Bulgarian Chemical Communications, Volume 57, Special Issue B (pp. 45-73) 2025 DOI: 10.34049/bcc.57B.A0009

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

J. Das[1], D. De[1], A. Mittal[1]*, V. Jamwal[1], A. Dhaundiyal[1], G. C. Jeevitha[1], S. Garg[2], M. G. Junior[3], R. Manian[1], V. Tomer[4], N. Rajpal[5]

[1]*School of Biosciences and Technology, Vellore Institute of Technology, Vellore, 630214, Tamil Nadu, India*
[2]*Department of Chemical Engineering, Dr. B. R. Ambedkar National Institute of Technology, Jalandhar, 144011, Punjab, India*
[3]*Department of Electromechanics, Federal Center for Technological Education of Minas Gerais CEFET-MG, 38180510, Araxá, Minas Gerais, Brazil*
[4]*VIT School of Agricultural Innovations and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore, 630214, Tamil Nadu, India*
[5]*Department of Chemical Engineering, MVJ College of Engineering, Bangalore, Karnataka, India*

Revised: February 05, 2025

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].

* To whom all correspondence should be sent:
E-mail: aanchal.mittal@vit.ac.in

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].

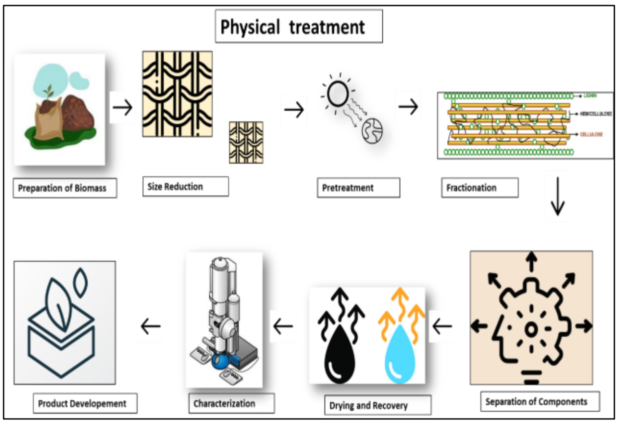

Fig. 1. Physical treatment method

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

