sisal fiber mat and stainless-steel wire mesh (SSWM) as reinforcements together with cashew nutshell liquid (CNSL) to generate a special type of hybrid polymer matrix. The composite materials were made using compression molding, and their performance was assessed by looking at their mechanical and thermal properties. When it comes to flexural strength, plain epoxy polymer composites (EP) outperform hybrid polymer composites (HP) [35].

The CNSL waste is packed tightly in an airtight container and heated to 500° C for one h in a stir casting furnace. This CNSL biochar is used to strengthen unsaturated polyester resin for making composites. The composites were prepared using the solution dispersion method at different weight percentages of 5, 10, and 15. The prepared specimens were subjected to tensile, flexural, and impact strength testing. With improvement percentages of 21, 41, and 37, respectively, the maximum tensile, flexural, impact, and hardness strength of a 10% biochar-filled composite surpasses that of an unfilled composite [36].

Table 1 presents a literature survey that provides valuable insights into the utilization of cashew nutshell-derived materials for developing efficient heat-absorbing panels and related thermal applications.

Table 1. Utilization of cashew nutshell-derived materials for developing efficient heat-absorbing panels.

Methodology	Materials used	Potential applications in heat-absorbing panels	Key findings	Ref.
Thermal oxidative stability testing was performed by TG/DTG and DSC analysis and PMMA films were doped with 1 % CNSL derived phenolic lipids.	CNSL derivatives (cardanol and cardol) and PMMA.	CNSL based additives can be used in composite materials for heat absorbing panels to improve thermal stability and resistance to oxidation.	CNSL derived phenolic lipids (cardanol and cardol) remarkably improv the thermal -oxidative stability of PMMA films. TG/DTG and DSC characterizations confirmed 37enhanced thermal resistance.	[37]
CNSL based resin composites was fabricated with coconut Fibers, followed by mechanical and thermal analysis.	Coconut fibers and CNSL based resin	CNSL based resins can be treated as sustainable binders in heat absorbing panels, enhancing mechanical integrity and reducing environmental impact.	Bio-composites prepared from CNSL resin and natural fibers show improved mechanical and thermal properties. Also enhanced biodegradability and sustainability.	[38]
Soxhlet extraction technique was adopted by using polar and non-polar solvents followed by HPLC characterizations.	CNSL, Various solvents	Extraction of CNSL improves thermal efficiency and modifying it into heat absorbing panel material.	CNSL contains cardanol, cardol and anarcardic acid showing excellent thermal stability. Different extraction techniques influence material efficiency.	[39]
Bio-based Mannich polyols was synthesized by oxazolidine route, followed by characterization through FTIR, NMR and mechanical testing.	CNSL-based Mannich polyols, polyurethane foam.	CNSL derived polyurethane foams can improve the insulation properties of heat absorbing panels, also making them energy efficient and fire resistant.	CNSL based polyols were used for developing rigid polyurethane foams with enhanced insulation properties and low thermal conductivity.	[40]
CNSL based coating was developed, followed by thermal efficiency testing on solar collectors.	CNSL copper plates, B_2O_3/Bi_2O_3 flux.	CNSL based coating can improve the efficiency of solar thermal collectors and heat absorbing panels.	By using CNSL based coating for solar thermal collectors, 42.86 % efficiency was achieved and showed a high absorptivity and low reflectance properties.	[41]
Alkylation was carried out for the modification of cardanol into antioxidants, followed by oxidative stabilization of gasoline.	CNSL derived hydrogenated cardanol, tert-butyl chloride.	CNSL derived hydrogenated cardanol can enhance the longevity and stability of heat-absorbing panels by preventing oxidative degradation due to its antioxidant properties.	Hydrogenated cardanol modified into antioxidants by alkylation with tert-butyl chloride exhibited superior stabilization compared to commercial gasoline additives.	[42]
Mannich polyols were synthesized using oxazolidine, followed by NMR, FTIR and mechanical testing.	CNSL-derived Mannich polyols, polyurethane foam	CNSL based polyurethane foams could be improved fire resistance and insulation in heat absorbing panels.	CNSL based Mannich polyols can be a good alternative to petrochemical based polyols. The resulting polyurethane foams showed high mechanical strength and low thermal conductivity.	[43]
Thiophosphorylated CNSL derivatives was synthesized, followed	CNSL phosphorus derived compounds	CNSL phosphorus derived compounds could improve the heat resistance of materials	A new thiophosphorylated CNSL derivative was synthesized, showed a significant enhancement in	[44]

by oxidative stability and thermal testing.	and mineral oils.	and durability in heat absorbing panels due to its antioxidant properties.	oxidative stability when tested in mineral oils.	
The larvicidal activity testing was performed against Aedes aegypti, followed by evaluation of cardol's effectiveness and toxicity.	CNSL-based cardol.	CNSL could contribute to develop antimicrobial coating for heat absorbing panels due to its biocidal properties.	CNSL based cardol exhibited strong larvicidal activity against Aedes aegypti, exhibited its and ability to penetrate cell membranes due to its liposolubility.	[45]
CNSL based bio-composite was fabricated with bamboo fibers, followed by thermal and mechanical testing and TGA analysis.	CNSL derived resin, bamboo fibers.	CNSL derived bio-composites could be developed lightweight, thermally stable and durable heat absorbing panel.	CNSL based bio-composites fabricated with bamboo fibers showed increased tensile strength, modulus and improved thermal stability.	[46]

Few researchers in India have studied cashew nutshells as a waste treatment and composite material. To the best of the authors' knowledge, no relevant research has been done on heat absorption panels that use cashew nutshells. The purpose of this study is to develop biochar-based heat panels using cashew nutshell (CNS) charcoal. Before being pulverized into a fine powder, CNS is dried, crushed, and pyrolyzed at 400–600°C. After combining 60–70% of biochar with 30–40% of resin binder, the mixture is reinforced with fiberglass or natural fibers, molded, compressed, and left to dry at room temperature or 80°C.

A black thermal coating enhances heat absorption. When tested for solar heating, heat retention, and industrial heat recovery, panels show better heat absorption, longer retention, and structural stability than conventional materials. Testing for waste heat recovery can be done at "Thermax Ltd.,pune" following panel development. Companies that manufacture solar panels can also conduct testing.

MATERIALS AND METHODS

To understand the methodology for development of heat absorbing panel, by using composite material obtained from cashew nutshell and epoxy resin in an easier way, a flowchart has been prepared as shown in Fig. 1. In the primary material processing step, collect cashew nutshells and extract CNSL for its heat-resistant properties. Thereafter, pyrolyze the remaining shell biomass in an environment with low oxygen levels to prepare biochar. Combine the prepared biochar with a binding material (like epoxy resin or biodegradable polymer) to create a heat-absorbing composite [25-31]. Secondly, compress the biochar-binder mixture into compact flat panels during the panel fabrication stage. To improve the efficiency of heat absorption, use a black coating. Next, undertake thermal performance testing, such as heat retention, solar heating, and industrial waste heat recovery, during the testing & evaluation stage. Examine the effectiveness of CNS biochar panels in comparison to more conventional materials like wood and metal. Test the panels in a variety of applications, including industrial heat recovery, building insulation, and solar water heating, at the final stage, application and validation. Examine how phase change materials (PCMs) might be incorporated to improve the effectiveness of heat storage.

RAW MATERIAL COLLECTION & PREPROCESSING

Cashew nutshells (CNS) must go through several crucial preprocessing and raw material collection processes in order to be ready for additional processing. The main raw material is cashew nutshells, an agricultural waste. In order to maintain structural integrity in the finished product and retain processed CNS particles together, binding elements are necessary. Epoxy resin is appropriate for long-lasting applications because of its excellent adherence and durability. Natural resins, which come from plants, provide a good bonding option that is also environmentally benign. By using fewer synthetic materials while retaining adequate strength and flexibility, biodegradable binders—such as adhesives based on lignin or starch—improve sustainability. The intended use and environmental factors influence the binder selection [9]. We have listed out some selected raw materials used for the development of heat absorbing panel, as shown in Table 2.

DESCRIPTION OF METHODS AND EQUIPMENT

Equipment for carbonization: a pyrolysis chamber or kiln

An essential step in turning CNS into a substance with a high carbon content is carbonization. In order to prevent combustion, the shells are heated in a regulated atmosphere with a restricted oxygen supply in a kiln or pyrolysis chamber. While pyrolysis chambers provide more sophisticated, effective thermal processing with better temperature control, kilns are still utilized for carbonizing biomass. Because of its high porosity and energy density, the resultant carbonized material can be used in composite panel production, filtration, and insulation [24, 26].

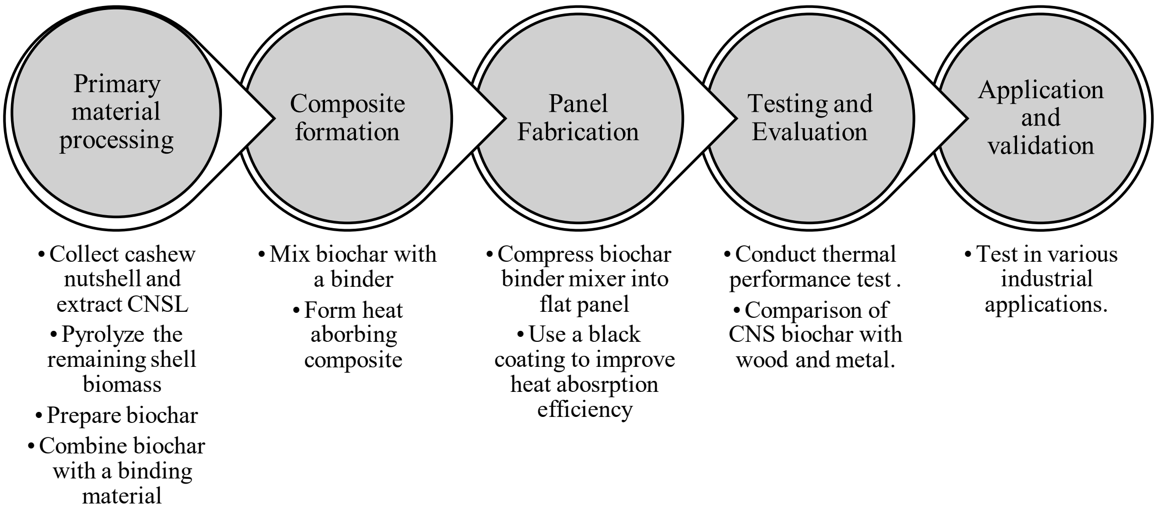

Fig. 1. Flowchart of the methodology for development of heat absorbing panel**.**

Table 2. Different raw materials used for the development of heat absorbing panel.

Raw material	Layer	Purpose	Ref.
Composite of Cashew Nutshell (CNS), Biochar (60-70) % and Resin (30–40%).	Heat-absorbing layer, or core layer	High carbon content and thermal stability make it the primary medium for absorbing and storing heat.	[47]
Natural fiber (such as jute or coconut fiber) or fiberglass mesh.	Layer of Reinforcement	Resists breaking under heat expansion and offers structural strength.	[48]
Thermal Black Paint or Nano-Carbon Mist.	Coating the Surface (outer layer)	Maximizes energy intake by improving absorption of solar and infrared heat.	[49]
Metal or silicone frame	(Optional) Edge Reinforcement	Improves durability and maintains the shape of the component. Also protects edges from damages due to pressure or external forces.	[50]

Panel mold: steel or wooden structures to form the panel

In order to transform processed CNS material into usable goods, panel molds are employed to compress and shape the mixture into homogeneous panels. Steel molds' remarkable longevity, precise shape, and resistance to heat and pressure make them ideal for industrial manufacture. Despite their lesser durability, wooden molds are affordable and suitable for experimental or small-scale applications. The molds ensure that the mixture solidifies into consistent panel dimensions, which facilitates its use in a range of applications such as insulating boards, construction materials, and solar heat absorbers [16].

Material for surface coating: black heat-absorbing paint or thermal coating

A surface coating is applied to enhance the panel's thermal properties and longevity. Black heat-absorbing paint is commonly used to improve heat retention and boost the efficiency of solar panels. Improved resistance to UV radiation, moisture, and mechanical damage are further benefits of thermal coatings. Because these coatings ensure longevity and efficacy, the final product is suitable for applications like solar cookers, insulation panels, and energy-efficient building materials.

METHODOLOGY DESCRIPTION

Preprocessing procedures

Preprocessing is a crucial step in preparing cashew nutshells for further thermal and industrial use. The process begins with the careful collection of raw cashew nutshells, which are then sun-dried to eliminate any residual moisture. Proper drying is essential because moisture content may reduce the efficiency of subsequent processing steps, leading to uneven thermal decomposition or incomplete combustion [9]. Additionally, drying prevents mold growth and microbiological deterioration, keeping the shells in the best possible condition for further treatment. When the shells have sufficiently dried, they are crushed into small bits. Size reduction is the term for this process. This step is crucial for boosting pyrolysis efficiency because breaking the shells into uniform pieces enhances heat transfer and allows for more controlled carbonization. The greater surface area allows for better conversion of the shells into activated carbon or biochar and faster breakdown. Furthermore, for applications such as thermal insulation panels, bio-composite materials, and energy-efficient industrial products, consistent end product from the homogenous particle size is essential. By carefully completing these preprocessing steps, cashew nutshells can be transformed into useful, sustainable materials that will help cut waste and advance eco-friendly concepts.

Production of biochar (thermal treatment)

A very efficient thermal breakdown method called pyrolysis is used to turn cashew nutshells into activated carbon or biochar, which has better heat retention qualities. In this procedure, the crushed cashew nutshells are heated to regulated temperatures between 400 and 600°C in a low-oxygen atmosphere [51]. A slow breakdown of organic materials while maintaining the carbon content is ensured by the absence of oxygen, which inhibits full combustion. Cashew nutshell liquid (CNSL) and other volatile chemicals are released during the gas removal process that occurs during this phase. The important phenolic chemicals found in CNSL can be extracted and used separately for commercial uses such adhesives, coatings, and bio-based resins. The pyrolysis process is a sustainable way to turn agricultural waste into a useful, carbon-rich substance with a variety of industrial uses. It has been observed in the literature that around 400–600°C is the optimal temperature range for pyrolysis to optimize the thermal efficiency of biochar [52]. This range minimizes full combustion while optimizing carbon retention. In order to assure a slow breakdown of organic matter while maintaining the carbon content, the heating rate should be slow to moderate, usually between 5 and 10°C per minute. Depending on the desired qualities of the biochar, the ideal time for the pyrolysis process is around 3 to 4 hours, as shorter pyrolysis time (less than 3 hrs) may lead incomplete carbonization and longer pyrolysis time may result to excessive carbon loss due to secondary reaction and hence resulting in reduced yield and thermal efficiency [53, 54]. A more stable, carbon-rich biochar with improved heat retention qualities results from a longer residence time, which permits more thorough volatile release. The process of recycling cashew nutshells through regulated pyrolysis and activation helps to reduce waste, promote environmental sustainability, and create environmentally suitable substitutes for synthetic products.

CNSL extraction: A waste product of agriculture, of cashew manufacturing, cashew nutshells (CNS) are frequently thrown away as garbage [26]. They can, however, be recycled for environmentally friendly uses and contain useful components. Carbonized CNS can be utilized in composite materials when treated appropriately, lowering agricultural waste and encouraging environmentally beneficial alternatives. They are perfect for thermal applications like bio-based panels and energy-efficient goods because of their high carbon content [29]. In order to extract CNSL through cold processing, the raw shell was then crushed into smaller pieces using a compressed screw mincer powered by a 5 HP engine, as shown in Fig. 2.

Cold-pressed hydraulic extraction

A 2 HP three-phase motor that rotates at 1430 rpm and a pump that can produce high-pressure output of up to 16 MPa at 15.8 cm3/rev are both part of the hydraulic system utilized in the extraction.

Fig. 2. Using a mincer, grind the cashew nutshells into tiny bits [51]

A 3-inch diameter, 18 mm thick steel cylinder with 2 mm holes drilled in the bottom was used to build the compression cylinder. Using the supported core, a hydraulic cylinder was used to push the compression cylinder higher, compressing the cashew nutshells inside. The compression compelled the CNSL to flow into an oil tray from the hole at the bottom of the compression cylinder after a certain amount of time [10]. The several parts of the specially constructed extraction machine are shown in Fig. 3.

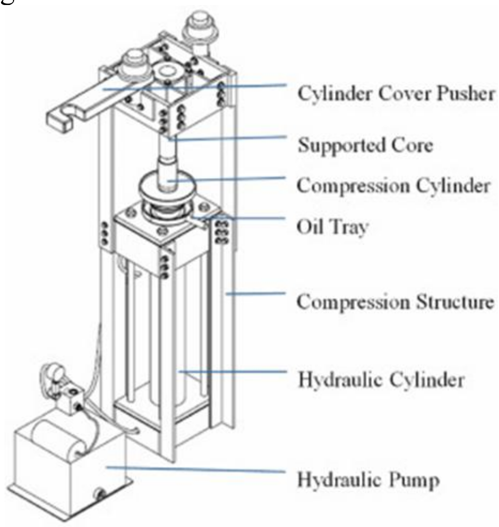

Fig. 3. Cold-pressed hydraulic extraction [10]

Heat in a low oxygen environment: The crushed shells are then subjected to thermal decomposition in a controlled low-oxygen environment to prevent complete combustion. The shells are heated for one to two hours at temperatures between 400 and 600°C in a metal drum, kiln, or pyrolysis chamber. Only volatile substances, including cashew nutshell liquid (CNSL), are released due to the lack of oxygen, leaving behind carbon-rich biochar. The temperature and duration of heating play a crucial role in determining the final properties of the biochar, including its thermal stability and adsorption capacity [22, 23].

Cooling & grinding

To avoid structural damage from abrupt temperature changes, the biochar must be cooled gradually after the pyrolysis process is finished. To prevent oxidation, cooling is typically carried out in a controlled or inert atmosphere. To guarantee consistent particle size and increase its usefulness in processes like soil improvement, energy storage, and water filtration, the biochar is ground into a fine powder after cooling. Fine grinding enhances surface reactivity and allows for better binding in composite materials.

Activation process

To further enhance the porosity and adsorption properties of the biochar, an activation process can be carried out. This entails processing the charcoal with chemical agents like potassium hydroxide (KOH) or phosphoric acid (H_3PO_4). Because of its superior ability to trap impurities and enhance chemical reactions, activated carbon is widely used in energy storage (supercapacitors), water purification, air filtration, and industrial catalysis. The activation process dramatically increases surface area and pore volume, turning the biochar into activated carbon with improved adsorption capacity [29].

Panel fabrication

Achieving a homogenous consistency is essential to maintaining structural integrity and improving heat retention properties for solar energy applications. To begin the fabrication process, a biochar-resin mixture is prepared by combining 60–70% biochar with 30–40% epoxy resin. This composition guarantees a robust, long-lasting panel with improved thermal and mechanical properties. The mixture is thoroughly stirred until it forms a thick, uniform paste, ensuring proper binding between the biochar particles and the resin.

Mold the panel: Once the mixture is ready, it is poured into a flat mold of predefined dimensions (e.g., 30 cm × 30 cm × 1 cm for experimental testing). The mold helps shape the panel into a uniform structure suitable for practical applications. After pouring, the material is compressed evenly to eliminate air pockets, ensuring a dense and compact panel with enhanced durability and thermal efficiency. Proper compression prevents defects such as voids or weak spots, which could reduce the panel's performance.

Curing process: The molded panel must undergo a curing process to harden and acquire its final strength. Basically, there are two approaches to curing: Room temperature curing and Heat assisted curing. Room temperature curing allows the panel to set naturally for 24–48 hours, which promotes gradual hardening and solid bonding between biochar and glue. While heat assisted curing speed up resin polymerization, placing the panel in an oven set between 60 and 80°C shortens the fabrication time. When a quicker turnaround is needed for large-scale production, this approach is especially helpful.

Surface coating for maximum heat absorption

A heat-absorbing surface coating is applied to the panel to improve its thermal efficiency. Black paint or a carbon-based coating, which both enhance absorption of solar light, can be used to accomplish this. For uses including solar thermal energy systems, heat insulation panels, and renewable energy sources, a properly placed coating optimizes the panel's capacity to trap and hold heat.

Thermal properties measurement test of heat absorbing panel

Thermal conductivity test: A TD 1002 Heat Conduction Base Unit was used to perform the thermal conductivity (TC) test for cashew nutshell biochar-epoxy resin composites in accordance with BS EN 12664 requirements. Before testing, cylindrical samples (30 mm in diameter by 20 mm in height) were oven-dried for 24 h at 105°C to eliminate moisture. Temperature observations were taken during ten min of a constant 9.9 W heat flow. Fourier's Law was used to calculate thermal conductivity as:

$$k = \frac{\Phi . \mathrm{t}}{A . \Delta \mathrm{T}}$$

where Φ is heat flow, t is specimen thickness, A is surface area, ΔT is temperature difference, and k is thermal conductivity. The test results indicate that the increasing the biochar content, thermal conductivity decreases, resulting in enhanced insulation properties. On comparison with conventional epoxy resin and concrete, the biochar-based epoxy exhibited lower thermal conductivity making it promising material for thermal insulation applications [55].

Specific heat capacity (SHC) test: Using the electro-calorimetry method, the cashew nutshell biochar-epoxy composite's specific heat capacity (SHC) was ascertained. Cubic specimens of 50 × 50 × 50 mm³ were constructed, and holes were drilled at two thirds of the depth for a thermometer and an immersion heater (2000 W, 220–250 V). Samples were placed in a calorimeter on the twenty-eighth day of curing, and temperature, current, and voltage readings were taken while power was provided. Since thermal expansion was minimal, the formula for the calculation of specific heat capacity can be given as:

$$C_p = \frac{Q_2 - Q_1}{\big((m_2 - m_1)\big)(t_2 - t_1)}$$

where C_p is the specific heat capacity, Q_2 and Q_1 are final and initial heat energy respectively, m_2 and m_1 are final and initial mass of material and t_2 and t_1 are final and initial temperature. This method effectively determines the thermal storage capacity of the cashew nutshell biochar-epoxy composite, which is crucial for its potential applications in thermal insulation and energy-efficient materials. It has been investigated that biochar epoxy resin has a higher specific heat capacity than other conventional epoxy resin and concrete [56].

Experiment with solar heating: In order to assess the solar energy absorption efficiency of the manufactured heat-absorbing panel, it is exposed to direct sunshine from 9 AM to 3 PM. Thermocouples or infrared thermometers are used to record the temperature every 30 min. The panel's capacity to retain heat is evaluated by contrasting it with more traditional materials like metal and wood panels. This comparison aids in determining whether the panel made from cashew nutshells has better thermal absorption and retention capabilities. The chosen heat source is applied to the panel for a predetermined amount of time, usually 30 to 60 min. The heating conditions and the panel material's thermal conductivity are taken into consideration while determining the exposure duration. This stage guarantees that the panel will have enough time to effectively absorb and store heat. Thermal sensors or infrared thermometers are used to take temperature readings every five minutes in order to track heat absorption. The recorded data aids in the analysis of the panel's long-term heat absorption efficiency. Good thermal absorption is confirmed by a gradual rise in temperature, whereas effective heat retention is indicated by a quick rise followed by stabilization. The results are later compared with conventional materials to assess the panel's overall performance.

Test of heat retention: The panel is exposed to an infrared lamp for two hours to replicate a controlled heating environment to assess its capacity to store and retain heat. The cooling rate is tracked over time once the heat source is switched off.

Table 3. Quantitative comparison with existing commercial materials: [9,10, 14,18,25,40,54]

Property	CNS biochar-epoxy composite	Standard epoxy resin	CNS biochar-cement composite	Conventional concrete	Polyurethane foam
Thermal Conductivity (W/mK)	0.10–0.25	0.3–0.4	0.5–0.7	1.4–2.0	0.02–0.03
Heat Retention Efficiency	19% higher than standard epoxy	Not more	15–20% higher	Less than CNS Biochar- cement composite	Very high
Insulation rating (R-value per inch)	6.5–7.5	4–5	2–3	Less than CNS biochar- cement composite	5–6
Flexural strength	12–23% higher	Not more	10–15% higher	Less than CNS biochar- cement composite	Low
Compressive strength	10–20% higher	Not more	5–10% higher	Less than CNS biochar- cement composite	Low

Comparing the panel's ability to sustain temperature to more conventional heat-absorbing materials is the goal. Better heat retention is shown by a slower cooling rate, which makes the panel more appropriate for thermal storage applications. A quantitative comparison of thermal properties of cashew nutshell biochar-epoxy composite with other materials is depicted in Table 3. It can be observed from the table that cashew nutshell epoxy composite has lower conductivity than standard epoxy resin, concrete and cement composite making it a better insulator. It has highest compressive and flexural strength making it a structurally viable alternative. *Test of industrial heat recovery:* To test the panel's capacity to capture and reuse waste heat, it is placed close to boiler exhaust pipes in an industrial environment. To track the panel's heat absorption and retention properties, the temperature is tracked for six hours. By analyzing the data, researchers can determine if the panel effectively recycles waste heat, making it useful for energy conservation in manufacturing plants and other industrial applications.

EXPERIMENTAL SETUP

The manufacture of biochar, panel construction, and controlled performance testing are all steps in the experimental setting used to assess the cashew nutshell (CNS)-based heat-absorbing panel's performance. In order to produce carbon-rich biochar, 10–15 kg of dry and crushed CNS must be heated in a low-oxygen kiln at 400–600°C for two to three hours. This process is known as pyrolysis. To improve porosity and thermal performance, the biochar is finely ground after cooling and, in certain situations, activated with chemical agents like KOH or H_3PO_4. 60–70% of biochar and 30–40% of resin binders are combined at the panel construction stage, and for structural stability, fiberglass mesh or natural fibers are added for reinforcement. After being poured into 50 cm × 50 cm × 2 cm steel or wooden molds, the mixture is compacted to achieve a homogeneous density. It is then allowed to cure for 48–72 hours at ambient temperature or for 5–6 hours in an oven set to 80°C. After that, a black thermal coating is put on to improve the absorption of solar heat. The experimental set up is shown in Fig. 4 [51]. The experimental setting includes industrial heat recovery, heat retention, and sun heating tests for performance evaluation. Using infrared thermometers, thermocouples, and data loggers, the panel is exposed to direct sunshine from 9 AM to 3 PM. Temperature readings are taken every 30 minutes during this experiment, and the outcomes are compared to those of control panels made of metal and wood.

In order to test for heat retention, the panel is exposed to an infrared heat source for two hours. After that, the heat is turned off, and the cooling rate is tracked over time. In order to assess the panel's viability for waste heat recovery applications, the industrial heat recovery test entails positioning the panel next to boiler exhaust pipes and monitoring the temperature rise and retention over a 6-hour period. These tests offer vital information about the panel's thermal stability, heat absorption efficiency, and potential for practical uses in energy storage, insulation, and solar thermal systems.

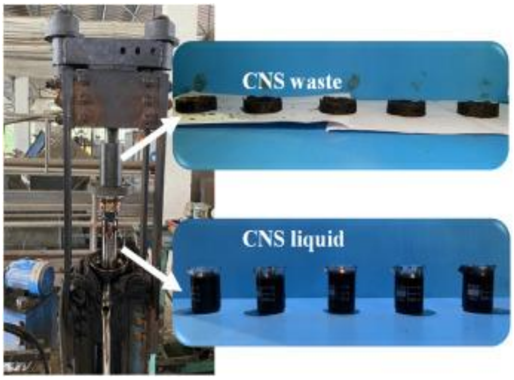

Fig. 4. Experimental setup [51]

A combination of thermal cycling tests and mechanical load evaluations can be used to evaluate the structural integrity of the cashew nutshell (CNS)-based composite panel under various load situations and thermal cycles. To evaluate the panel's thermal stability and replicate real-world temperature fluctuations, it should undergo repeated heating and cooling cycles in accordance with ASTM D3045 and other standards. To assess strength retention and durability, mechanical testing, such as tensile (ASTM D638), compressive, and flexural tests (ASTM D790), should be carried out both before and after thermal exposure. Using methods like scanning electron microscopy (SEM) or dynamic mechanical analysis (DMA), important factors including flexural strength, tensile properties, dimensional stability, and the existence of defects like delamination or cracks should be examined. The outcomes will establish the composite's ability to withstand mechanical loads and heat-induced stress, offering information on its viability for structural uses [57]. Costa *et al*. [58] have been investigated the thermal stability and mechanical properties of cashew nut shell liquid. They have examined tensile and flexural strength, proposing valuable data on the materials performance under thermal cycling and mechanical load.

RESULTS AND DISCUSSION

When compared to more conventional materials like metal and wood, the cashew nutshell-based panel exhibits greater heat absorption. Its black surface covering and carbon-rich composition allow it to absorb solar or infrared radiation more efficiently, which speeds up heating.

Because of this, it is a material that shows promise for solar heating and thermal energy storage applications [59].

The panel's capacity to hold heat for a long time is one of its main benefits. Compared to traditional materials, the biochar-based construction is more efficient since it releases stored heat gradually. This feature is quite advantageous.

Long-term durability is ensured by the panel's ability to retain its integrity even after numerous heating and cooling cycles. The mix of the biochar and resin offers exceptional thermal stability, in contrast to certain materials that stretch, shatter, or deteriorate at high temperatures. Because of this, it can be used for energy-efficient heating systems, environmentally friendly building insulation, and industrial applications that need reliable performance in a range of temperatures.

Cashew nutshell-based heat absorbing panel are having various important alternative applications as shown in Fig. 5 [10]. The cashew nutshell-based heat-absorbing panel can be integrated into solar thermal systems for water and air heating applications. Its high heat absorption and retention capabilities allow for efficient energy capture from sunlight, making it a cost-effective and eco-friendly alternative to conventional solar heating materials. These panels can be used in solar water heaters, drying systems, and space heating solutions to improve energy efficiency. The panel's excellent thermal retention properties make it ideal for insulating homes, offices, and industrial buildings. When used in walls, ceilings, or floors, it reduces heat loss, enhancing energy efficiency and lowering heating or cooling costs. Additionally, its sustainable composition provides an environmentally friendly alternative to synthetic insulation materials, promoting green building initiatives. A lot of waste heat produced by industries is frequently wasted. To capture and repurpose thermal energy, these heat-absorbing panels can be placed next to boilers, exhaust pipes, or heat-emitting equipment. This application increases overall production unit efficiency, lowers fuel consumption, and promotes energy conservation. By combining cashew nutshell-based panels with phase change materials (PCMs), energy storage efficiency can be increased. PCMs enhance the panel's capacity for thermal management by storing excess heat and releasing it gradually. Some specific types of PCMs are paraffin wax, stearic acid, and polyethylene glycol (PEG), which can counter the biochar due to their high latent heat storage capacity and compatibility [60].

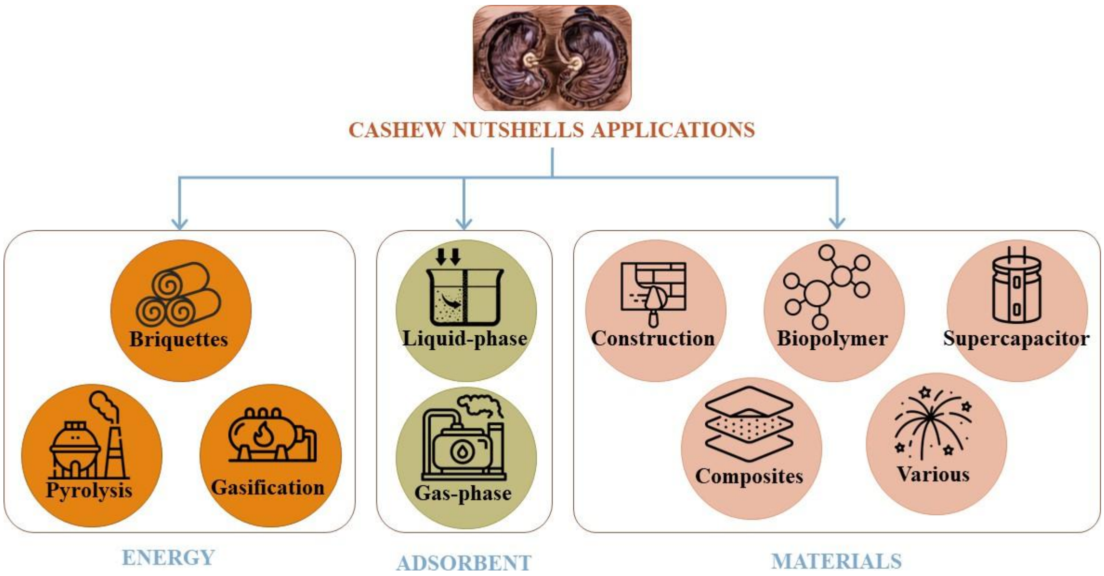

Fig. 5. Main cashew nutshell alternative applications [10]

The integration of paraffin PCM into CNS biochar not only improve the thermal conductivity but also enhance their long-term stability, hence, offers long-lasting and sustainable energy storage choices that can be applied to off-grid heating systems, smart grids, and renewable energy systems.

CONCLUSIONS

This work reviews the current research on the systematic approach to develop a cashew nutshell-based heat absorbing panel**.** By turning cashew nutshell (CNS) trash into biochar-based heat panels, this study promotes environmental sustainability and provides a number of advantages. It provides a cost-effective alternative to traditional thermal materials like concrete and metal, while also enhancing heat absorption and retention for greater energy efficiency. In order to reduce dependency on non-renewable energy sources and the carbon footprint, the sturdy and lightweight panels can be utilized for a number of applications, such as solar water heating, building insulation, and industrial waste heat recovery. Furthermore, heat storage capacity might be further increased by future advancements that use phase change materials (PCMs). Overall, this study encourages green energy initiatives, energy efficiency, and the development of sustainable materials for both residential and commercial use.

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Assessing the potential of apricot shell biochar from *Prunus Armeniaca* of Kargil: a comprehensive review

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Apricot seed shell biochar, derived from agro-waste through thermal and hydrothermal processes, has demonstrated significant potential in addressing environmental challenges and advancing sustainable practices. The review discusses the production, characterization, and application of apricot-based biochar, emphasizing physicochemical properties and performance in adsorption and soil improvement. Apricot biochar is distinguished by its porous carbon microsphere structure and the abundant oxygen-containing functional groups that result in better adsorption for atrazine, nitrates, and heavy metals. The selected responses present some common preparation techniques found in biochar preparation: hydrothermal and pyrolytic techniques, with some chemical activation processes. For this reason, kinetic models, pseudo-second-order kinetics, and the Freundlich isotherms apply to govern the adsorption performance of such biochar samples. Mechanisms that might underlie such behavior are hydrogen bonding and hydrophobic interactions. Biochar based on apricots has given promise in regulating pesticide residues; enhancing the quality of saline soils through their improvement can bring a halt to agricultural nonpoint source pollution as well. However, it is pH-dependent, ion concentration-dependent, and dosage-dependent. The review will emphasize the promise of apricot biochar as an inexpensive and environmentally friendly tool for environmental remediation while uncovering difficulties in mass production, optimization of activation processes, and performance in applications. Potential research directions are the development of biochar's functional properties and its role in sustainable agriculture and pollution control.

Keywords: Apricot seed shell, oxygen-containing functional groups, environmental remediation, sustainable agriculture

Fig. 1. Graphic abstract

INTRODUCTION

Biochar is carbon-rich material produced from the heating of organic matter in a low or oxygen-free environment. Recently, people have taken an interest in biochar as it can be used to enhance soil grade and crop growth and sequester carbon. Among the good uses of apricot shells would be making charcoal, which is biochar. Kargil is a distant town in the Ladakh region of India. It has beautiful views, but the climate is harsh.

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The major activity here is farming, and apricots are grown abundantly. Yet, the countless apricot shells that are thrown away can be converted into biochar, benefiting the environment as well as the economy. Studies are being carried out on the application of apricot shells with minimal environmental impact. Apricot shell biochar has worked efficiently in amending soil and promoting crop yields. It also serves as an environmentally friendly and sustainable waste management method. We shall see if we can make biochar from apricot shells in Kargil and check how well it improves soil quality.

A great deal of research on has been conducted on the effect of biochar the properties of the soil, crop productivity, and yield. Biochar is very helpful in retaining nutrients in the soil, preventing the nutrients from washing away, and improving the general health and quality of the soil. According to Agegnehu et al., it has been found through a review that incorporation of biochar and biochar-compost improves the soil and helps crops to grow better [1]. The present review shall discuss in-depth the current work on biochar and its potential use in agriculture. Other benefits of applying biochar encompass its potential ability to improve the water retention characteristics of soil in addition to the rehabilitation of both degraded soils and landscapes. Biochar has been found to promote healthy growth in plants, which postulates that its use can also be as a sort of fertilizer. Toxic levels of biochar impair earthworm and vegetable crop yield. Biochar is a product that improves soil value and offers several environmental advantages, such as carbon storage, mitigation of greenhouse gases, and increased plant growth [2-4]. Biochar has been found to provide various benefits throughout its life cycle when used for soil conditioning. These benefits include improving the quality of ecosystems, reducing the consumption of resources, and mitigating the effects of climate change. Overall, biochar is considered a positive option for enhancing soil health and sustainability [5]. The incorporation of biochar into soil has the potential to greatly benefit plant growth and enhance soil quality by acting as a stimulant for plant growth [6]. By conducting additional research on the use of biochar as a soil amendment, we can enhance our knowledge regarding its interactions with various components of problematic soils. This, in turn, will expedite our progress in soil remediation and contribute to the improvement of crop yields in such challenging environments [7]. Algal biochar from wastewater can boost soil grade and generate income as a fertilizer and soil ameliorant, besides its water remediation and C-sequestration benefits [8]. Producing biochar from oil palm biomass can potentially lead to a healthier environmental, societal and economic growth for the oil palm industry specifically, and enhances sustainability in worldwide context [9]. Biochar production technologies are among the environmentally friendly technologies that aim to reduce greenhouse gas (GHG) emissions and promote a cleaner environment [10]. Biochar can be applied at suitable levels under dry conditions, as it has the ability to retain more water compared to treatments without biochar [11]. Since the beginning of the twenty-first century, biochar has garnered significant attention from various fields of research due to its unique properties, diverse applications, and promising potential for further development [12].

Biochar-based carbon sequestration may have long-term benefits, but it comes at the expense of short-term CO_2 emissions that can accelerate climate change [13]. The addition of biochar to soil has a quick and robust impact on both the nutrient content of the soil and the composition of plant communities [14].

Compost and biochar, either applied alone or in combination with fertilizer, have been shown to enhance soil fertility and plant growth while reducing nutrient leaching [15]. Biochar is recognized to have improved soil physical and chemical properties, enhanced soil biota, increased crop yield, remediated polluted soil, and recycled agricultural waste. It offers several interrelated direct and indirect benefits when used as a soil amendment [16]. For the sustainable and economically viable use of biochar for environmental applications, its economic impacts and recyclability must be taken into account during development [17].

LITERATURE REVIEW

Biochar has gained significant attention as a sustainable solution for soil enhancement, greenhouse gas mitigation, and environmental remediation. Biochar application is considered a viable strategy for reducing greenhouse gas emissions, particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). By sequestering carbon in stable forms, biochar prevents CO_2 from being released into the atmosphere and contributes to long-term carbon storage. Moreover, it influences nitrogen dynamics in the soil, potentially reducing N_2O emissions from agricultural activities. However, optimizing the nitrogen efficiency of biochar-based fertilizers remains a challenge, requiring further research on their interaction with soil microbes and plant uptake [18]. Its potential to improve soil health, support rural economies, and function as an effective adsorbent makes it a promising material in agriculture and environmental applications. However, the effectiveness and scalability of biochar depend on factors such as feedstock source, production costs, and technological advancements. Biochar has the potential to support rural economies by creating new revenue streams through its production and sale. Small-scale biochar production units can provide employment opportunities while promoting sustainable agricultural practices. However, widespread adoption faces significant challenges, including high production costs, technological limitations, and inconsistent availability of suitable feedstocks. Developing cost-effective biochar production technologies and establishing standardized guidelines for its agricultural use are critical steps toward mainstream implementation. This review explores the role of biochar in soil nutrition and biology, its impact on greenhouse gas emissions, pollutant remediation, economic benefits, and challenges associated with its widespread adoption [19]. Table 1 shows the various key findings of research papers.

METHODS OF PREPARATION OF BIOCHAR

Pyrolysis The process of thermal decomposition of organic materials in an oxygen-free environment under the temperature range of 250-900 ^{0}C is called pyrolysis. Table 1 shows the key findings from studies comparing the effectiveness of different biochar types, conditions, and application rates in diverse environmental settings.

Table 2 shows the summary of research findings on how different pyrolysis temperatures affect biochar surface area, porosity, and carbon stability. Figure 1 shows the graphical abstract for the biochar uses.

Table 1. Key findings from studies comparing the effectiveness of different biochar types, conditions, and application rates in diverse environmental settings

S. No.	Title	Year	Key findings	Ref. No.
1	Biochar enhances yield and quality of tomato under reduced irrigation.	2014	Biochar application has increased tomato yield and quality under the reduced irrigation set-up.	[3]
2	Biochar: potential for countering land degradation and for improving agriculture.	2012	Biochar particles have a wide surface area and complicated inner structure that provides an environment for the thriving of microorganisms, thereby biofilm formation.	[5]
3	Using poultry litter biochars as soil amendments.	2008	The addition of biochar in hard-setting soil showed major changes in its properties: increasing carbon, nitrogen, pH, and available phosphorus, though it decreases soil strength.	[6]
4	Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils.	2018	Biochar with low clay content and sandy soil without nutrients and organic matter improves the fertility of soil to a considerable extent.	[7]
5	Effect of biochar application on seed germination and seedling growth of Glycine max (l) under drought stress.	2017	Biochar application counteracts the damaging effects of drought stress on the seedlings of soybean effectively have been observed.	[8]
6	Using agricultural residue biochar to improve the soil quality of desert soils.	2016	Cotton gin trash biochar boosts organic matter and nutrients in sandy and loamy soils but may raise soil salinity due to increased electrical conductivity.	[9]
7	Effects of biochar application on vegetable production and emissions of N_2O and CH_4.	2012	In farm-based applications, it was found that the use of biochar leads to a huge decrease in N_2O and N_2O-N emissions and yet allows the production of successfully grown vegetables.	[13]
8	Comparison of the efficacies of peanut shell biochar and biochar-based compost on two leafy vegetable productivity in an infertile land.	2019	It can be gathered from this research that incorporation of specially designed, peanut-shell biochar, PBC-based amendments (PAD) made from composted PBC was efficient in overcoming soil infertility, and Application of PAD at 1.5% to 3% improved vegetable yields by enhancing soil quality and nutrient availability.	[14]

9	Soil organic carbon characteristics affected by peanut shell biochar in saline-sodic paddy field.	2022	Study results showed that Biochar boosts soil organic carbon by forming humus-like substances, increasing aromaticity, and enhancing soil hydrophobicity.	[15]
10	Coconut shell-derived biochar to enhance water spinach (Ipomoea aquatica Forsk) growth and decrease nitrogen loss under tropical conditions.	2019	Coconut shell biochar was found to enhance the yield of water spinach and decrease nitrogen leaching; hence, it can be used as an amendment for enhancing soil quality in tropical regions	[16]
11	Effect of biochar and hydrochar from cow manure and reed straw on lettuce growth in an acidified soil.	2022	It has also been shown that chemically activated biochar (CBC) enhances soil organic matter, pH and also influences the nutrient contents of the soils, such as P, K, Ca, Mg, Zn, Fe, and Mn.	[18]
12	Understanding the role of biochar in agriculture	2022	Black carbon enhances crop growth and soil health in arid, poor soils by improving water retention, structure, nutrient uptake, and microbial diversity.	[19]
13	Effect of biochar application at different adding rates on garlic (Allium sativum) growth and production.	2020	Observation shows that 1.5% biochar addition boosted garlic production, while 3% hindered it, guiding optimal biochar use for garlic.	[20]
14	Observation shows that 1.5% biochar addition boosted garlic production, while 3% hindered it, guiding optimal biochar use for garlic.	2021	Incorporation of Biochar improved the tomato seedling growth and resilience in saline soil by enhancing physiological and biochemical mechanisms.	[21]
15	Biochar and hydrochar from agricultural residues for soil conditioning: Life cycle assessment and microbially mediated C and N cycles.	2022	The Findings show that, Biochar produced at a temperature of 500–700°C exhibited superior physicochemical properties.	[22]
16	Impacts of biochar concentration on the growth performance of a leafy vegetable in a tropical city and its global warming potential.	2020	Higher biochar levels increased nitrate, potassium, and cation exchange capacity (CEC) but reduced phosphate availability.	[23]
17	Water extract from straw biochar used for plant growth promotion: an initial test.	2016	Hot water extracts of biochar boost plant growth, increasing Chinese cabbage yield in pot experiments, as it contains organic compounds and mineral nutrients.	[24]
18	Potential of integrating biochar and deficit irrigation strategies for sustaining vegetable production in water-limited regions	2019	There is evidence that adding biochar to soil under limited irrigation can mitigate crop yield losses and improve water use efficiency for vegetables. However, there is a lack of comprehensive field studies that provide a conclusive understanding of the long-term effects of biochar on soil-moisture interactions under drought conditions.	[25]
19	Biochar induced modifications in soil properties and its impacts on crop growth and production.	2021	The addition of biochar to soil as an amendment has had a notable impact on the physical, chemical, and biological characteristics of the soil.	[26]
20	Biochar: effects on crop growth.	2018	The growth of oil palm and rubber seedlings was improved by adding a small amount of biochar to the soil.	[27]
21	Algal biochar: effects and applications.	2012	In pot trials, biochar treatments resulted in remarkable plant growth rate improvements, ranging from 15 to 32 times, compared to no biochar controls in Carbon and nutrient-poor soil. The addition of fertilizer further enhanced the growth. Biochar amendment also had a significant but relatively smaller impact on plant growth in a fertile agricultural soil.	[28]
22	Biochar-induced modification of soil properties and the effect on crop production.	2019	Biochar typically improves soil health by changing its physical, chemical, and biological characteristics, such as water retention ability, pH level, capacity to retain nutrients, and promoting the growth of beneficial fungi	[29]

23	Biochar to improve the quality and productivity of soils.	2015	Biochar use can be helpful in the modification of soil properties because it improves fertility, increases water retention capacity, enhances cation exchange capacity, and regulates pH levels.	[30]
24	Effects of compost and biochar amendments on soil fertility and crop growth in a calcareous soil.	2020	Numerous studies have reported the favorable agronomic outcomes of applying compost and biochar derived from diverse biomass sources on soil fertility, as well as the uptake of nutrients by crops and their growth, across a broad spectrum of soil types.	[31]
25	Low-cost and environmental-friendly Triticum aestivum-derived biochar for improving plant growth and soil fertility.	2018	After physicochemical analysis of the soil and studying the plant growth and dry matter yield, it was observed that the treatment increases both dry matter yield and soil fertility along with improvements in plant growth.	[32]
26	A comprehensive review of engineered biochar: production, characteristics, and environmental applications.	2020	A mixture containing a total of 15 g of rice-straw biochar per kilogram of soil was applied; the results observed showed that these amendments had increased effects on plant height, tiller quantity, and biomass yield as compared with the control groups, which had no biochar application.	[33]
27	Environmental benefits of biochar.	2012	Temperatures at varying levels were applied to create birch wood biochar, and the effects that were induced by different temperatures were studied on various components of the soil ecosystem. Although their physical properties exhibit dramatic differences, all the biochar types showed similar impacts on soil properties and plant growth.	[34]
28	Impacts of different sources of biochar on plant growth characteristics.	2018	Biochar affects plant productivity positively, neutrally, or negatively; low rates, low-temperature biochar, or hydrochar may immobilize nitrogen, reducing benefits.	[35]
29	Comprehensive review on the production and utilization of biochar.	2019	This study investigated the impact of date palm residues biochar on sandy desert soil and showed that biochar's produced at lower temperatures (300-400 ◦C) with a mineral fertilizer enhanced the growth of wheat and increased soil water retention over time whereas, Bio-chars produced at higher temperatures have enhanced specific soil physical properties like bulk density and total porosity.	[36]
30	Production, activation, and applications of biochar in recent times.	2020	Application of biochar to a depth of up to 10 cm can minimize denitrification and reduce N2O emissions with a better regulation of leaching of mobile nutrients like potassium; hence, increasing water use efficiency, nutrient availability, and eventually, plant growth.	[37]

Table 2.Summary of research findings on how different pyrolysis temperatures affect biochar surface area, porosity, and carbon stability.

S. No.	Material sources	Temperature	Key finding	Ref. No.
1	Feedstock maize	750 ^{0}C	The incorporation of biochar decreases the bulk density of soil, increases the total volume of pores, and increases the water-holding capacity at the permanent wilting point.	[1]
2	Soybean stover, Peanut shells	300 ^{0}C 700 ^{0}C	Different carbonization temperatures affected biochar properties, increasing hydrophobicity, surface area, and aromatic condensation while reducing polarity. These changes influenced trichloroethylene (TCE) adsorption capacity.	[38]

3	Pine Rice husk Wheat straw	350 ^{0}C 450 ^{0}C 550 ^{0}C 650 ^{0}C	Wood biochar had 3–10 times more humification materials than rice husk biochar and ash, while bamboo biochar had none. Wood biochar's superior sorptive and humification properties make it useful in composting. The stability of biochar from pine, rice husk, and wheat straw was analyzed using proximate, ultimate analysis, and the Edinburgh stability tool, confirming that higher pyrolysis temperatures increased stability and total carbon by releasing volatiles.	[39]
4	Canola Corn Soybean Peanut straws	300 ^{0}C 500 ^{0}C 700 ^{0}C	Biochar's from canola, corn, soybean, and peanut straws became more alkaline with higher pyrolysis temperatures. Carbonates were the main alkaline species at 500 and 700°C. FTIR–PAS and zeta potential analysis showed that –COO− and –O− groups influenced biochar alkalinity, especially at lower temperatures.	[40]
5	Orange peel	150-700 ^{0}C	Biochar prepared at 150–600 ^{0}C showed strong 1-naphthol sorption due to specific interactions, while at 200 ^{0}C had the highest capacity at high concentrations. Biochar at 700 ^{0}C was most effective at low concentrations, highlighting biochar's potential as engineered sorbents.	[41]
6	Wheat straw Poplar wood Spruce wood	400 ^{0}C 460 ^{0}C 525 ^{0}C	Wheat straw biochar had high salt (4.92 mS cm−1) and ash (12.7%) content. H/C ratios ranged from 0.46 to 0.40 at 525°C. Higher temperatures increased surface area (1.8–56 m²/g) but reduced CEC (162 to 52 mmol/kg).	[42]

Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a cost-effective biochar production method operating at low temperatures (180–250°C). The resulting product, called hydrochar, differs from biochar produced via dry processes like pyrolysis and gasification. In HTC, biomass mixed with water is heated in a closed reactor, gradually increasing in temperature. Below 250°C, hydrothermal carbonization occurs, producing biochar; between 250–400°C, hydrothermal liquefaction forms bio-oil; and above 400°C, hydrothermal gasification generates syngas (CO, CO_2, H_2, CH_4). The process involves reactions like dehydration, fragmentation, isomerization, condensation, and polymerization, forming intermediates such as 5-hydroxymethylfurfural. Lignin before repolymerization and cross-linking resulting in hydrochar [43-45] decomposition follows dealkylation and hydrolysis, yielding phenolic compounds.

Gasification

Gasification is a thermochemical process that converts carbonaceous materials, such as biomass or coal, into syngas (a mixture of CO, H_2, CH_4, and CO_2) by reacting them with a controlled amount of oxygen, steam, or air at high temperatures (700–1000°C). Unlike combustion, which fully oxidizes the fuel, gasification partially oxidizes it, producing versatile syngas that can be used for power generation, synthetic fuels, or chemical production. The process includes drying, pyrolysis, oxidation, and reduction stages, making it an efficient method for energy recovery and waste management. Gasification offers advantages like lower emissions, higher efficiency, and the potential for carbon capture, making it a promising technology for sustainable energy production.[46]

Torrefaction and flash carbonization

Torrefaction is a mild pyrolysis process that thermally treats biomass at 200–300°C in an oxygen-free environment. This process removes moisture and volatile compounds, increasing the energy density, hydrophobicity, and grindability of the biomass. The resulting product, known as torrefied biomass or bio-coal, has improved combustion properties and is used as a renewable alternative to fossil fuels in co-firing and gasification applications. Flash carbonization is a rapid thermochemical process that converts biomass into biochar at high temperatures (300–600°C) under pressurized conditions. Unlike traditional slow pyrolysis, flash carbonization occurs within minutes, achieving higher biochar yields and energy efficiency. This method enhances carbon sequestration and provides a sustainable way to produce high-quality biochar for soil amendment and energy applications [47].

CHARACTERIZATION TECHNIQUES

The characterization of biochar is essential to understand its physicochemical properties, which influence its effectiveness in applications such as soil amendment, carbon sequestration, and pollutant remediation. Various analytical techniques are employed to assess the structural, elemental, and functional attributes of biochar [48]. Currently, numerous modern characterization techniques have been reported for characterizing biochar such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), thermo-gravimetric analysis (TGA), nclear magnetic resonance spectroscopy (NMR), Brunauer-Emmett-Teller (BET), proximate and ultimate analysis, Raman spectroscopy, etc.

Biochar stability

Biochar stability, defined by its resistance to biotic and abiotic soil degradation, is crucial for carbon sequestration. Various methods assess biochar stability, with pyrolysis temperature often considered an indicator, though it provides only a rough estimate. Proximate analysis, traditionally used for coal and charcoal, determines moisture, volatile matter, ash, and fixed carbon, but may overestimate carbon content due to ash underestimation. Biochar stability assessment methods fall into three categories: (a) structural characterization (e.g., aromaticity), (b) chemical and thermal quantification of stable carbon, and (c) incubation-based carbon mineralization modeling. Incubation and modeling provide the most direct and reliable results, but are time-consuming. Stability is influenced by biochar's carbon structure, consisting of crystalline and amorphous phases, with aromatic condensation and C-C bonds enhancing resistance to degradation. Other properties, such as pore structure, pH, and sorption mechanisms, also contribute. Emerging methods, like ^{14}C isotope tracking, offer insights into biochar-microbial interactions, while thermochemical oxidation assesses degradation resistance. Despite advancements, current techniques lack precision. Developing improved stability evaluation methods is essential for optimizing biochar's role in carbon sequestration and climate change mitigation, ensuring its long-term environmental benefits [49-51].

Scanning electron microscopy (SEM)

The surface morphology of biochar is commonly analyzed using scanning electron microscopy (SEM). SEM imaging has revealed that variations in processing methods and pyrolysis temperatures lead to significant changes in the surface structure of biochar particles, although their overall shape remains largely intact. The development of pores in biochar tends to increase with rising pyrolysis temperatures, resulting in enhanced pore properties. Additionally, higher pyrolysis temperatures may contribute to increased crystallinity of mineral components and the formation of highly ordered aromatic structures. SEM provides detailed insights into the distribution of micropores and mesopores, as well as the arrangement of pores within biochar. It is also used to observe changes in surface morphology before and after adsorption processes. Furthermore, SEM, when combined with energy dispersive X-ray spectroscopy (EDX), facilitates the elemental analysis of biochar by identifying the various elements present on its surface. Many studies on biochar applications have employed SEM-EDX to assess surface modifications after contaminant adsorption. However, a key limitation of this technique is its unsuitability for detecting organic contaminants [52].

Functional groups

The sorption properties of biochar are significantly influenced by the presence of various surface functional groups, including carboxylic (-COOH), hydroxyl (-OH), amine, amide, and lactone groups. The primary factors determining the abundance and nature of these functional groups are the type of biomass used and the pyrolysis temperature. However, an increase in properties such as pH, surface area, and porosity may lead to a reduction in the concentration of these functional groups. Fourier transform infrared spectroscopy (FTIR) is commonly employed to characterize the functional groups present on the biochar surface. Additionally, biochar produced at different temperatures exhibits notable variations in its surface chemistry. Beyond FTIR, nuclear magnetic resonance (NMR) spectroscopy can also be utilized to analyze the structural composition of biochar functional groups [53].

X-ray diffraction (XRD)

X-ray diffraction (XRD) is a widely used technique for analyzing the crystallinity and structural characteristics of biochar. XRD diffractograms reveal specific features of amorphous materials, particularly those formed at temperatures above 350°C, indicating their structural consistency. Modern XRD systems are equipped with computerized controls, including a monochromator, a radiation source, and a stepping motor, enabling precise analysis. The presence of sharp and intense XRD peaks suggests the formation of crystalline nanostructures within biochar. Additionally, prolonged processing time leads to an increase in particle diameter, further influencing crystallinity.

XRD patterns provide a rapid, non-destructive means of characterizing biochar, facilitating the production of high-quality materials with enhanced sorption efficiency [54].

Raman spectroscopy

Raman scattering is a widely used molecular spectroscopy technique that analyzes vibrational transitions in molecules when exposed to electromagnetic radiation. The Raman effect occurs due to the scattering of light with a shifted frequency, resulting from the absorption or loss of vibrational energy within a molecule. This technique is valuable for reliably assessing chemical and nanostructural changes during biomass carbonization. It also enables the rapid estimation of heat treatment temperatures (HTTs) used in biochar production. Raman spectroscopy offers high sensitivity, minimal sample preparation, and reduced interference, making it a powerful tool for biochar characterization. However, its high cost limits its widespread application despite its effectiveness in structural analysis [55].

X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy (XPS) is a valuable technique for analyzing the composition and structural properties of biochars derived from different biomass sources and thermal treatment conditions. XPS enables the identification and quantification of functional groups and key elemental components present on the biochar surface. Changes in oxygen-containing functional groups, as detected by XPS, are indicative of short-term biochar stability. Additionally, XPS can be employed to determine the elemental O/C molar ratio, which serves as a key indicator of biochar stability. This technique provides critical insights into the surface chemistry of biochar, contributing to a better understanding of its long-term environmental behavior and sorption capabilities [56].

Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared (FTIR) spectroscopy is a valuable non-destructive technique for characterizing the surface functional groups of biochar. The chemical composition and structural arrangements of biochar undergo significant transformations with increasing pyrolysis temperature, and these changes can be effectively monitored *via* FTIR. Specifically, at higher temperatures (650–800°C), FTIR spectra reveal a progressive loss of aromatic functionalities. While diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) typically involves preparing samples as potassium bromide pellets, attenuated total reflectance (ATR)-FTIR allows for direct analysis by contacting the sample with an ATR crystal, enabling the identification of surface functional groups [57].

Nuclear magnetic resonance spectroscopy (NMR)

Nuclear magnetic resonance (NMR) spectroscopy is a powerful technique for analyzing the structural composition of biochar. This method utilizes a strong magnetic field and radio frequency (RF) pulses to investigate molecular structures by detecting resonance frequencies of specific atomic nuclei. Solid-state NMR techniques are particularly useful for characterizing biochar, allowing for the identification of carbon functional groups, the extent of aromatic ring condensation, and the overall molecular structure of char. Additionally, NMR spectroscopy enables the analysis of aliphatic and aromatic hydrocarbon content, providing insights into the stability and carbonization of different biochar samples. Despite its advantages, NMR spectroscopy has limitations. The presence of ferromagnetic minerals in biochar can interfere with signal detection, leading to distortions in the results. Furthermore, biochar produced at high pyrolysis temperatures often exhibits a low signal-to-noise ratio, which can hinder accurate spectral analysis [58].

Thermo-gravimetric analysis (TGA)

Thermogravimetric analysis (TGA) is a widely used technique for thermal analysis, enabling the assessment of the physical and chemical properties of materials as a function of increasing temperature. This method has been extensively applied to evaluate the thermal behavior of various samples, including biochar and biomass/biochar mixtures. TGA is particularly useful in examining the combustion characteristics of biochar, helping to determine whether synergistic interactions occur between different components in biomass/biochar blends. The findings from such analyses provide valuable insights into the thermal stability, decomposition patterns, and overall behavior of these materials under heat exposure. During TGA, biochar samples are subjected to controlled heating from ambient temperature up to approximately 1000°C. Several studies have utilized different heating rates, including 10°C/min, 20°C/min, and 10 K/min, to analyze variations in thermal degradation. Understanding these thermal properties aids in optimizing biochar applications and improving its utilization in various industrial and environmental processes [59].

Surface area and porosity

Biochar with a high surface area and well-developed porosity exhibits superior sorption properties. The formation of a porous structure occurs during the pyrolysis process as water loss intensifies during dehydration. According to the International Union of Pure and Applied Chemistry (IUPAC), biochar pores are classified into three types: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm). The ability of biochar to adsorb pesticide molecules depends on its pore size, irrespective of molecular polarity or charge. Scanning electron microscopy (SEM) is commonly used to characterize biochar pore size. Surface area is a critical factor in determining sorption capacity, with temperature playing a significant role in biochar formation. The surface area varies between treated and untreated raw materials, with commercially available activated carbon exhibiting a larger surface area. Biochar produced without an activation process tends to have lower surface area and porosity. To enhance these properties, biochar production often incorporates an activation process, which can be achieved through physical or chemical activation. This step is crucial in improving biochar's adsorption efficiency and expanding its applications in environmental remediation and pollutant removal [60].

Brunauer-Emmett-Teller analysis (BET) The surface area of biochar can be assessed through Brunauer–Emmett–Teller (BET) analysis, a crucial technique for evaluating its effectiveness in pollutant removal from soil and aqueous environments. The comparison between raw feedstocks and their corresponding biochar reveals a substantial increase in BET surface area following pyrolysis. Notably, the original feedstocks lack significant micropores, whereas pyrolysis induces the formation of new micropores within the biochar structure.

For different feedstock types, porosity characteristics—such as BET surface area and micropore volume—exhibit improvements with an increase in power levels from 2100 to 2400 W.
This enhancement is attributed to the accelerated release of residual volatile compounds and the intensified development of micropores at elevated heating rates. Additionally, the extensive release of volatile matter during pyrolysis contributes to the formation of highly porous biochar with diverse pore structures and lower density. These properties make biochar a promising material for applications requiring high adsorption capacity and pollutant sequestration [61].

APPLICATIONS OF APRICOT SHELL BIOCHAR

Apricot shell biochar, derived from the pyrolysis of apricot shells, has been investigated for various applications across multiple fields.

Table 3. Characterization of apricot seed shell biochar in soil and parameters thereof.

Parameters	Before adding apricot seed shell biochar	After adding apricot seed shell biochar
Soil pH	6.5	7.0
Nitrate concentration (mg/L)	30	50
Soil organic matter (%)	2.0	3.5
Water holding capacity	20	25
Cation exchange capacity (meq/100 g)	10	15
Microbial activity (CFU/g)	1 × 10^6	5 × 10^6
Soil electrical conductivity (dS/m)	1.2	1.5
Total nitrogen (%)	0.1	0.2
Phosphorus content (mg/kg)	15	25
Potassium content (mg/kg)	20	35

Research indicates that apricot shell biochar exhibits effective adsorption properties for pollutants such as atrazine, a common herbicide. The biochar's adsorption capacity is influenced by factors like preparation temperature, pH, and the presence of ions like calcium. The primary mechanisms include hydrogen bonding and hydrophobic interactions, suggesting its potential in mitigating agricultural non-point source pollution. Atrazine adsorption kinetics on the biochar followed a quasi-second-order kinetic model with $R^2 \geq 0.995$, and isothermal adsorption data fitted the Freundlich model with $R^2 \geq 0.911$. The adsorption process was accompanied by surface adsorption and diffusion. The prepared temperature increased and the pH and Ca^{2+} concentration increased the adsorption process, and the mechanism of adsorption mainly involved hydrogen bonding and hydrophobic interactions. Biochar from agricultural waste, apricot shells, showed good potential for atrazine adsorption and could help manage agricultural non-point source pollution, especially pesticide residue pollution [62], and bioavailability of heavy metals like zinc (Zn) and cadmium (Cd). This suggests its potential role in reducing heavy metal mobility and bioavailability in polluted soils, thereby contributing to soil remediation efforts. Adsorbents were prepared from apricot seed shell agro-waste that is available locally. Biochar at 370°C from pyrolysis in the shape of 80-mesh particle size was further modified with 1N HCl. ASSP, biochar (ASSB), and activated biochar (AASSB) from aqueous solution nitrate adsorption were observed. FTIR and pH PZC are used for the characterization of the adsorbent. Optimum conditions were pH 2, dosage 0.3 g, 50 mg/L initial concentration, and 90 min contact time. AASSB exhibited the highest nitrate removal, followed by ASSB and ASSP. Nitrate adsorption kinetics followed a pseudo-second-order model, showing favorable and improved sorption. This agro-waste can be developed into sustainable adsorbents for water treatment, potentially replacing commercial sorbents [63-65].

Biochar was prepared through a hydrothermal process and studied with the help of SEM and FTIR for atrazine adsorption on apricot kernel shell biochar, which exhibited a uniform carbon microsphere structure with many oxygen-containing groups. Functional groups were enhanced by increasing temperature, hence improving the adsorption efficiency. The kinetics of atrazine adsorption onto the biochar followed quasi-second-order kinetic models ($R^2 \geq 0.995$) and the Freundlich model ($R^2 \geq 0.911$). Surface adsorption and diffusion were involved in the process, which is favored by hydrogen bonding and hydrophobic interactions. Adsorption capacity increased with temperature and decreased with pH and Ca^{2+} concentration. The biochar derived from agricultural waste could be applied for pesticide residue pollution control [66].

CHALLENGES AND FUTURE PERSPECTIVES

Biochar has been demonstrated as an effective tool for soil amendment in crop production and pollutant removal from water and soil. Most of the studies on the effect of biochar on soil properties (such as bulk density, porosity, water holding capacity, acidity, and mineral content) are conducted in the laboratory. Properties of biochar produced under various pyrolysis conditions (temperature, heating rate, residence time) have been widely researched. For large-scale commercialization, the advantages and disadvantages of biochar for soil applications must be discussed, taking into account technical, environmental, economic, and social factors. This review evaluates biochar for soil amendment within a sustainability framework and offers recommendations for future research and applications [67].

The speedy growth of the technology of renewable energies and the critical need for response to the challenges of the environment made it apparent that biochar is a multi-use tool for energy, water, and environmental sustainability. The review highlights recent advances in biochar production and functionalization toward enhanced roles in energy conversion, wastewater treatment, reduction of CO_2, improvement of soil, and carbon neutrality. Functionalization approaches such as chemical activation and metal impregnation significantly enhance catalytic activity, energy storage, and stability of the biochar; hence, there is a potential for its usage in water splitting, fuel cells, and supercapacitors. Additionally, it is a potential catalyst and adsorbent in wastewater treatment through the removal of pollutants and facilitation of resource recovery. The review points out the ability of biochar in CO_2 capture and conversion into valuable fuels and chemicals. In conclusion, in a nutshell, biochar has great potential to be a sustainable material for a cleaner future.

This technology is still at the nascent stage in Indian agriculture but promises several benefits, such as improved soil carbon sequestration, GHG offset, improvement in soil health, and increased crop yields. Crop residues from major crops, logging and processing residues, and organic residues from municipal solid waste were evaluated for availability. Approximately 249 million tons of crop residue is being generated annually. Using the residues for biochar will reduce GHG emissions by 4.8% to 10.7% of total net annual emissions. Collection and transportation of residues would be the challenges, but institutional systems at the grassroots are established to get participation from the farmers as well, which will enhance the climate mitigation potential of biochar. Biochar production can improve waste management and offset GHG emissions for all sectors [68].

The development of effective and sustainable biochar production techniques, as well as their potential application in resolving global environmental issues, will receive particular attention.

RESULTS AND DISCUSSION

Biochar showed a positive impact on soil quality, crop performance, and yields. Biochar enhances the properties of soil such as water retention, water repellency, and carbon sequestration. The inclusion of biochar also increased crop productivity, nutrient uptake, and seed germination, especially in infertile soils. It depends on the kind of soil, crop type, and feedstock on the optimal application rate. The feedstock selection, combined with the selected pyrolysis conditions, influences biochar properties such as pH, surface area, and nutrient content. The study of biochar reveals that it has the potential to reverse land degradation as well as enhance agriculture.

Comparative soil benefits before and after adding apricot biochar in the soil are illustrated in Table 3. Apricot seed shell biochar adds the following to soil: It raises pH from 6.5 to 7.0, thereby making it alkaline. The nitrate concentration increases from 30 mg/L to 50 mg/L, which will promote plant growth. Soil organic matter improves considerably from 2.0% to 3.5%, making it fertile. Water holding capacity increases from 20% to 25%, thus helping retain moisture. Cation exchange capacity increases from 10 meq/100 g to 15 meq/100 g, which enhances nutrient availability. Microbial activity increases by as much as 1 ×10^6 CFU/g to 5 × 10^6 CFU/g, enhancing soil health and plant resistance. Electrical conductivity increased from 1.2 dS/m to 1.5 dS/m, indicating good salinity management in the soil. Total nitrogen increased from 0.1% to 0.2%, which contributed to better plant nutrition. From 15 mg/kg to 25 mg/kg, phosphorus increased, while potassium increased from 20 mg/kg to 35 mg/kg; all these added to better development and growth of plants. As a whole, soil with apricot seed shell biochar is much richer and more fertile.

Based on this research, there are certain limitations discussed and directions for possible future study recommended. For example, if the sample only consisted of individuals from a certain geographic area or age, the limitation would need to be incorporated into the discussion, and the reader should be made aware that future studies ought to include a more diverse sample. In case the study used a particular methodology or tool, it would be necessary to talk about possible biases or limitations that might be linked with the methodology and provide alternative ways for future research. Implications for practice: This section describes how the results of the study can be applied in real-life settings. For instance, if the study found that a specific intervention improved mental health outcomes, discuss how this intervention can be implemented in clinical practice to improve patient outcomes.

CONCLUSION

The findings of this study demonstrate a continued necessity to study apricot seed shell biochar. If we delve further into the area of research, it will lead us closer to the complexities and nuances that lie in that field. More effective strategies for the challenges can be developed if more research is done in this area. We hope this research will be a good point of starting for future studies and eventually contribute to the ongoing endeavor to improve in the field of relevance - industry.

Our study indicates the feasibility of preparing biochar from the apricot shell in Kargil and thus its use can be well authenticated for enriching the quality of soil. Apricot shell biochar, apart from other by-products of organic wastes, could play an active role in this regard for eradicating waste management and enhancing productivity. The potential area of investigation to be covered may include a critical analysis of its long-term implications on crop yields and soil quality.

Some of the limitations that appeared during the production of biochar included using energy to heat at a higher temperature and nitrogen supply avoiding combustion during a production cost process. Future research could address these limitations by the use of solar energy as Kargil Ladakh on an average experience more than 300 sunny days in the year could be a promising solution with one-time investment. Overall, it contributes to the body of knowledge in the use of biochar made of locally growing plants in the indigenous soil in the same cold desert climate by providing benefits for agricultural produce. The findings and results of this study can be applied in practical settings, such as a decline or replacement with synthetic fertilizer. The hope is that this study will stimulate further investigation into "assessing the potential of apricot shell biochar derived from apricot seed shell collected sourced from Kargil", Ladakh.

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Valorization of fruit waste for bio-refinery approach

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The magnitude of food waste across the food supply chain is intricate and can exert a substantial influence on various domains, including agriculture, food security, economics, waste utilization and management, environmental preservation, and human health. The crucial factor in effectively utilizing and managing fruit waste is the development of suitable environmentally sustainable reprocessing technologies. These technologies should be capable of converting all the valuable constituents found in the trash into valuable products, while simultaneously minimizing the quantity of waste destined for landfill disposal. A biorefinery can effectively utilize the variations in biomass components and intermediates by diversifying its product portfolio, so optimizing the value obtained from the biomass feedstock, and minimizing waste generation.

Keywords: Fruit waste valorization, bio-refinery, bioactive compounds, phenolic compounds

INTRODUCTION

Globally, fruit discards pose a major challenge due to their environmental, economic, and social impacts. Researchers are actively exploring methods to manage this waste. Food loss, distinct from food waste, refers to the decline in the quality and quantity of food caused by choices made within the supply chain before it reaches retailers. Food waste, in contrast, happens at the retail, food service, and consumer levels. Rapid population growth and our consumption habits are key drivers of both food loss and waste. Food loss exacerbates the environmental burden associated with food production within the food system. Data from the Food and Agriculture Organization (FAO) shows a critical situation: 15% of people in developing countries face hunger. This paradox highlights the global problem of food waste (FW). A significant amount of food that could be consumed is lost or discarded, throughout the food supply chain. Food waste isn't just a resource issue; it presents environmental, economic, and ethical challenges for modern society. FW occurs at every stage of the food lifecycle, from farms to processing facilities, retailers, and even in our homes. In lower-income countries, fruit waste is most prevalent during processing, with losses ranging from 15% to 20%. While at the consumption stage, only 4% to 10% of fruits go to waste. Interestingly, global fruit waste reached nearly 50% in 2011, a significant increase compared to 16 years prior [1].

Many scientific studies explore replacing fossil fuels with biomass resources, a concept known as biorefining. The food industry, encompassing agriculture and processing, is a prime candidate for biorefineries due to the potential utilization of its leftover materials. The initial step in utilizing these synergies involves identifying, measuring, and understanding the characteristics of these food processing residues. Due to the potential health benefits found in fruit waste (nutraceutical properties), there's a growing emphasis on finding ways to utilize it effectively (fruit valorization) [2]. One promising strategy is to use this waste as a starting material in bio-refineries. Bio-refineries are facilities that convert biomass, like fruit waste, into a range of valuable products. This can include things like heat, fuels, power, and even useful chemicals – all from materials that would otherwise be discarded [3].

According to the report of FAO 2023, Eating healthy is too expensive for many people in 11 African countries, especially those with lower incomes. These families, particularly those in suburbs and rural areas, would need to spend way more than they currently do on groceries to afford a diet that meets all their nutritional needs. The recovery of bioactive compounds from fruit waste has gained significant interest [4, 5]. Researchers are exploring green solvent extraction techniques to harness valuable components from fruit peels, seeds, pulp, and other byproducts generated during processing. Extracting valuable nutrients from fruit

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leftovers can make healthy foods cheaper and more accessible to everyone [6, 7].

Food waste (FW) is a global issue since a sizable portion of food that should have been eaten along the food value chain ends up as waste. In addition to being a resource issue, this also poses environmental, economic, and moral challenges for contemporary society. The first step for using industrial synergy in the food processing industry is detection, quantification, and characterization of residue. The objective of this article is: (a) to review the literature concerning the possible use of FW for producing usable compounds that reduce the burden on main raw materials. (b) to search for a novel valorization method for FW which overcomes the limitations faced during large scale implementation (c) to present different analytical techniques available for qualitative screening of bioactive compounds.

LITERATURE SURVEY

The burgeoning field of biorefinery necessitates the exploration of efficient and environmentally friendly methods that will be utilized for the valorization of fruit waste. Biorefinery approaches are increasingly exploring fruit waste as a sustainable source of health- promoting bioactive compounds. Recent studies highlight the potent antioxidant activity found within fruit byproducts. In the past, research focused on solid-liquid extraction (SLE) as the primary method. This technique simply involves using a solvent to dissolve and extract the target compounds from the material. SLE encompasses traditional methods such as Soxhlet extraction (SE), maceration extraction (ME), and percolation. [8]. Despite the effectiveness of conventional solvent extraction (CSE) in extracting polyphenols from plant materials, including fruit waste, its limitations are well documented like high time and energy consumption, along with the use of potentially hazardous organic solvents, make it an expensive and environmentally unfriendly option. The scientific community has been actively investigating towards finding more sustainable and cost-efficient methods for extracting these valuable compounds [9-12]. Emerging as a sustainable alternative, non-conventional extraction methods address the limitations of traditional techniques. These "green" approaches prioritize efficiency and selectivity while minimizing environmental impact. They achieve this through shorter processing times, reduced solvent use, and lower energy consumption [13].

Fruit waste valorization through biorefinery approaches can benefit from environmentally friendly extraction techniques. These methods, like microwave, enzyme, ultrasound, supercritical fluid, and pulsed electric field extraction, often utilize renewable resources and generate products that decompose naturally, minimizing the creation of harmful waste [14]. These methods champion several key principles: (i) Use sustainable source materials by utilizing fruit waste (FW) as a renewable resource. (ii) Apply alternative solvents by replacing traditional, often toxic, solvents with safer options, although limitations like high viscosity might exist. (iii) Reduced energy consumption by lowering the environmental footprint of the extraction process. (iv) Generation of coproduct by finding valuable uses for byproducts alongside the target compounds. (v) Ensure minimal environmental impact from the extracted biodegradable and pure extracts. (vi) Minimize the number of steps required for extraction streamlining the processes [15-18]. It's important to note that solvent selection, process design, and the type of fruit waste being processed all play a role in the final extraction yield. Additionally, to enhance the extraction process novel techniques can be employed as pretreatment with alternative solvents [19].

Table 1 indicates a different conventional method their advantages and disadvantages with the potential to extract bio-active compounds.

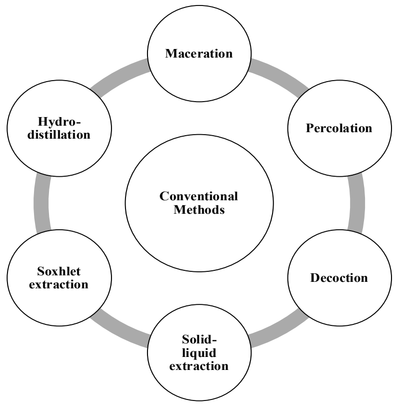

Fig. 1. Graphical representation of conventional methods of valorization.

Supercritical fluid extraction (SFE)

This method that uses a highly compressed fluid to separate a desired substance from a mixture. This mixture can be solid or even liquid. While supercritical fluid extraction (SFE) utilizes a gas-like solvent, its effectiveness improves compared to traditional liquid organic solvents. This is due to a unique combination of properties:

SFE utilizes a solvent in a state where it possesses both liquid and gas-like properties. This solvent, often referred to as the SFE solvent, has a reduced viscosity. In simpler terms, it is thinner than a typical liquid.

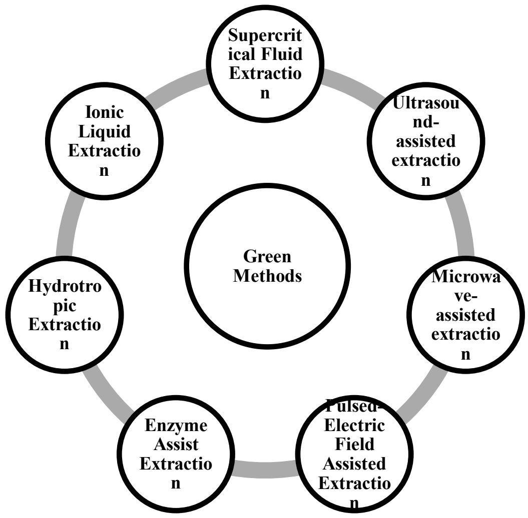

Fig. 2. Graphical representation of green methods of valorization

Table 1. Different conventional methods, their advantages and disadvantages with potential to extract bio-active compounds:

Techniques	Advantages	Disadvantages	Bio-active compound	Ref.
Maceration	• Maceration is a suitable method for extracting thermolabile components, meaning those that can degrade at high temperatures. • Since it operates at room temperature, it minimizes the risk of damaging these delicate compounds. • Maceration is a relatively cheap method compared to other extraction techniques. It requires minimal equipment and can be performed at ambient temperature, reducing energy consumption.	While maceration is a simple technique, it can be less efficient than other methods of extracting desired compounds from a material. • Maceration often requires extended steeping times, which can be a drawback if faster processing is needed. Compared to some other techniques, maceration necessitates a larger amount of solvent to ensure proper submersion and adequate extraction.	Polyphenols, anthocyanins, flavonoids, and essential oils	[20-22]
Percolation	• Percolation offers greater efficiency than maceration in extracting desired compounds.	• Percolation exhibits lower extraction efficiency compared to some alternative methods. • Percolation is characterized by extended extraction times.	Alkaloids, sterols, flavonoids, glycosides, saponins,	[23,24]
			phenols, lignin, sterols, and tannins	
Decoction	• Decoction is a highly economical method due to its reliance on water, a readily available solvent. • Decoction utilizes only water as a solvent, eliminating the need for expensive and potentially hazardous organic solvents. By using water as the solvent, decoction minimizes environmental impact compared to methods that require harsh chemicals.	• A decoction is best suited for extracting compounds that can withstand high temperatures without degrading. • Light-sensitive compounds can be damaged during the boiling process. A decoction may not be the ideal method for these materials. • The efficiency of extracting desired compounds through decoction is heavily influenced by how well heat and the target compounds move throughout the	Antioxidants and Polyphenol	[25,26]

		solution.		
Solid- liquid extraction	• This method is efficient, using less solvent to achieve the desired extraction. • Compared to other techniques, this method boasts a shorter extraction time. • This method is straightforward to implement in a laboratory setting.	• These methods are not recommended for extracting volatile compounds. • They are also not suitable for heat- sensitive compounds.	Essential oils, flavonoids, and polyphenols	[27,28]
Soxhlet extraction	• The Soxhlet extraction method offers a highly efficient way to extract target compounds from solid materials. Soxhlet extraction is a relatively low-cost technique, making it accessible for a wider range of research budgets. • The underlying principles of Soxhlet extraction are fundamental, allowing for a straightforward understanding of the process. The Soxhlet extractor itself is a user-friendly apparatus, requiring minimal technical expertise to operate.	• The method is not ideal for extracting volatile and heat-sensitive compounds. Soxhlet extraction requires relatively large volumes of solvent. Sample preparation for Soxhlet extraction can be time- consuming.	Phenolics, antioxidants, essential oils, and flavonoids	[29,30]
Hydro-distillation	• Hydro-distillation is a time-tested and straightforward technique, making it one of the oldest and simplest methods for extracting bioactive compounds. This versatile process can be further classified into different methods, including steam distillation, water disstillation, and hydro-diffusion distillation.	Hydro-distillation is not ideal for extracting bioactive compounds from heat- sensitive components, as the high temperatures can degrade their delicate chemical structures. While a well-established technique, hydro- distillation can be time-consuming, requiring longer processing times.	Essential oils and phenolics.	[31,32]
	• Due to its relative simplicity, hydro- distillation remains a popular choice for small-scale bioactive compound production. • For extraction of bioactive compounds, this method utilizes water as a solvent.	compared to some alternative methods. The process of hydro-distillation can be energy-intensive, as it relies on boiling large volumes of water to generate steam for extraction.		

The thinness allows for better penetration into the fruit waste, ensuring good contact with the target compounds [33]. SFE solvents also exhibit lower surface tension. Surface tension is a property that can hinder the interaction between a liquid and a solidThe lower surface tension of the SFE solvent allows for superior contact between the solvent and the desired compounds within the fruit waste, promoting efficient extraction. SFE provides unmatched tunable extraction power. By adjusting the operating pressure and temperature of the SFE process, researchers can precisely target specific compounds for extraction. This level of control allows for the selective extraction of high-value components from the fruit waste. Carbon dioxide in its supercritical state is often the preferred choice because it reaches its critical point at relatively mild conditions (31.1 °C and 73.8 MPa), is non- toxic, and doesn't react easily with other chemicals [34]. The utilization of supercritical CO_2 in extraction processes yields purer extracts compared to conventional extraction methods. Supercritical fluid extraction has several advantages, including comparable solvating capabilities to liquid organic solvents, enhanced solute diffusivities, reduced viscosity, decreased surface tension, and the ability to modify solvating power by pressure or temperature adjustments [35]. It is a popular method applied to extract a wide range of materials, from insecticides and environmental samples to food ingredients like flavorings and essential oils, as well as polymers and other natural products. Despite its versatility, SFE faces two main challenges hindering its widespread commercial use. First, the technology can be expensive to implement. Second, SFE has traditionally been developed as a standalone process, not considering how it would integrate with other processing steps needed to create a final product. This lack of integration adds complexity and cost, further limiting commercial adoption [36].

Ultrasound-assisted extraction (UAE):

It is a method employed for bioactive compound recovery like antioxidants, essential oils, steroids, and lipids, from various plant sources [37]. Sound waves, characterized by frequencies over 20kHz, propagate across various mediums and encompass cycles of expansion and compression.

During green solvent extraction, manipulating pressure plays a crucial role. Expansion forces molecule During green solvent extraction, manipulating pressure plays a crucial role. Expansion forces molecules apart, while compression brings them closer together. Liquid expansion can lead to the formation and collapse of bubbles, which can be harnessed to improve mass transfer between the solvent and the fruit waste. Near a solid barrier, these collapsing bubbles create an asymmetrical effect. High-speed jets of liquid shoot out, potentially impacting and disrupting the fruit material, aiding in the extraction processes apart, while compression brings them closer together. Liquid expansion can lead to the formation and collapse of bubbles, which can be harnessed to improve mass transfer between the solvent and the fruit waste. Near a solid barrier, these collapsing bubbles create an asymmetrical effect. High-speed jets of liquid shoot out, potentially impacting and disrupting the fruit material, aiding in the extraction process. Ultrasound waves enhance solvent penetration into the cellular material of the fruit, facilitating increased mass transfer of target compounds into the solvent. Additionally, ultrasound can disrupt biological cell walls, promoting the release of valuable cellular contents. Notably, the effectiveness of ultrasound in this process depends on the frequency used. The optimal frequency will vary based on the specific characteristics of the fruit material being extracted [38].

Compared to traditional methods, ultrasound-assisted extraction offers a more efficient approach to fruit waste valorizations within the biorefinery framework. This technology drastically reduces the high temperature and pressure requirement, leading to faster processing and potentially higher yields of valuable bioproducts. Additionally, the equipment for ultrasound-assisted extraction is generally less expensive compared to microwave-assisted extraction [39]. Ultrasound-assisted extraction offers many benefits, but there are some limitations to consider. One issue is that sound waves travel less effectively (attenuate) when there are solid particles mixed in with the liquid (dispersed phase). This can happen with fruit waste, which may not be completely homogenized. Another challenge is the difference in how readily the particles and liquid heat up and compress (compressibility and heat capacity) and how quickly heat moves between them (thermal diffusion). These differences can make it harder to extract all the desired compounds [40] efficiently. Finally, the effectiveness of ultrasound weakens the farther you get from the source (emitter) inside the extractor. This means that some areas of fruit waste may not be exposed to the same level of sound energy. Ultrasound allows for extraction at lower temperatures and pressures than traditional methods. The efficiency of ultrasound-assisted extraction (yield and kinetics) depends heavily on both the frequency used and the specific properties of the plant material being processed [41].

Microwave-assisted extraction (MAE)

Microwaves are a type of electromagnetic radiation characterized by the presence of both electric and magnetic fields. Microwave technology presents a viable alternative to the conventional solid-liquid extraction method for the extraction of nutraceuticals from plants due to its ability to significantly reduce extraction time and solvent use, while also enhancing extraction yields. [42] Microwaves offer a promising avenue for solvent-free or reduced- solvent extractions. Unlike traditional heating methods, microwaves directly interact with the material at a molecular level, leading to faster and more uniform heating. This translates to quicker extraction times, minimized thermal degradation, and potentially lower energy consumption, making it an attractive green technology [43]. Biorefinery processes for fruit waste valorization require the development of techniques to extract heat-sensitive compounds. Vacuum microwave-assisted extraction is a valuable tool, employing a vacuum environment for efficient extraction under mild conditions.

Microwaves utilize a specific type of energy to heat. They work by rapidly changing electric and magnetic fields that interact with certain molecules in food. This interaction is most effective with molecules that have a positive and negative end, like tiny magnets. These "polar" molecules are more likely to absorb the microwave energy, which makes them vibrate and heat up. This targeted heating is what allows microwaves to cook food quickly and efficiently. This technique relies on the fact that microwaves interact differently with materials based on their electrical properties. Materials with high polarity, like water in fruit waste, absorb microwave energy more readily. This internal heating disrupts plant cell walls, releasing the trapped chemicals and making them easier to collect [44,45]. Conventional solid-liquid extraction methods for nutraceuticals from plants often require large volumes of solvents and lengthy processing times. This raises concerns about environmental impact and cost-effectiveness. Microwave technology offers a greener alternative [46].

Microwave technology significantly reduces extraction time and solvent use compared to traditional methods. This translates to a more environmentally friendly process. Additionally, it can enhance the yield of extracted nutraceuticals. Microwave-assisted extraction shares some advantages with supercritical fluid extraction, such as process simplicity and cost-effectiveness. However, it's generally less expensive than ultrasound-assisted extraction. Researchers have developed various microwave extraction techniques, including methods suitable for extracting heat-sensitive compounds under milder conditions. These methods offer several advantages over traditional solvent extraction, such as reduced environmental impact and improved efficiency. Vacuum Microwave-Assisted Extraction: This approach utilizes a vacuum to gently draw out the desired compounds from the fruit material. This is particularly beneficial for heat-sensitive molecules [43].

Nitrogen-protected microwave-assisted extraction: In this extraction method nitrogen gas is used to create a pressurized environment within the extraction vessel. This technique is particularly well-suited for the biorefinery approach as it protects oxygen-sensitive compounds abundant in fruits. Ultrasonic Microwave-Assisted Extraction: This method combines the power of microwaves with ultrasonic waves. The ultrasonic waves create microscopic vibrations that disrupt plant cell walls, allowing for a more efficient release of valuable compounds.

Pulsed-electric field assisted extraction (PEFE)

Pulsed electric field has garnered significant interest in the food sector as a promising developing technique to enhance mass transfer operations. The process of electroporation involves subjecting cell material to brief applications of strong external electric fields, typically ranging from 1 to 50 kV/cm, for a duration of microseconds to milliseconds. This results in the permeabilization of cell membranes [47]. The utilization of pulsed-electric field (PEF) presents numerous advantages in comparison to alternative methodologies, including elevated temperatures and enzymatic treatments. The PEF process offers the advantage of reduced energy costs.

Pulsed electric field (PEF) treatment weakens the cell wall, making it easier for valuable bioactive compounds to escape. This significantly increases the amount of these compounds extracted from the fruit waste. PEF offers several advantages over traditional methods like heat or enzymes. Unlike these methods, PEF uses less energy and keeps temperatures low. This is important because high temperatures can damage cell membranes, releasing unwanted molecules and destroying heat-sensitive bioactive compounds. PEF avoids this by creating small, temporary pores in the cell wall, allowing the desired compounds to pass through without harming the cell or the valuable molecules inside [48].

Enzyme assisted extraction (EAE): Enzymes offer a promising method to extract valuable bioactive compounds from fruit waste in biorefineries. By employing enzymes, either alone or combined, this green technique disrupts the cell wall, enhancing permeability. This translates to increased extraction yields of various target compounds like polysaccharides, oils, natural colors, flavors, antioxidants, and medicinal components, all without resorting to harsh chemicals [49]. In the domain of green extraction, enzyme-assisted extraction (EAE) leverages enzymes derived from various eco-friendly sources like bacteria, fungi, plant extracts, and even byproducts from animal sources. Optimizing factors like processing time, temperature, pH, and the enzyme to substrate ratio is crucial to maximize the yield of target compounds while minimizing environmental impact [50].

Enzyme-assisted extraction (EAE) offers an environmentally friendly solution. Specific enzymes, like pectinases, cellulases, and hemicelluloses, act like microscopic scissors, snipping apart the components of fruit cell walls. This increases cell wall permeability, allowing researchers to extract more of the desired compounds – from polysaccharides and oils to natural colors, flavors, antioxidants, and even medicinal components. The beauty of EAE lies in its versatility. Enzymes can be derived from various sources, including bacteria, fungi, animal organs, and even plants themselves. To maximize extraction yields, researchers can fine-tune the process by adjusting factors like time, temperature, pH, and the amount of enzyme used compared to the amount of fruit waste (enzyme to substrate ratio). This technique utilizes enzymes at the beginning of the processing line to achieve several advantages. It can significantly reduce extraction times, minimize the amount of solvent required, and ultimately improve the yield and quality of the extracted products. However, enzyme-assisted extraction does face some technical limitations. A primary concern is the cost associated with processing large volumes of fruit waste. Enzymes can be expensive, and their large-scale application can translate to high overall processing costs. Our current enzyme cocktails lack the complete power to break down all components of plant cell walls. This limits the potential yield of extracted compounds [49]. Scaling up enzyme-assisted extraction for industrial applications remains a hurdle. Enzymes are sensitive to their environment, and their effectiveness can change significantly based on factors like oxygen levels, temperature, and nutrient presence.

HYDROTROPIC EXTRACTION (HE)

Hydrotropes are molecules readily water-soluble and contain a single negatively charged group with a water-repelling aromatic ring structure. Fruit waste valorization is significantly enhanced by employing hydrotropes. This approach overcomes the challenge of extracting poorly water-soluble compounds, leading to improved efficiency in recovering valuable chemicals from fruit discards [51]. Examples of these non-toxic hydrotropes include substances derived from common sources like fruits (polyhydroxy benzene) and fermentation processes (sodium salts of lower alkanols), along with naturally occurring aromatic compounds like cumene, toluene, and xylene [52]. Hydrotrope separation of active chemicals is the simplest but most important step. Hydrotropes lower interface surface forces during extraction, improving cell wall wettability and allowing hydrotrope molecules to penetrate phytochemical cellulose structures [53]. Limonin can be successfully extracted from citrus fruit waste using a range of eco-friendly solvents, such as sodium benzoate, niacinamide, sodium salicylate, sodium acetate, urea, and sodium citrate [54].

Ionic Liquid Extraction (ILE)

Fruit waste valorization can benefit from ionic liquids (ILs), unique salts that are liquid at room temperature (below 100 °C). These ILs are typically composed of a large organic molecule (cation) paired with another molecule, either organic or inorganic (anion). These compounds are sometimes referred to as "designer solvents" due to their unique characteristic of being customizable [55]. Ionic liquids (ILs) offer a unique set of advantages for extracting valuable compounds from fruit waste. These designer solvents boast exceptional stability under heat and resist burning. Additionally, ILs conduct electricity efficiently and can operate within a broad range of electrical conditions. Furthermore, their ionic nature translates to high density and minimal evaporation, simplifying the process of isolating the extracted organic materials [56]. Table 2 indicates a literature survey on different novel valorization methods

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Table 2. Literature survey on different novel valorization methods**.**

Fruit waste	Method	Optimum condition	Product extracted	Reference
Banana peel (*Musa Paradisiaca Cv. Tanduk*)	Supercritical water extraction	Temperature: 140 °C Time: 5 min Solvent: Water Particle size: 1.18 mm	Pectin yield: 4.23 %	[57]
Mango kernel (*Mangifera. Indica cv.*)	Solvent extraction	Weight: 0.5 gm Solvent: 25 ml Me-OH: water ratio: 3:2 (v/v)	Total polyphenols: 72.05 mg GAE/g DM	[58]
Litchi seeds (*Litchi chinensis Sonn*)	Solvent extraction	Solid to liquid ratio: 1:20 ethanol concentration: 41% Temperature: 51°C Time:139 min	Extraction yield: 8.9 mg/ 100g DW Extraction of phenolic compound: 967 mg GAE/ 100g DW	[59]
Longan seeds (*Dimocarpus longan*)	Solvent extraction	Solid to liquid ratio: 1:20 Ethanol concentration: 53% Temperature: 58°C Time: 220 min	Extraction yield: 14.2 mg/100g DW Extraction of Phenolic compound: 6144 mg GAE/100g DW	[60]
Jackfruit (*Artocarpus heterophyllus*)	Acid extraction	Solid to liquid ratio: 1:29 (w/v) Temperature: 80 °C PH: 2.0 Solvent:1 M H_2SO_4 Extraction time: 105 min	% Yield of Pectine : Core: 35.13 Tandem: 28.21 Peel: 25.35	[60]
Mango kernel (*Mangifera. Indica cv. Nam Dokmai*)	Supercritical CO extraction 2	Pressure: 50 Mpa Temperature: 40 °C Flowrate: 30 g/min	Polar lipid yield: 3.28%	[61]

Apple seed (*Malus pumila*)	Supercritical CO extraction 2	Pressure: 24 Mpa, Temperature: 40 °C Flowrate:1 L/h Time:140 min	Linoleic acid content: 63.76 g/100 g Phloridzin content: 2.96 µg/g	[62]
Citrus peel (*Satsuma Mandarin*)	Pulsed electric field extraction + Subcritical water extraction	For Hesperidin: PEF treatment time: 120 sec	Hesperidin extraction yield: 46.96% Narirutin extraction yield: 8.76%	[63]
		SWE at 150 °C for 15 min, For Narirutin, PEF treatment time: 120 sec SWE at 190 °C for 5 min		
Lemon peels (*Citrus limon*)	Microwave-assisted extraction	Solvent: ethanol Concentration: 80% (v/v) Liquid to solid ratio: 1:10 Temp: 80°C Time: 50 min	Essential oil yield: 2% Pigment yield: 6%	[64]
Watermelon rind (*Citrullus lanatus*)	Microwave-assisted extraction	Solvent: 0.5 N sulfuric acid Time: 15 min Solid to liquid ratio: 1:08 Microwave power: 39.9 W	Pectin yield: 11.25%	[65]
Mango peel (*Mangifera. Indica cv.*)	Microwave-assisted extraction	Microwave power: 700 W Time: 3 min HCl concentration: 2 M pH: 1.5	Pectin yield: 13.85%	[66]
Mango peel (*Mangifera Indica cv.*)	Microwave-assisted extraction	Microwave power: 500 W Time: 20 min HCl concentration: 1 M pH: 1.5	Pectin yield: 10.33%	[67]
Banana peel (*Musa acuminata x Musa balbisiana)*	Microwave-assisted extraction	Microwave power: 1000 W Time: 60 s Temperature: 195°C pH: 3.0	Pectin yield: 14.2%	[68]
Dragon fruit peels (*Hylocereus polyrhizus*)	Microwave-assisted extraction	Microwave power: 600 W Extraction time: 65 s pH: 2.07 Solid to liquid ratio: 66.57	Extraction yield: 17.2% Pectin yield: 69.68%	[69]
Jackfruit peel (*Artocarpus heterophyllus*)	Ultrasound-assisted extraction	Solvent: Citric acid Frequency: 2450 MHz Ultrasound power: 500 W	Pectin yield: 21.5%	[70]
		Time: 29 min Temperature: 86°C pH: 2.0		
Acerola residue (*Malpighia emarginata*)	Ultrasound-assisted extraction	pH: 2 Ethanol to residue ratio: 8.7 mL/g Temperature: 30 °C Time: 49.3 min	Anthocyanin: 2.00 to 11.16 mg TA/100 g	[71]
Dragon fruit peel (*Hylocereus undatus*)	Ultrasound-assisted extraction	Solvent: 80% acetone Ultrasound time: 15 min Temperature: 100°C	Betalains: 101.04 mg/100g Carotenoids: 1.58 µg βCE/g	[72]
Pineapple peel (*Ananas comosus*)	Ultrasound-assisted extraction	Temperature: 70.83°C pH: 1.0 Liquid to Solid ratio: 15.20 mL/g Sonication time: 21.88 min	Pectin yield: 16.24%	[73]
Pomegranate peel (*Punica granatum*)	Ultrasound-assisted extraction	Solvent: Sunflower and Soy oil Time: 30 min Peels to solvent ratio: 0.10 Temperature: 51.5 °C	Sunflower oil: 0.6134mg carotenoids/100g of DW Soy oil: 0.6715 mg carotenoids/100g of DW	[74]
Banana peel (*Musa acuminata x balbisiana*)	Enzyme-assisted extraction	Temperature: 55 °C Time:120 min Pectinase: 0.103 g/mL pH: 5.0 Enzyme: *Aspergillus niger*	Pectin Yield: 10.8%	[75]
Watermelon seeds (*Citrullus lanatus*)	Enzyme-assisted extraction	Temperature: 47.13 °C pH: 7.89 Enzyme: Protex 6L Enzyme dose: 2.63% Time: 7.8 h	Acid yield 97.92%	[76]
Banana peel (*Musa Paradisiaca Cv. Tanduk*)	Enzyme-assisted extraction	Types of enzymes: Viscozyme L, cellulose, pectinase Enzyme concentration: 1.0% Extraction time: 9 hr	TPC: 25.37 mg GAE/g DM TFC: 13.99 mg QE/g DM, DPPH: 81.59%, ABTS: 88.25%,	[77]

		Extraction temperature: 55°C Solute:liquid ratio: 1:25	α-glucosidase inhibitory effect: 74.67%	
Litchi (*Litchichinensis cv. Bombai*)	Enzyme-assisted extraction	Enzyme concentration: 1.0%, Extraction temperature: 55°C pH: 4 Incubation time: 1 h	TPC: Peel: 40.78 mg GAE/g DM Seed: 5.04 mg GAE/g DM TFC: Peel: 9.31 mg QE/g DM Seed: 0.13 mg QE /g DM	[78]
Litchi (*Litchichinensis cv. Bombai*)	Pressurized hot water extraction	Solid to liquid ratio: 1:20 Pressure: 20 psi. Temperature: 120°C Time: 30 min	TPC: Peel: 103.57 mg GAE/g DM Seed: 75.64 mg GAE/g DM TFC: Peel: 13.64 mg QE/g DM Seed: 8.96 mg QE /g DM	[78]
Lemon seed (*Citrus limon*)	Hydrotropic Extraction	Temperature: 44°C Time: 4 hr Hydrotropic solution: Sodium Salicylate(Na-Sal) Hydrotrope concentration: 1.65 M 8.08% of raw material loading.	Limonin: 6.41 mg/g	[79]
Sour orange seed (*Citrus aurantium L.*)	Hydrotropic Extraction	Temperature: 45°C Solid loading:10% Hydrotropic solution: Sodium Salicylate (NaSal) Sodium Cumene sulphonate (Na-CuS) Concentration: 2 M	Using Na-CuS: Limonin yield: 0.65 mg/g Using Na-Sal: Limonin yield: 0.46 mg/g	[80]
Mangosteen pericarp (*Garcinia mangostana L*)	Hydrotropic Extraction	Hydrotrope concentration: 2M Temperature: 40°C Solid loading: 3%	Xanthones yield: 4.69 mg/g	[81]
		Hydrotropic solution: Sodium Salicylate (Na-Sal)		
Jackfruit rind (*Artocarpus heterophyllus*)	Pulsed electric field extraction + Microwave treatment	Microwave power density: 647.30 W/g Pulsed-field strength: 11.99 kV/cm Time of exposure: 5 min	Pectin yield: 18.24%	[82]
Mangosteen pericarp (*Garcinia mangostana L*)	Pulsed electric field extraction	Hydrotrope concentration: 2 M Temperature: 40°C Solid loading: 3%	Xanthones yield: 4.69 mg/g	[83]
Watermelon Rind (*Citrullus lanatus*)	Ionic liquid-based ultrasound-assisted extraction	Ionic liquid concentration: 1.5 M Solid to liquid ratio: 1:40 Salt concentration: 35% Ultrasound Power: 100 W Ultrasonic time: 15 min	Amino acid recovery: 90.45%	[84]
Orange peel (*Citrus sinensis*)	Ionic liquid-based ultrasound-assisted extraction	Sample Weight: 5.0 g Ultrasound power: 200 W Frequency: 20 kHz Amplitude: 80% Time: 5 min Solid-liquid ratio: 1:3	Carotenoids yield: 39.99 µg/g	[85]

QUALITATIVE METHODS

A. Determination of total phenolic compounds (TPC)

Plant secondary metabolites, known as phenolic compounds, encompass a diverse array of molecules characterized by the presence of an aromatic benzene ring substituted with one or more hydroxyl moieties. These compounds exhibit various functionalities due to the existence of derivatives such as glycosides, esters, and methyl esters. Fruit and vegetable processing byproducts serve as a plentiful source of these phenolic constituents.

The Folin-Ciocalteu (FC) method was employed to quantify the total phenolic content (TPC) of the extract. Briefly, the extract (0.5 ml) was reacted with FC reagent (2.5 ml, 10%) for 5 minutes, followed by the addition of sodium carbonate solution (2.5 ml, 7.5%). The mixture was incubated for 30 minutes at ambient temperature without light exposure. A blank, prepared without the extract, was included for comparison. Following incubation, the absorbance was measured at the maximum wavelength (λ_max= 765 nm) using a spectrophotometer. This procedure was replicated to obtain reliable data, and the mean absorbance was used for further analysis.

The calibration line was construed and the total phenolic content of extract was calculated using the equation presented in Eq (i).

$$\text{Total phenolic content (TPC)} = (C \times Ve)/M \quad \text{Eq(i)}$$

where C indicates the standard concentration (gallic acid), Ve indicates extract volume, and M weight of the material.

Giri *et al.,* (2016) have applied Folin-Ciocalteu (FC) method for the quantitative analysis of total phenolic compounds for the ultrasound assisted phytochemical extraction of persimmon fruit peel. Ultrasonic power has the highest effect on total phenolic compound followed by temperature, solvent to solid ratio and solvent concentration. Combining solvent extraction with ultrasonication offers a significant advantage for extracting phenolic compounds from plant material. This technique utilizes acoustic cavitation, a process that creates microscopic bubbles within the solvent. The collapse of these bubbles generates high shear forces that effectively break down cell walls. This enhances solvent penetration into the cells, promoting the release and dissolution of the target phenolic compounds, ultimately leading to increased extraction yield [86]. Velderrain-Rodriguez *et al.* (2021) investigated the total phenolic content (TPC) of avocado peel and seed extracts using maceration with 80% ethanol. Maceration involved stirring the avocado material (solid) in the solvent at a 1:15 solid-to- solvent ratio for 20 hours at 40°C. The avocado peel extract exhibited a significantly higher TPC (142.23 mg gallic acid equivalents (GAE)/g) compared to the seed extract (63.19 mg GAE/g). This difference in TPC likely contributes to the higher antioxidant activity expected in the avocado peel extract. Phenolic compounds are well-documented for their antioxidant properties, and their abundance can influence the overall antioxidant capacity of a plant extract [87].

B. Determination of total flavonoid compounds (TFC)

Flavonoids represent a remarkably diverse and abundant class of secondary metabolites found within the plant kingdom. These polyphenolic compounds are ubiquitous throughout the plant world, with a presence in a vast array of edible plant species. They are recognized for their potential health benefits due to their possession of numerous biologically and physiologically active moieties. This widespread occurrence and structural diversity within flavonoids contribute significantly to their potential advantages for human health. The total flavonoid content of the extract was determined using a spectrophotometric method. Briefly, the extract was reacted with sodium nitrite and aluminium chloride, followed by the addition of sodium hydroxide. The resulting mixture's absorbance was measured at 510 nm using a UV spectrophotometer. A calibration curve was generated using known concentrations of quercetin (QE) standard solution, following the same reaction protocol. The total flavonoid content in the extract was then expressed as milligrams of quercetin equivalents (mg QE) per gram of dry weight.

$$Total\ Flavonoid\ content\ (TFC) = (Ce\ \times Ve \times D)/M \quad \text{Eq(ii)}$$

where Ce is the extract concentration (mg QE/mL) obtained from the calibration curve; Ve is the volume of extract; D is the dilution factor; M is the mass of the extract.

Da Silva Francischini *et al*., (2020) performed Homogenizer assisted extraction, Ultrasound assisted extraction and microwave assisted extraction on the passion fruit peels and HAE stand out as the one of the best extraction methods with better extraction yields and lowest energy consumption. 0.1 sample/solvent ratio, 70% solution of ethanol in water and 2 min of extraction time set as optimum parameter for HAE with highest recovery of 0.94, 1.11 and 0.34 mg/g for orientin, isoorientin and isovitexin, respectively, which is higher than UAE and MAE [88].

C. Determination of antioxidant activity

1. 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay

The antioxidant activity was measured using the DPPH (2,2-diphenyl-1- picrylhydrazyl) assay. It is based on reduction of 2,2-diphenyl-1-picrylhydrazyl radicals, which are scavenged by antioxidant compounds. This involved mixing 50 µL of the extract with 2 mL of DPPH ethanolic solution (20 µM) and measuring the absorbance after 960 s at 517 nm. Colour changes were observed indicating the reaction of the reactive antioxidant compound with the reagent. To calculate the antioxidant activity (%AA) the eq. (iii) is used:

$$\%AA = \left(\frac{\text{AbsControl} - \text{AbsSample}}{\text{AbsControl}}\right) \times 100 \quad \text{Eq(iii)}$$

Solvent with extract used as a blank. DPPH with solvent used as negative control [89]. Catechin, ascorbic acid, and Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2- carboxylic acid) were used as pure standards. The effective concentrations necessary to scavenge 50% of DPPH radicals (EC50) were calculated for all analyzed samples and Trolox using graphical regression analysis and expressed as v/v% (relative to the volume of DPPH solution) [90].

2. Ferric reducing antioxidant power (FRAP) assay

The ferric reducing antioxidant power (FRAP) assay was employed to assess the reducing potential of the sample extracts. The reducing ability of the sample is determined by its capacity to convert ferric tripyridyltriazine ($Fe3+$-TPTZ), a colorless complex, to its ferrous form ($Fe2+$-TPTZ), which exhibits a distinct blue color [91].

The difference in light absorption at 593 nm can be used to estimate the antioxidant potential of the extracted bioproducts. Methodology was established by Benzie and Strain (1996). A FRAP reagent was prepared by mixing a 300 mM sodium acetate buffer solution, 10 mM 2,4,6-tripyridyl-s-triazine (TPTZ) solution, and 20 mM ferric chloride solution in a 10:1:1 volume ratio. Samples (20 µL) were combined with freshly prepared FRAP reagent (280 µL) and incubated for 10 minutes at 37 °C. Following incubation, the light absorption of the samples was measured at a wavelength of 593 nm. To quantify the antioxidant activity, a calibration curve was constructed using known concentrations of ascorbic acid (0-50 µg/mL). The final results are expressed as milligrams of ascorbic acid equivalents (AAE) per gram of fresh sample weight. [92,93].

3. 2,2′ -Azinobis(3-ethylbenzothiaziline-6-sulfonate) (ABTS) assay

The 2,2'-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical cation assay was employed to evaluate the antioxidant capacity of fruit waste extracts. Solutions of ABTS and potassium persulfate were prepared at concentrations commonly used in antioxidant activity assays. The ABTS concentration was 7.4 millimolar, and the potassium persulfate concentration was 2.6 millimolar. A working solution of ABTS radical cations was generated by mixing equal volumes of these stock solutions and incubating for 12 h at room temperature in the dark to allow for complete radical formation. The working solution was then adjusted to an absorbance of 1.1 units at 734 nm using a dilution with methanol (1:60, ABTS: methanol). Fresh ABTS working solution was prepared for each experiment to ensure consistent radical activity.

The antioxidant capacity of the extracts was determined by their ability to quench the ABTS radical cation. Fruit waste extracts (150 µL) were mixed with 2850 µL of the ABTS working solution and incubated for 2 hours under dark conditions. The reduction in absorbance at 734 nm was measured using a spectrophotometer, reflecting the extract's antioxidant potential. A Trolox standard curve (25-600 µM) was used for calibration, and results are expressed as micromolar Trolox equivalents (TE) per gram of fresh sample mass. To ensure reliable measurement of antioxidant activity (represented by the ABTS value), samples exceeding the standard curve's range required further dilution [94].

Marjanovic *et al.,* (2021) measured the antioxidant activity and polyphenolic content of eight berry species from Bosnia and Herzegovina. They found that the berries had significant antioxidant activity and high levels of polyphenolic compounds, with black chokeberry having the highest anthocyanin content [95]. Uuh-Narváez et al., (2023), reported that mango (*Mangifera indica L cv Ataulfo*) peels and seeds waste are a rich source of bioactive compounds and have significant antioxidant activity. Mango seed flour had the highest antioxidant activity (DPPH: 1.10 mg Trolox/g, FRAP: 1.30 mg Trolox/g) [96].

Bansod *et al.* (2023) investigated the microwave-assisted extraction (MAE) of bioactive compounds from pineapple peel waste. They optimized the extraction process using a Box-Behnken design (BBD) to identify the most favourable conditions for yield. The optimal parameters were found to be a solvent-to-substrate ratio of 20 mL/g, microwave power of 600 W, and extraction time of 40 minutes. Under these optimized conditions, the extract exhibited strong antioxidant activity, with a DPPH radical scavenging capacity of 75%. Additionally, the researchers quantified the proteolytic activity of bromelain, an enzyme present in pineapple peel, and determined it to be 1647.612 GDU/g concentrate [97].

Capeletto *et al.* (2016) investigated the effect of extraction method on the phenolic content and antioxidant activity of extracts from *Campomanesia xanthocarpa* seeds. They compared supercritical CO_2 extraction at 40 °C and 250 bar with n-butane extraction at 35 °C and 10 bar. Notably, n-butane extraction yielded a significantly higher amount of total phenolic compounds (17.18 mg/g) compared to supercritical CO_2 extraction (68.58 mg/g). Furthermore, n-butane extracts exhibited stronger antioxidant activity as measured by FRAP, DPPH, and deoxyribose assays. These findings suggest that n-butane extraction, despite yielding lower total phenolics, might be a more efficient method for obtaining antioxidants from *C. xanthocarpa* seeds [98].

D. Determination of carotenoids

Carotenoids, the preeminent naturally occurring pigments, have garnered significant interest in recent years owing to their advantageous attributes. These pigments boast low toxicity, exhibit a diverse structural landscape, and possess a ubiquitous presence. Notably, they are naturally sourced and contribute to physiologically important functions, thereby promoting human health. It is well-established that the concentration of carotenoids within foodstuffs is susceptible to a multitude of post-harvest factors and processing techniques [100].

Lima *et al*., (2019) demonstrated method for quantification of total carotenoids content. Briefly, the isolated extracts were transferred to petroleum ether, a non-polar solvent suitable for carotenoid extraction. To disrupt cell walls and release bound carotenoids, saponification was performed using a 10% sodium hydroxide methanolic solution for 16 hours. Following saponification, the extracts were washed with ultrapure water to remove residual contaminants and then dried with sodium sulfate to eliminate water [100]. The absorbance of the final extracts was measured at a specific wavelength (λ = 470 nm) using a spectrophotometer. This absorbance value, along with established equations eq. (iv) and eq. (v), was used to calculate the total carotenoid content present in the original samples.

where x is the carotenoid concentration, A is the absorbance, v is the volume of the solution, w is the sample weight, $A^{1\%}$ is the absorption coefficient of the carotenoid in the solvent used ($A^{1\%}_{1}$ = 3450 for lycopene in petroleum ether).

Carotenoids were quantified using hyphenated techniques to minimize degradation from light and oxygen exposure. High-performance liquid chromatography (HPLC) with C30 columns provided selectivity for quantification of the major carotenoid stereoisomers (Z and E isomers). To definitively identify these isomers, the HPLC system was coupled online with two complementary techniques: atmospheric pressure chemical ionization mass spectrometry (APCI-MS) and nuclear magnetic resonance (NMR). While HPLC-APCI-MS differentiates between lutein and zeaxanthin, HPLC- NMR allows for the identification of all the major Z and E isomers present in the sample [101].

Boukroufa *et al*. (2015) reported recovery of carotenoid from the citrus peel waste using solvent free microwave assisted extraction, ultrasound assisted extraction and steam distillation. The best result was obtained in ultrasound assisted extraction. Effect of n-hexane as compared to limonene is quite negligible. But considering limonene as a green solvent combined with UAE make valorization process more environment friendly. At optimized conditions (ultrasound power, temperature and time were 208 W cm^{-2}, 20 °C and 5 min), 11.25 mg/L of carotenoid can be extracted. The ultrasonic probe-assisted extraction resulted in the greatest degradation of carotenoids [102]. This is likely due to the increased formation of free radicals caused by the high-intensity cavitation generated during the process. Cavitation is the phenomenon of rapid bubble formation and collapse in a liquid medium, and the high energy associated with this collapse can lead to the generation of reactive oxygen species (ROS) that can degrade carotenoids [103].

Mesquita *et al.* (2020), performed valorization of *bactris gasipaes* waste using ionic liquid assisted extraction technique. Maximum yield of carotenoids = 88.7 μg carotenoids/ g of dried waste was achieved at the optimum conditions of extraction time: 8.2 min; concentration 140 mM of IL, and Solid to liquid ratio of 0.15. Further Carotenoids were applied on chitosan -based film which is applicable in food industries for packaging purpose [104].

Chutia and Mahanta (2021) investigated a novel green approach for extracting carotenoids from passion fruit peel waste. They employed ultrasound-assisted extraction (UAE) with olive oil as a solvent, achieving a high extraction yield of 91.4% under optimized conditions. These optimized conditions consisted of a treatment time of 39 minutes, a temperature of 47 °C, and a solid-to-liquid ratio of 0.30 g/mL. This study suggests that UAE with olive oil offers a promising green alternative to conventional solvent extraction methods for the recovery of valuable carotenoids from food byproducts [105].

E. Determination of dietary fibers.

Plant cell walls are reinforced by dietary fibers, which are complex carbohydrates like cellulose, hemicellulose, pectin, and lignin. These fibers provide structural stiffness to the plant. Additionally, dietary fibers can be classified into soluble and insoluble types based on their water solubility. Soluble dietary fibers, such as mucilage, gums, and pectin, dissolve easily in water. Insoluble dietary fibers, including lignin, cellulose, and hemicellulose, do not dissolve in water.

The analytical method for estimation of total dietary fibers was established by Lee et al., (1992). According to this method, add 4 volumes 95% EtOH (heated to 60°C) to digested samples (1 volume). Precipitate at room temperature (1 h). Transfer digestate through Celite bed on crucible. Wash residue with specific solvents under vacuum. Dry residue overnight (105°C), cool, and weigh. Subtract crucible and Celite weight. Analyze separate sample duplicates for protein and ash content using established methods [106].

Khanpit *et a*l., (2023) reported that extrusion improves the recovery of soluble dietary fibers as compared to Ultrasonication process from 22.27% to 24.28 % from orange peel waste. Also, extrusion has 1.5 kg CO_2 equivalent of Global warming potential, which is very low as compared to

Ultrasonication [107].

Kaur *et al.,* (2021) has reported comparative work on novel extraction techniques like enzymatic, ultrasound, and ultrasound-assisted enzymatic extraction for the extraction of dietary fibers from mango peels. Ultrasound waves assisted enzyme extraction significantly increased the yield (71%) of total dietary fibers. The optimal conditions for this process were found to be 25 °C temperature, 40% amplitude, a 1:50 solid-to-liquid ratio, and a 9-minute extraction time [108].

Dietary fiber concentrates used in bakery, meat, dairy snacks and pasta products [109, 110] Soluble dietary fibers are incorporated into beverages to manipulate their rheological properties (flow behavior) and enhance their colloidal stability. Upon hydration, these fibers interact with water molecules, forming a three-dimensional network that increases the beverage's viscosity. This thickening effect contributes to a desirable mouthfeel and prevents undesirable phenomena like sedimentation or phase separation of ingredients [111, 112].

F. Total anthocyanin content

The anthocyanin concentration in samples was determined using the pH differential method. A produced sample solution (0.5 mL) was combined with 0.025 M KCl buffer pH 1.0 (1.5 mL), whereas another portion (0.5 mL) of the same extract was combined with 0.4 M NaOAc buffer pH 4.5 (1.5 mL). Both mixes were aggressively stirred for 30 seconds and left for 15 minutes in the dark. The extinction coefficients of samples were determined at specified wavelengths using buffer as a reference solution. The total anthocyanins content (C), given in mg of cyanidin-3-O-glucoside (Cy3G) equivalents per L, was determined as follows.

$$C = ((A \times MW \times R \times 1000)/(\epsilon \times l) \qquad \text{Eq(vi)}$$

Here, absorbance is denoted by A, cyanidin-3-O-glucoside's molecular weight (449.2 g/mol), dilution factor R, molar extinction coefficient (26900 L/(mol.cm)) for cyanidin- 3-O-glucoside, and route length are represented by l and ϵ, respectively. The final results were given as cyanidin-3-O-glucoside equivalents in milligrams per gram of dry matter (DM) [95]. Ivankovic *et al.*, (2024) performed extraction using maceration process from berries pomace and reported anthocyanin content present in the blackberry, raspberry, strawberry, and chokeberry as 0.32, 0.09, 0.26, 0.68 cyanidin-3-O-glucoside equivalents in milligrams per gram of dry matter (DM) respectively. Excessive maceration can lead to anthocyanin degradation due to enzymatic activity or exposure to light and oxygen. Water-based solutions with mild acidity are often preferred as they effectively extract anthocyanins while minimizing degradation [114].

SUMMARY AND OUTLOOK

Throughout this review, an overview of the current status of fruit waste generation and valorization has been presented. Discarded fruit parts hold immense potential. They're packed with nutrients, functionality, and nutraceutical properties, making them ideal for various applications in food design. This approach can address economic, social, and environmental issues. To minimize natural resource depletion, environmental harm, and potential threats to food security, rigorous research is crucial in the realm of fruit waste valorization. These fruit residues can be directly incorporated into food products or used to extract valuable components like proteins, lipids, vitamins, and antioxidants. Additional biomolecules can be isolated using physical or chemical methods to create functional and nutritious food ingredients. Maintaining the safety and quality of biomaterials derived from fruit waste is crucial. Drying techniques are essential to prevent microbial growth and ensure the physicochemical and microbiological stability of these materials. We can delve deeper into the potential of emerging valorization techniques like microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), pulsed-electric field-assisted extraction (PEF), and supercritical CO_2 extraction by employing various optimization methods. The development of a bio-refinery concept for the recovery of value-added products from fruit waste has big opportunities over the landfilling and incineration methods of disposal. Researchers are finding success with solvents like ionic liquids and hydrotropes. Government support is needed to establish infrastructure and technologies for utilizing food waste and byproducts effectively in production and storage facilities. Further research is needed to develop new functional food formulations that are high-quality and appealing to consumers. Industries should explore ways to valorize their fruit waste byproducts by integrating them into novel products. This might involve redesigning processing steps to reincorporate waste streams into the original food product on an industrial scale. It's important to address other potential risks, such as the presence of toxins or antinutrients, in these materials. These solvents not only improve the overall yield of bioactive compounds but they are also considered Generally Recognized as Safe (GRAS) for consumption due to their low toxicity. Increased public funding for research and development (R&D) can lead to breakthroughs in several areas. (a) Food production: Techniques like vertical farming or drought-resistant crops could increase food yields and improve nutrition. (b) Food processing: Innovations in food preservation and fortification could extend shelf life, reduce waste, and ensure essential vitamins and minerals reach consumers. (c) Distribution: Investments in infrastructure and logistics could connect remote areas to fresh produce markets and incentivize the sale of healthy options in underserved communities. (d) Consumer behavior: Research into food preferences and marketing strategies could nudge people towards healthier choices without sacrificing taste or convenience. By tackling these challenges, a future is created where healthy eating is an accessible and affordable option for everyone.

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Investigation on mechanical properties of surface treated jute-basalt fiber reinforced hybrid epoxy composites: a review

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Globally, accommodating and utilizing electronic plastic waste is one of the major challenges and it is not easy to use due to its non-biodegradability nature. Green polymer composites came to existence to overcome the issue of minimizing plastic waste. So, this study delves into enhancing the mechanical properties of jute-basalt fiber-reinforced hybrid epoxy composites through surface treatment methods, considering the eco-friendly nature of natural fibers. Natural fibers, such as jute, possess inherent sustainability due to their renewable sources, biodegradability, and low environmental impact compared to synthetic alternatives. The investigation arises from the demand for sustainable materials with superior performance in engineering applications. The focus is on optimizing interfacial bonding between fibers and the epoxy matrix to improve overall mechanical performance. Experimental studies assess the impact of different treatments and fiber compositions on mechanical properties such as tensile strength, flexural strength, and impact resistance. Ultimately, this research aims to advance the development of sustainable, high-performance composite materials by clarifying the relationship between surface treatments, fiber composition, and mechanical properties in jute-basalt fiber-reinforced hybrid epoxy composites.

Keywords: Jute fiber, basalt fiber, surface treatment, hybrid epoxy composites, mechanical properties, natural fibers.

INTRODUCTION

Recently, there has been a growing interest in sustainable and biodegradable natural fiber-reinforced composites (FRC) because of their lower environmental impact [1].

Plant-based fibers have several benefits, including favorable thermo-physical properties such as low density, improved thermal conductivity, and effective insulation. Additionally, they possess many benefits like affordability, biodegradability, and minimal energy requirements during material processing.

Natural fiber composites (NFCs) are emerging as promising alternatives to synthetic fiber-reinforced composites in various applications. Technological advancements have enabled the incorporation of jute fiber with synthetic polymers and resins, offering a cost-effective substitute for purposes requiring less load-bearing and expensive synthetic fibers. A few advantages of natural fibers include their reasonable specific strength, affordability, low density, great toughness, and favorable thermal characteristics. Their increased specific strength and stiffness are the results of their low specific weight compared to synthetic fibers like carbon, aramid, and glass. Additionally, they are less abrasive to processing tools and are safe for humans and the environment. However, the mechanical properties of natural fibers are influenced by factors such as moisture content, cultivation area, and processing methods, and they generally exhibit poor thermal stability. Despite these limitations, combining natural fibers with biodegradable matrices creates environmentally friendly 'green' products that fulfill current societal demands. Typically, these composites use biodegradable polymers as the matrix phase and natural fibers for reinforcement. Among lignocellulosic fibers, jute fiber is notable for its high specific strength and modulus, making it particularly effective in enhancing composites. Natural fibers have found applications as strengthening components in the aerospace and automobile sectors, where their high strength-to-weight ratio, renewable nature, and reduced environmental impact make them an attractive alternative to traditional synthetic materials. Furthermore, their use in these industries not only enhances fuel efficiency and reduces emissions but also promotes sustainability and aligns with increasing regulatory and consumer demands for eco-friendly solutions.[2-3].

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Despite several drawbacks such as poor adhesion and leakage, chemical treatments enhanced the mechanical characteristics of polymer composites reinforced with jute fiber (JFRPC). The study highlights the positive effect of chemical treatments on JFRPC, resulting in enhanced mechanical properties in comparison to composites without treatment. These treatments typically involve the use of agents such as alkali, silane, or other coupling agents, which modify the fiber surface and improve the interfacial bonding between the jute fibers and the polymer matrix. Consequently, treated JFRPC exhibits superior tensile strength, flexural strength, and impact resistance, making it a more viable option for high-performance applications in various industries [4].

1. In composite materials, the matrix plays a crucial role as a binding agent, facilitating the transfer of fiber stiffness. However, weak adhesion between the matrix and fibers can lead to undesirable properties, making the composite vulnerable to environmental factors and reducing its lifespan. Therefore, researchers focus on enhancing fiber-matrix adhesion through physical treatments or chemical treatments to improve overall performance. Physical treatments may include methods such as plasma treatment, corona discharge, or ultraviolet irradiation, which modify the fiber surface to increase its roughness and reactivity. Chemical treatments, on the other hand, involve the application of coupling agents, such as silanes, or the use of surface modifiers, such as alkalis or acetylation, to introduce functional groups that enhance bonding at the interface. These enhancements not only improve mechanical properties like tensile and shear strength but also enhance the composite's resistance to moisture, thermal variations, and other environmental stressors. By optimizing the fiber-matrix interface, researchers aim to develop composites with superior durability, reliability, and performance for applications in demanding fields such as aerospace, automotive, and construction [5].

Natural fibers offer numerous advantages, such as low cost and eco-friendliness, which make them a better alternative to synthetic fibers in various applications. These fibers, sourced from plants, animals, or minerals, are renewable and biodegradable, significantly reducing environmental impact compared to their synthetic counterparts. Additionally, natural fibers often exhibit excellent mechanical properties, such as high specific strength and stiffness, which can be advantageous in load-bearing applications. Their inherent biodegradability ensures that they do not contribute to long-term pollution, aligning with the growing global emphasis on sustainability and reducing carbon footprints [6].

Based on where they came from, these fibers might be divided into three categories: plant, animal, and mineral fibers. Natural minerals provide the basis for mineral fibers like asbestos and basalt, which are valued for their exceptional strength and heat resistance in high-temperature and fire-resistant applications [7-8].

Natural fibers excel due to their affordability, lightweight quality, durability in processing, and widespread accessibility. Furthermore, their non-toxic characteristics make them a popular and environmentally friendly choice. The cost-effectiveness of natural fibers stems from their abundance and renewable nature, which ensures a steady supply and lower production costs compared to synthetic fibers. Their lightweight nature contributes to easier handling and transportation, as well as improved energy efficiency in applications where weight reduction is crucial, such as in the automotive and aerospace industries [8].

Figure 1 depicts the categorization of natural fibers.

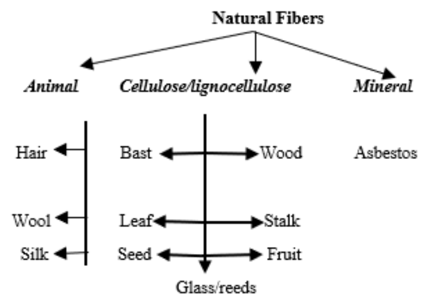

Fig. 1. Classification of natural fibers (Open assess) [9]

Jute fibers are eco-friendly since they are fully recyclable and biodegradable. They have a moderate moisture absorption capacity, provide good thermal and acoustic insulation, and do not irritate the skin. Nowadays, 3.2 million tons of jute fiber are produced annually across the world and are utilized in many different applications [10].

Jute is a bast fiber extracted from the inner part of the plant and holds significant importance as a natural fiber on a global scale. Predominantly produced in countries such as Bangladesh, India, China, Nepal, and Thailand, these nations collectively account for 95% of the world's jute fiber production. Jute fibers exhibit varied chemical properties based on their type, with cellulose, hemicelluloses, lignin, pectin, wax, and moisture being their main constituents. The fiber and the matrix in the composite structure don't stick together well because cellulose, hemicellulose, and lignin lead to poor interfacial adhesion between the fiber and matrix. Therefore, chemical treatments are the most effective method to improve how well dissimilar materials stick together and make them stronger [11]. This makes the material not as strong as it could be due to the presence of chemical constituents in the untreated jute fiber. Kokot [12] found that sodium hydroxide (NaOH) treatment is used to clean and purify cellulose, removing both natural and artificial impurities. This process also enhances the amount of crystalline cellulose and gives the material a textured (rough) surface. The original crystal structure of cellulose I is transformed into cellulose II during this treatment.

Mukherjee [13] delved into an in-depth exploration of jute fiber mechanical properties in their research, revealing significant insights into the effects of alkali treatment on their tensile characteristics. Their investigation focused on a targeted treatment methodology aimed at eliminating hemicelluloses and/or lignin from the fibers, thereby altering their inherent composition and structure. Through meticulous experimentation and analysis, they elucidated the profound influence of this treatment process on the tensile properties of jute fibers, uncovering key correlations between treatment parameters and mechanical performance. This comprehensive understanding of the interplay between chemical treatment and mechanical behavior not only advances fundamental knowledge in the field but also holds immense potential for informing the development of tailored treatment protocols to optimize jute fiber properties for various applications. Mukherjee *et al.*'s research thus represents a pivotal contribution to the broader body of knowledge surrounding natural fiber mechanics, offering valuable insights that can catalyze advancements in material science and engineering.

Gassan [14] recently conducted a study focusing on the fatigue behavior of epoxy composites reinforced with untreated and alkali-treated jute. Through an incremental loading approach, the researchers measured the dynamic modulus, strength, and specific damping capacity of the composites.

The findings from the study unveiled a significant trend: the utilization of treated fibers and a higher fiber content displayed a correlation with reduced fatigue resistance. Specifically, the investigation focused on key mechanical parameters of jute fabrics, including tensile strength, flexural strength, and interlaminar shear strength, to evaluate the effects of oligomeric siloxane treatment. These parameters served as critical indicators in assessing the efficacy of the treatment and its impact on the overall mechanical performance of the jute fabrics [15].

Khondker [16] conducted a study that demonstrated that composites comprising jute and polypropylene (PP), integrating specially treated jute yarns, showcased notable enhancements in tensile and bending properties. The incorporation of these treated jute yarns resulted in substantial improvements, with both strength and modulus experiencing approximate increases of 14% and 10%, respectively. These findings underscore the effectiveness of treating jute yarns in enhancing the mechanical properties of jute-PP composites, thereby suggesting a promising avenue for reinforcing such materials.

Gupta [4] presents a method to enhance mechanical properties by doing chemical treatments of jute fiber as opposed to untreated jute fiber.

With an average annual growth rate of 30%, the basalt fiber composite materials industry in China is growing quickly. China's rapidly developing society needs high-performance, low-cost fiber with independent intellectual property rights. Applications for basalt fiber are numerous and include aircraft, architecture, the chemical industry, medicine, electronics, and agriculture. It is a material that finds usage in both military and civilian contexts [17].

The rapid pace of technological advancement has always pushed the limits of engineering materials. Over the past century, the development of new materials has accelerated to keep up with the changing demands in construction, transportation, and other fields. To achieve superior performance from existing materials, engineers have created combinations of different materials that together exhibit enhanced properties compared to their components. Modern technologies often require materials with unique combinations of properties that traditional metals, ceramics, and polymers cannot provide. This is particularly true for materials needed in construction and transportation. Composites have emerged as viable alternatives to metal alloys in various applications, including construction, automotive, marine, aerospace, and sports equipment. These composites are made by combining different materials to achieve performance levels that no single material could achieve on its own. Today, most materials are not used in their pure form because no single material possesses all the necessary properties. The concept of composite materials is not new, the use of composites dates back to ancient times. Even the human body can be considered a composite, composed of bones and flesh. Basalt fiber, derived from solidified volcanic lava, is renowned for its exceptional strength and high-performance characteristics. Utilizing advanced manufacturing techniques, basalt fibers (BFs) are produced by melting basalt rocks at high temperatures and then extruding the molten material into thin fibers. These fibers exhibit remarkable mechanical properties, including high tensile strength, resistance to corrosion, and thermal stability [18].

Basalt fiber production mirrors the process used for making glass fibers, commencing with the extraction of basalt from quarries, followed by crushing and thorough cleaning. At a scorching temperature of 1500°C, the basalt undergoes melting, transforming into a molten state. This liquefied material is then extruded through minuscule apertures to create continuous strands of basalt fiber. These fibers boast superior mechanical properties, particularly heightened tensile strength, rendering them highly desirable for various applications. Notably, manufacturing basalt fiber proves to be more economically viable compared to producing glass fibers. Moreover, the energy consumption during production is relatively moderate, averaging around 5 kilowatt-hours per kilogram of material. This eco-friendly aspect further contributes to the appeal of basalt fibers as a sustainable alternative in the composite materials industry [19].

Basalt fibers, derived from natural basalt, offer unparalleled strength and reliability, ideal for crafting robust structures. Originating from rocks infused with various minerals such as sodium, potassium, magnesium, calcium, and iron, basalt fibers inherit a diverse array of properties. Within these fibers lie resilient bundles, comprised of sturdy threads and fabrics, enhancing their durability. This strength renders basalt fibers indispensable for creating a diverse array of cost-effective structural components. Whether used in construction, aerospace, automotive, or marine applications, these fibers serve as the backbone of modern engineering, ensuring longevity and performance in a multitude of scenarios [20].

Lee [21] evaluated the weight retention and tensile strength retention of basalt fiber in alkaline solutions as well as its chemical stability. They saw differences in the distribution of weights that were impacted by the different alkaline conditions that were investigated. In the early phases of immersion, there was a noticeable decrease in tensile strength regardless of the alkaline solution utilized. It's interesting to see that basalt fibers retained significantly more weight in a 0.4% NaOH solution than in a 10% NaOH solution. In conditions where cement hydrates, basalt fiber demonstrated superior weight retention compared to glass fiber and exhibited greater stability under alkaline conditions. This suggests that basalt fiber may offer advantages over glass fiber in terms of durability and performance in applications where exposure to alkaline environments is a concern. The findings underscore the potential of basalt fiber as a reinforcement material in construction and other industries where chemical stability and strength retention are paramount. Further research could delve deeper into understanding the mechanisms underlying the observed differences in stability and performance between basalt and glass fibers, informing more efficient and sustainable material choices in various engineering applications.

Qin [22] conducted a comprehensive study investigating the influence of various lengths (6 mm, 9 mm, and 15 mm) and proportions (ranging from 3% to 10%) of basalt fibers on the properties of asphalt mastics. Their research revealed a notable enhancement in the characteristics of asphalt mastics upon the inclusion of basalt fibers, particularly in terms of crack resistance. Remarkably, among the different fiber lengths examined, the 6 mm basalt fibers exhibited superior performance in both asphalt adsorption and strength. This superiority was attributed to their ability to establish a more extensive contact area with the asphalt mastic compared to the longer 9 mm or 15 mm fibers. The study highlighted the significant role played by the number of fibers and their adsorption characteristics in influencing the high-temperature rheological properties and crack resistance of the asphalt mastics. This observation underscores the complex interplay between fiber content and asphalt matrix interaction, which ultimately dictates the performance of the composite material. By elucidating these relationships.

John [23] examined how basalt fiber, including chopped fibers, minibars, rebars, and meshes, can be utilized to reinforce concrete. Concrete typically struggles with transmitting tensile loads due to its low strength and flexibility, leading to the formation of faults and the expansion of cracks under strain. The findings of the review revealed that incorporating basalt fiber into concrete, with specific characteristics such as a length ranging from 6 to 36 mm, diameter between 10 and 25 µm, and a maximum volume percentage of approximately 2%, can significantly enhance the strength performance of the concrete.

The objective of this review is to give insight into the basics of jute and basalt fiber, its structure, its constituents, and its chemical, physical, and mechanical properties. This study also provides information about the various surface treatments used on the fibers and their effects on the mechanical properties. The purpose of the surface treatments is to remove the hemicellulose and lignin for better interfacial bonding between the fiber and the matrix. It also gives an insight into the various methods used to develop the jute/basalt-reinforced hybrid composites.

Chemical properties of jute and basalt fibers

Fibers possess distinct compositions and exhibit varying chemical properties, influencing their utility in different applications. Jute fibers, for instance, are prized for their biodegradability and eco-friendliness, whereas basalt fibers are celebrated for their exceptional resistance to high temperatures and superior mechanical attributes.

Jute fiber consists of various constituents such as cellulose, hemicellulose, lignin, pectin, wax, etc. and Figure 2 illustrates a perspective of jute fabric, showcasing its texture and weave pattern. In jute fiber, the major content is cellulose (45-73%), hemicellulose (12-24%), lignin (5-26%), and others mentioned in Table 1. To improve the adhesion between jute fiber and matrix constituents like hemi-cellulose, lignin, and pectin need to be removed or modified so that hindering can avoid the interaction of jute fiber and matrix. Thus, alkaline treatment is a common method to remove these constituents, and this promotes better interfacial bonding.

To improve the adhesion between jute fibers and the matrix in composite materials, it is essential to modify or remove certain constituents like hemi-cellulose, lignin, and pectin. These components can interfere with the bonding process, leading to weaker composites. One effective method to enhance fiber-matrix adhesion is alkaline treatment, which involves immersing jute fibers in an alkaline solution. This treatment removes impurities and increases surface roughness, thereby promoting better interfacial bonding and enhancing the overall strength of the composite.

Basalt fibers, in contrast, are composed mainly of silica (SiO_2: 43-60%), alumina (Al_2O_3: 11-20%), calcium oxide (CaO: 5-15%), magnesium oxide (MgO: 1.3-16%), and iron oxide (Fe_2O_3: 4.02-16%), along with other minor constituents (Table 2). The high silica content endows basalt fibers with excellent thermal stability, enabling them to withstand extreme temperatures. Alumina and iron oxide enhance the mechanical strength, while calcium oxide and magnesium oxide contribute to the chemical resistance and overall durability of the fibers. Figure 3 provides a visual representation of basalt fabric, showcasing its dense weave and robust texture, which are critical for applications requiring high mechanical strength and thermal stability.

The combination of jute and basalt fibers into a hybrid composite material leverages the unique advantages of each fiber. Jute contributes to the composite's lightweight and sustainable nature, while basalt offers robustness and thermal resistance. This synergy results in a composite material that is not only strong but also environmentally friendly, suitable for applications across various industries such as automotive, aerospace, construction, and sports equipment.

The integration process involves customizing fiber orientation, volume fraction, and matrix composition to optimize the properties for specific applications. Current fabrication techniques for bio-composites, such as pultrusion, hand lay-up, spray lay-up, resin transfer molding, compression molding, extrusion, injection molding, and filament winding, offer diverse benefits in terms of processing efficiency, material properties, and cost-effectiveness. For example, compression molding, depicted in Figure 4, is highly valued for producing high-strength parts with excellent surface finish, while filament winding is ideal for manufacturing strong, hollow, cylindrical structures.

Fig. 2. Jute Fabric

Fig. 3. Basalt Fabric

Future research may focus on developing more sustainable resins, utilizing recycled fibers, and optimizing fiber-matrix interfaces. Such innovations will promote the broader adoption of these composites, supporting a more sustainable future in material design and engineering.

Table 1. Chemical constituents of jute fiber

Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Wax (%)	Pectin (%)	Moisture (%)	Ref.
45-71.5	13.6-21	12-26	-	-	-	[24]
58-64	18-24	15.75	0.4-0.8	0.2-0.5	-	[25]
61-73	13.6-23	12-16	-	-	-	[26]
61-63	13.0	5-13	-	-	-	[27]
64.4	12	11.8	0.5	0.2	1.1	[4]
60-72	12-24	11-24	0.5	0.2	-	[11]
61-71.5	12-13	13.6-20.4	0.5	0.2	12.6	[1]
71.5	13.4	13.1	0.6	0.2	-	[28]

Table 2. Chemical constituents of basalt fiber

Key constituents	Composition (%)					
	[29]	[30]	[31]	[32]	[33]	[34]
SiO_2	48.8-51	52.8	43-58	45-60	51.56	56.81
Al_2O_3	14-15.6	17.5	11-20	12-19	18.24	16.89
CaO	7-11	8.59	7-13	6-15	5.15	9.68
MgO	6.2-16	4.63	4-12	3-7	1.30	2.40
Na_2O+ K_2O	1.9-2.2	-	-	2.5-6	-	-
Na_2O	-	3.34	-	-	6.36	-
Fe_2O_3+FeO	7.3-13	-	-	7-18	-	-
Fe_2O_3	-	10.3	8-16	-	4.02	10.77
TiO_2	0.9-1.6	1.38	-	0.9-2	1.23	-
P_2O_5	-	0.28	-	-	-	-
Cr_2O_3	-	0.06	-	-	-	-

Table 3. Physical properties of jute fiber

Properties	Values					
	[35]	[36]	[37]	[38]	[39]	[40]
Diameter (μm)	5-25	20-200	25-30	20-200	-	90-115
Density (g/cm^3)	1.23	1.3-1.45	-	1.3-1.49	1.46	1.5
Length (mm)	0.8-6	-	120	1.5-120	1.5-5	-
Moisture content (%)	-	-	-	12.5-13.7	12	-
Areal density (g/m^2)	-	-	-	-	-	-

Table 4. Physical properties of basalt fiber

Properties	Values			
	[41]	[42]	[17]	[33]
Moisture content (%)	0.15	-	-	-
Density (g/cm^3)	2.64	-	2.65-3.05	2.733
Diameter (mm)	0.0166	-	-	0.01025
Areal density (g/m^2)	-	300	-	-

PHYSICAL PROPERTIES OF JUTE AND BASALT FIBER

Jute is a natural plant fiber widely recognized for its environmentally friendly characteristics, making it a viable alternative to synthetic fibers [34]. The diameter of jute fibers generally spans from 5 to 200 micrometers, and its density typically varies between 1.23 and 1.5 grams per cubic centimeter. Additionally, the moisture content of jute fibers usually falls within the range of 12 to 13.7%, as indicated in Table 3.

Jute, often hailed for its sustainability, serves as an eco-friendly substitute for man-made fibers due to its biodegradability and renewable nature. This plant-based fiber generally features diameters ranging from 5 micrometers at the finer end to as much as 200 micrometers at the coarser end. The density of jute fibers, which influences their weight and strength, is typically observed to be between 1.23 and 1.5 grams per cubic centimeter. Moreover, these fibers possess a moisture content that usually lies between 12 and 13.7%, providing a balance between flexibility and durability, as detailed in Table 3.

Basalt, derived from volcanic rock, is highly esteemed for its remarkable heat resistance. This natural material forms the basis for basalt fibers, which are noted for their exceptional tensile strength, surpassing that of E-glass fibers. Furthermore, basalt fibers exhibit a robust resistance to chemical degradation, outperforming carbon fibers in this regard. Table 4 provides an in-depth look at the physical properties of basalt fibers, including their moisture content, density, and diameter. Basalt, a product of volcanic activity, is celebrated for its outstanding thermal resistance, making it an ideal candidate for high-temperature applications. The fibers produced from basalt rock are particularly notable for their impressive tensile strength, which is significantly higher than that of traditional E-glass fibers. In addition to their mechanical strength, basalt fibers also offer superior resistance to chemical corrosion when compared to carbon fibers, making them highly durable in harsh chemical environments. The detailed physical properties of these fibers, such as moisture content, density, and diameter, are comprehensively outlined in Table 4.

DEVELOPMENT OF JUTE/BASALT EPOXY COMPOSITES

Jute and basalt epoxy-reinforced composites represent a frontier in material science, combining high performance with distinctive properties. Researchers have developed these composites by integrating natural jute fibers and basalt fibers with epoxy resin, achieving a balance between mechanical strength and sustainability. Jute fibers, known for their biodegradability and low cost, pair excellently with basalt fibers, which are prized for their superior mechanical properties and thermal stability. The result is a composite with an impressive strength-to-weight ratio, enhancing material performance while reducing the environmental footprint. The development of these reinforced composites signifies a crucial advancement towards creating environmentally friendly materials suitable for diverse industrial applications. These composites are particularly valuable in sectors such as automotive, aerospace, construction, and sports equipment, where there is a growing demand for materials that are lightweight, durable, and sustainable. The adaptability of these composites allows for customization in fiber orientation, volume fraction, and matrix composition, enabling precise optimization for specific use cases [43].

Currently, bio-composites are manufactured using a variety of techniques traditionally used for synthetic composites. These techniques include the pultrusion method, hand lay-up, spray lay-up, resin transfer molding, compression molding, extrusion, injection molding, and filament winding. There are distinct advantages to each of these methods in terms of processing effectiveness, material properties, and cost-effectiveness. For example, compression molding is renowned for producing high-strength components with excellent surface finishes, while filament winding is ideal for creating robust, hollow, cylindrical structures.

Table 5 outlines the fabrication methods used for hybrid composites, demonstrating the flexibility and adaptability of these processes to handle different material combinations and design requirements. Figure 4 depicts compression molding machines, which are frequently used in the production of reinforced composites. These machines apply heat and pressure to mold and cure the composite material, ensuring uniformity and high structural integrity.

Fig. 4. Compression molding machine

Table 5. Fabrication methods to develop jute/basalt composites.

Matrix	Reinforcement	Process	Outcomes	Ref.
Epoxy	Jute epoxy (treated with 20% NaOH)	Compression molding technique	Reports indicate that jute treated with sodium hydroxide exhibited enhanced mechanical properties compared to untreated jute, with a tensile strength of 97 MPa and flexural strength of 80 MPa.	[44]
Epoxy	Jute/basalt reinforced hybrid epoxy composites	Hybrid composite laminates are prepared using the hand lay-up process	The results indicate that the composite's tensile strength, bending resistance, in-plane shear strength, and bearing capacity were all improved by hybridizing jute and basalt fibers.	[45]
Epoxy	Jute/basalt hybrid epoxy composites	Vacuum-assisted resin infusion	The study findings indicate that jute/basalt hybrid laminates exhibited superior impact energy absorption and flexural properties compared to laminates made solely of jute fibers. These hybrid laminates also showed greater resistance to aging over time. Moreover, the results suggest that jute/basalt hybrid laminates, Particularly, hybrid laminates having a sandwich-like structure showed better aging endurance than hybrid laminates with an intercalated configuration.	[42]
Polyester	Jute/glass fiber reinforced polyester	Pultrusion	The research examined how a hybrid composite made of polyester, jute, and glass fibers interacts with water. It was discovered that integrating glass fibers into the composite increased its ability to resist water absorption and exposure to moisture led to a significant decline in the flexural and tensile properties of the hybrid composites due to water absorption.	[46]
PLA (Polylactic acid)	Green composites reinforced with jute fiber and polylactide	Injection molding	The results indicate that using well-combined pellets in the injection molding process can improve the produced composites' tensile strength and Young's modulus.	[47-49]
PBS (Polybutylene Succinate)	Basalt fiber reinforced with PBS	Injection molding method	Since more basalt fibers work synergistically to improve the tensile and flexural characteristics of the PBS matrix, the tensile strength of the matrix increases from 31 to 46 MPa, while the flexural strength increases from 18 to 71 MPa.	[50]
Epoxy	Basalt epoxy contains tourmaline micro/nano particles (0.5-2 wt%)	Resin transfer molding with vacuum technique	While the tensile and flexural modulus exhibited increases of 27% and 153%, respectively, the tensile and flexural strength rose by 16%.	[51]

PLA (Polylactic acid)	Basalt fiber/polylactic acid composite	Plasma polymerization is used in hot press compression molding and air pressure glow discharge (APGD) to modify the surface of basalt fiber.	The study revealed that the composite showed a 45% increase in strength and an 18% increase in modulus compared to the untreated composite. The most effective plasma polymerization treatment for basalt fibers was found to be at a plasma exposure time of 4.5 min.	[52-53]

SURFACE TREATMENT OF FIBER

a) *Alkaline treatment.* This treatment alters the surface chemistry of the fibers by eliminating impurities, waxes, and hemicelluloses, resulting in increased surface roughness and enhanced fiber-matrix adhesion. The primary objective of the alkaline treatment was to mitigate the hydrophilicity of the jute fibers. Prior research indicated that alkaline treatment not only decreases hydrophilicity but also enhances the wettability of epoxy with jute fibers. In this study, the jute fibers underwent immersion in a 5% NaOH solution for 2 hours at a temperature of 25°C. This treatment process is a well-established method for modifying the surface characteristics of natural fibers, promoting better adhesion and compatibility with polymer matrices such as epoxy. By reducing the hydrophilicity and enhancing wettability, the alkaline treatment lays the groundwork for improving the overall performance and mechanical properties of jute-based composite materials [54].

The most used chemical modification process for jute fibers is alkaline treatment. Sodium hydroxide, or NaOH, is a popular alkaline treatment for jute fiber. Alkali is used to treat jute fiber to eliminate non-cellulosic materials including hemicellulose, lignin, wax, and oils from its exterior. Jute fibers treated with alkali lose their moisture-associated hydroxyl groups, which reduces their hydrophilicity. Water molecules are created when NaOH interacts with jute fiber, and Na-O joins forces with the fiber's cell wall to produce fiber-cell-O-Na groups. Fiber-cell-OH + NaOH = Fiber-cell-O-Na + H2O + pollutants.

Alkalization is a basic surface treatment for natural fibers, involving sodium hydroxide. This process alters cellulose's structure, producing short crystallites. When cellulose is placed in a solution containing alkali metal hydroxide, it transforms from cellulose I to cellulose II. Water is created when the OH- of NaOH and the H+ of cellulose mix, forming Cell-O-Na+. Alkalization removes impurities from jute fibers' surfaces. It has been used aqueous NaOH for different periods, followed by washing and neutralizing with dilute acetic acid. Used an ultrasonication bath, oven-drying for 24 hours, and ultrasonicated with aqueous NaOH for 1 hour. Alkalization improves the mechanical properties of fiber-reinforced composites, including impact strength, fatigue, compressive strength, flexural strength, and dynamic behaviors [55]. Jute fiber is used to chemically treat to enhance the interfacial bonding between fiber and hydrophobic matrices. The common method used is alkali to do surface modification of natural fibers and jute fiber is treated with 0.5, 4, and 25 wt.% of NaOH solution at ambient temperature for 24 hours, 30 min, and 20 min respectively, and it been found that jute fiber treated with 0.5 wt.% NaOH is an efficient way to optimize the mechanical properties of natural fiber-reinforced composites [56].

b) *Alkali-bleaching.* The effects of hydrogen peroxide bleaching and alkali treatment on the tensile properties of short jute fiber composites have been investigated. For the composites, different weights of treated and untreated jute fiber were mixed with the PLA matrix. The tensile strength and modulus of the composites treated with 10% NaOH and bleached with H_2O_2 were found to be 7.5% and 40% higher, respectively, than those of the untreated composites. Climate, age, and digestion all influence the structure and chemical composition of jute fibers. They are made up of 60% cellulose, 12% lignin, pectin, moisture, and ash content. They also withstand air temperatures of up to 100°C without degrading [55]. Alkali bleaching plays a crucial role in enhancing the quality and performance of jute fibers for various applications, including composite materials, by refining the fiber surface and removing undesirable components.

c) *Silane and alkali-silane treatment.* Silane treatment, utilizing reactive silane molecules, plays a crucial role in enhancing the bonding between fibers and polymers in composite materials. Specifically, alkali-silane treatment intensifies the reactivity with the fiber surface, resulting in superior bonding. Both silane treatments contribute to improving interfacial adhesion, consequently strengthening the composite's overall performance, durability, and strength. This heightened bonding between fibers and the polymer matrix not only enhances mechanical properties but also reinforces the material's ability to withstand environmental stresses, making it an indispensable technique in composite material fabrication.

Silane molecules have special parts on both ends that work together to build a bridge: one end connects with the water-loving parts of the jute fiber, and the other end connects with the water-repelling parts of the polymer matrix [56]. When natural fibers are treated with silane, it reacts with the fibers' surface to create stronger bonds. This happens when silane molecules hydrolyze and form silanol groups, which then bond with the hydroxyl groups on the fiber surface. These bonds can be either covalent or hydrogen. Common types of silanes used include alkyl, amino, meth acryl, and glycidoxy. Silane treatment enhances the strength of fibers and increases their resistance to water, especially when there is a strong bond between the silane and the matrix [57].

In this study, a silane solution was mixed with methanol and stirred for 5 minutes. The fibers were then soaked in this solution for 60 minutes to ensure thorough infiltration and surface treatment. After soaking, the fibers were meticulously rinsed with distilled water to remove any residual chemicals and impurities, ensuring that the silane coating adhered uniformly to the fiber surface. The treated fibers were then left to dry for 12 hours in a controlled environment to allow complete evaporation of any remaining solvent and to enable the formation of a strong chemical bond between the silane and the fiber surface [58].

In another experiment, fibers were submerged in a 0.5 wt% silane solution for 1 min and then kept at 50°C for 4 h. A solvent was prepared by dissolving a liquid siloxane solution, and the jute fabrics were treated with an alkaline solution and sonicated to enhance surface reactivity. The fabrics were then immersed in the siloxane solution for 1 h to ensure thorough treatment. Following this, the treated fabrics were dried at 60°C for 24 h to ensure complete curing and stabilization of the chemical treatment, enhancing their mechanical properties and adhesion characteristics [59].

The study concludes that silane treatment of alkalized jute fiber can increase specific tensile strength due to the effective interaction between silane and hydroxyl groups on the fiber surface.

d) *Hydroxybenzene diazonium salt treatment.* Typically, treatments of jute fiber are conducted to modify the surface properties, with one such treatment involving the use of benzene diazonium salts. Jute fibers were immersed in a 5% NaOH solution for 10 minutes in an ice bath. Then, a cooled solution of o-hydroxy benzene diazonium chloride was added and stirred for 10 minutes. The fibers are then washed with soap solution and water, followed by drying. Similar treatments were done using m-hydroxy benzene diazonium chloride and p-hydroxy benzene diazonium chloride in both alkaline and acidic conditions. It has been found that treated jute fibers showed decreased tensile strength, tenacity, and moisture absorption compared to untreated fibers. Among treatments using ortho, meta, and para hydroxy benzene diazonium salts, the highest tensile strength and tenacity were observed with o-hydroxy benzene diazonium salts, followed by m-hydroxy benzene diazonium salts, and then p-hydroxy benzene diazonium salts [60].

e) *Plasma and alkali-plasma treatment.* Plasma treatment and alkali-plasma treatment are advance. ed techniques used to modify the surface of natural fibers like jute, enhancing adhesion with the matrix. Sever [61] conducted a study on jute fiber/high-density polyethylene (HDPE) composites, focusing on enhancing the properties of jute fabrics through surface treatment with oxygen plasma. Both low-frequency (LF) and radiofrequency (RF) plasma systems were utilized, with plasma power adjusted to 30, 60, and 90 W for 15 min. X-ray photoelectron spectroscopy (XPS) analysis was employed to assess the impact of oxygen plasma treatment on the functional groups of jute fibers. Another study investigated the improvement of jute fiber quality through treatment with plasma generated from helium and acrylic acid. Treatment duration varied from 30 s to 120 s at a plasma power of 3 kV and 20 kHz. Additionally, alkali treatment using different NaOH concentrations (3%, 5%, and 7% w/w%) was applied to the jute fibers. Composite materials were created by combining 20% jute with 80% polylactic acid (PLA) in the injection molding process. Comparative analysis revealed that plasma-treated jute/PLA composites exhibited superior mechanical properties compared to untreated or alkali-treated counterparts. Specifically, the plasma-treated jute/PLA composite demonstrated significant enhancements, including a 28% increase in tensile strength, a 17% increase in Young's modulus, and a 20% increase in flexural strength, highlighting the beneficial effects of plasma treatment on the mechanical performance of jute/PLA composites [62].

f) *Permanganate treatment.* Permanganate is a chemical compound that contains the permanganate group, represented by the formula MnO_4.In this treatment, alkaline-treated jute fibers are immersed in a 50% permanganate acetone solution for a specified duration, followed by drying at 40°C for 5 hours to eliminate excess solvent and moisture. This permanganate treatment reduced the hydrophilic nature of the jute fibers, resulting in decreased water content in the JFRP (jute fiber reinforced polymer composite [63]. Thus, moisture content was eliminated from the fiber, resulting in increased strength.

g) *Glycine treatment.* Treatment aims to modify the surface properties of the yarns, potentially enhancing their performance in diverse applications. Cotton yarn samples were treated with a 20% w/v glycine solution at a 1:100 yarn-to-liquor ratio and reflux at 100°C for 24 hours with constant stirring. Treatments were conducted at pH 3, 4, 7, and 11, adjusted using sodium hydroxide or hydrochloric acid. Control treatments without glycine were also performed. After treatment, the yarns were washed with deionized water and dried at 50°C overnight. Remadevi [64] Alkali-treated and untreated jute yarns were subjected to treatment with aqueous glycine solutions at various concentrations (5, 10, 15, and 20 g/l) at 100°C and pH 7 for 1.5 h using an infrared lab dyeing machine. Additionally, four pH levels (3, 5, 7, and 11) were tested using 10 g/l aqueous glycine solutions to evaluate their impact on alkali-treated jute yarns. Afterward, all samples were rinsed with distilled water and then dried in an oven at 50°C for a minimum of 5 h. Glycine treatment can affect the characteristics of jute yarns, such as their strength, flexibility, and compatibility with other materials. It was observed that glycine treatment applied to alkali-treated jute yarn resulted in a notable improvement in the packing of fibers within the yarn structure as well as tensile strength and strain properties showing an impressive increase of approximately 105% and 50%, respectively, compared to untreated jute yarns [65].

MECHANICAL PROPERTIES OF JUTE/BASALT COMPOSITES

Natural fibers offer a host of advantages, including impressive mechanical properties, significant specific strength, cost-effectiveness, lightweight composition, biodegradability, and non-abrasiveness. To enhance the mechanical properties of composite materials reinforced with basalt fibers, hybridization with other natural fibers such as jute, kenaf, hemp, and sisal can be employed. Basalt fiber is often preferred for its cost-effectiveness and widespread availability, making it a popular choice in this regard.

Mishra [18] examined a combination of jute and epoxy to create a hybrid composite and discovered that it resulted in stronger flexural, tensile, and impact properties. It was noticed that the composite displayed improved mechanical bonding between the jute fibers and the epoxy matrix, attributed to the effective stress transfer at the fiber-matrix interface. This enhancement in bonding likely resulted from the inherent compatibility between the jute fibers and the epoxy resin, as well as potential surface treatments applied to the fibers to increase adhesion. The study's findings underscore the potential of jute-epoxy hybrid composites in applications requiring high mechanical performance, where the synergy between natural fibers and polymer matrices can be leveraged to produce durable, lightweight, and environmentally friendly materials.

Zamri [67] examined the effects of water absorption on a glass-fiber and jute composite. It was discovered that once the composite absorbed water, its mechanical attributes—such as its flexural and compression strengths—significantly dropped. Therefore, surface treatments of the fiber are necessary to improve the mechanical characteristics of reinforced composites. Researchers combined a substance known as polylactide with 50% jute fiber to create a composite. They applied a 5% solution of a substance known as aqueous NaOH (Sodium hydroxide) to cure it. Because of this treatment, the fiber's surface became rougher, improving the jute fibers' ability to adhere to the polylactide substance. Tensile strength and flexural modulus were enhanced as a result of the rougher surface's higher interfacial adhesion between the jute fibers and the polylactide matrix. Additionally, the hydrophilic nature of the jute fibers was reduced, resulting in decreased water absorption and enhanced dimensional stability of the composite [68].

The jute/epoxy composite was crafted using a hand lay-up technique, followed by treatment with a 20% NaOH solution to enhance the adhesion between the jute fibers and the epoxy matrix. Similarly, a jute/polypropylene composite was formed using the same technique, with the jute fibers treated using a 7% NaOH solution. Investigations revealed that alkaline treatment increased tensile strength and flexural strength, indicating improved interfacial bonding and compatibility between the treated jute fibers and the polymer matrices [44].

Jute fiber is renowned for its lightweight nature and relatively high specific modulus, making it particularly suitable for applications that require both stiffness and strength in composite materials. This natural fiber, derived from the jute plant, is also prized for its biodegradability, renewability, and cost-effectiveness, which contribute significantly to the sustainability of composite materials. Its high specific modulus means that jute fiber provides considerable stiffness per unit weight, an advantage that is crucial in industries like automotive and aerospace where weight reduction is essential for improving fuel efficiency and performance.

In contrast, basalt fibers are celebrated for their exceptional ability to withstand high temperatures and their outstanding mechanical properties. These fibers are produced by melting and extruding basalt rock, resulting in a material that can endure extreme thermal environments, such as those encountered in airplane or car engines.

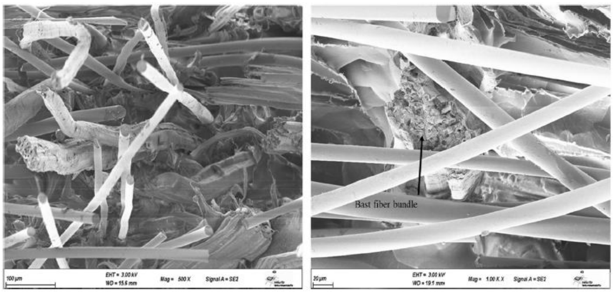

Figure 5. SEM images of PP – hybrid basalt/kenaf composite shows homogeneous distribution of fibers in thermoplastic matrix (Open source) [75]

Basalt fibers exhibit high tensile strength, excellent chemical resistance, and superior thermal stability, making them an ideal choice for reinforcing composites used in demanding conditions. Figure 5 shows the SEM image of PP-hybrid basalt/kenaf composites.

The innovative hybridization of jute and basalt fibers in an epoxy matrix results in a composite material that leverages the unique properties of both fibers. The resulting reinforced epoxy composite benefits from the high-temperature resistance of basalt and the flexibility and lightweight nature of jute fiber. This hybrid composite exhibits a balanced combination of properties that neither fiber could achieve alone. This synergy makes jute-basalt epoxy composites particularly attractive for applications in transportation, construction, and energy sectors, where materials must perform under diverse and challenging conditions.

The mechanical characteristics of jute and basalt fibers, such as tensile strength, Young's modulus, and elongation at the break, are covered in detail in this paper. Various tables offer a thorough summary, showing how the combination of various fibers improves the composite material's performance. A significant factor in the composite's flexibility and capacity for energy absorption is the modest tensile strength and elongation at break that jute fibers generally exhibit. Conversely, basalt fibers have a high Young's modulus and tensile strength, which improve the stiffness and load-bearing capability of the composite.

The fusion of jute and basalt fibers in epoxy composites not only improves mechanical performance but also contributes to sustainability. Jute fibers, being a natural and renewable resource, reduce the overall environmental impact of the composite material. When combined with basalt fibers, which are also derived from natural rock, the composite material supports sustainable development goals by minimizing reliance on synthetic, non-renewable fibers.

Advanced fabrication techniques such as resin transfer molding, compression molding, and filament winding are employed to produce these hybrid composites. Each method offers distinct advantages in processing efficiency and material properties. For instance, resin transfer molding allows for precise control over fiber alignment and resin distribution, resulting in high-quality composites with uniform properties. Compression molding, depicted in Figure 4, is favored for its ability to produce high-strength parts with excellent surface finishes, crucial for structural applications.

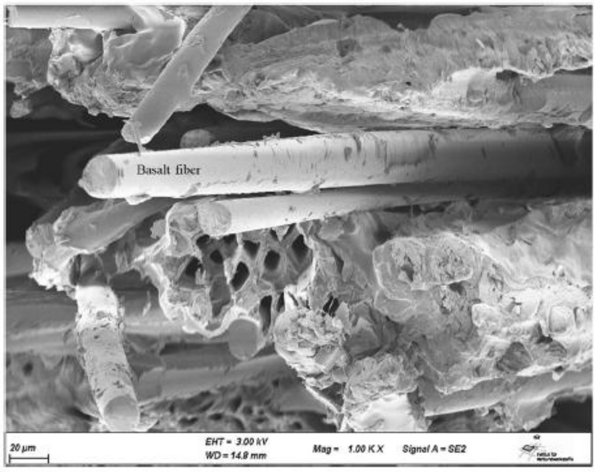

Figure 6. SEM Image of thermoset composite with bast and basalt fibers showing matrix remains on pull out fibers indicating an effective wetting of fibers by matrix (Open source) [75]

The hybrid composite's mechanical properties can be further optimized by fine-tuning the fiber-matrix interface, adjusting fiber volume fractions, and employing novel processing techniques. This level of customization enables the development of composites tailored to specific application requirements, enhancing their performance in real-world conditions. Figure 6 shows the SEM image of bast-basalt/Kenaf Composites. Figure 7 shows the SEM image of basalt composite at 50ºC curing temperature.

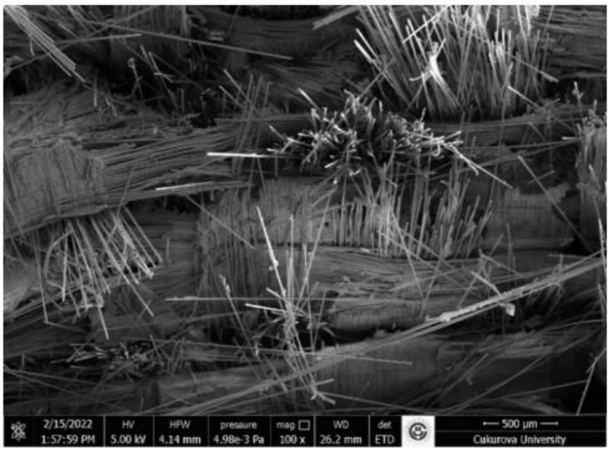

Figure 7. BE composites at 50°C post cure temperature SEM micrograph (Open source) [76].

CONCLUSION

In conclusion, the study underscores the significant potential of natural fibers, particularly jute, in enhancing the mechanical properties of hybrid composites while concurrently promoting environmental sustainability. This investigation has demonstrated that through effective surface treatment techniques, the optimization of the bonding between jute fibers and epoxy matrices can be achieved, which in turn leads to markedly improved mechanical performance of the composites.

The inherent characteristics of jute fibers, such as their high specific strength, low density, and biodegradability, make them an excellent candidate for use in composite materials. These attributes not only contribute to the mechanical enhancement of the composites but also align with the growing demand for sustainable and environmentally friendly materials in various engineering applications. As industries increasingly pivot towards sustainability, the integration of natural fibers like jute into composite manufacturing processes becomes ever more pertinent.

Table 6. Mechanical properties of jute fiber

Properties	Jute fiber							
	[4]	[69]	[41]	[54]	[70]	[39]	[40]	[71]
Tensile strength (MPa)	393-773	450-550	-	290	393-773	400-800	393-773	393-773
Young’s modulus (GPa)	13-26.5	10-32	-	28	26.5	10-30	19.0-26.5	13-26.5
Elongation at break (%)	1.16-1.5	1.1-1.5	1.56	-	1.5-1.8	1.5-1.8	1.16-1.80	1.16-1.5
Compressive strength (MPa)	30	35	40	42	36	39	48	50
Flexural strength (MPa)	110	130	100	140	180	185	190	200
Hardness (Shore D)	30	25	20	27	26	28	30	20
Shear strength (MPa)	20	22	27	29	30	21	22	26
Thermal stability (Decomposes at ºC)	210	200	230	220	210	205	230	230
Poisson’s ratio	0.2	0.3	0.4	0.3	0.2	0.3	0.3	0.4

Table 7. Mechanical properties of basalt fiber

Properties	Basalt fiber		
	[72]	[73]	[74-76]
Tensile strength (MPa)	2900-3100	2800-4800	2200-2500
Young's modulus (GPa)	85-87	86-90	85-100
Ultimate elongation (%)	3.15	-	-
Compressive strength (MPa)	400	500	800
Flexural strength (MPa)	500	800	900
Hardness (Mohs scale)	6-7	-	6-7
Shear strength (MPa)	60	50	100
Thermal stability up to (ºC)	700	800	900
Poisson's ratio	0.2	0.2	0.3

Surface treatment techniques play a crucial role in enhancing the compatibility between jute fibers and epoxy matrices. The research has explored various methods such as chemical treatments, physical treatments, and hybrid treatments. Chemical treatments often involve the use of substances like silane, alkali, or benzoyl peroxide, which modify the fiber surface, thereby improving adhesion to the matrix. These treatments can effectively remove impurities and increase the surface roughness of the fibers, leading to better mechanical interlocking and stress transfer between the fiber and matrix.

On the other hand, physical treatments which are less harmful to the environment, include procedures like plasma treatment, which change the fiber surface without the use of chemicals. Physical treatments increase the wetting qualities of jute fibers by altering their topography and surface energy. This allows the epoxy resin to penetrate the fibers more easily, improving the mechanical properties of the composites.

The study's conclusions demonstrate how significantly the treated jute-epoxy composites' mechanical qualities such as their tensile strength, flexural strength, and impact resistance improved over those of the untreated equivalents. This improvement is directly related to the enhanced stress transfer efficiency at the fiber-matrix interface, which is made possible by the surface treatments' better bonding. These gains are not just slight but significant, suggesting that in some composite applications, surface-treated jute fibers can be a competitive substitute for synthetic fibers.

.Moreover, the environmental benefits of using jute fibers in composite manufacturing cannot be overstated. Jute is a renewable resource that grows abundantly in regions with suitable climatic conditions. Its cultivation requires relatively low inputs of water, fertilizers, and pesticides compared to other fiber crops. Furthermore, jute fibers are biodegradable and pose minimal environmental hazards at the end of their life cycle. By replacing or supplementing synthetic fibers with jute, the overall environmental footprint of composite materials can be significantly reduced.

The integration of jute fibers into composite materials aligns with broader sustainability goals, such as reducing dependence on non-renewable resources and minimizing waste generation. This is particularly relevant in the context of the increasing regulatory and societal pressures to adopt greener manufacturing practices. As industries seek to comply with stricter environmental regulations and meet the sustainability expectations of consumers and stakeholders, the use of natural fibers like jute presents a compelling solution.

Additionally, the adoption of jute fibers in composite manufacturing can have positive socio-economic impacts. Jute cultivation and processing provide livelihoods for millions of farmers and workers, particularly in developing countries. By creating a stable demand for jute fibers, the composite industry can contribute to rural development and poverty alleviation in these regions.

This research underscores the critical importance of integrating sustainable materials into composite manufacturing processes, thereby mitigating environmental impact, and fostering a greener future for engineering applications. By advancing the understanding and application of jute fibers in composites, this study contributes to the broader effort of developing sustainable materials and technologies that can meet the demands of modern engineering while preserving environmental integrity.

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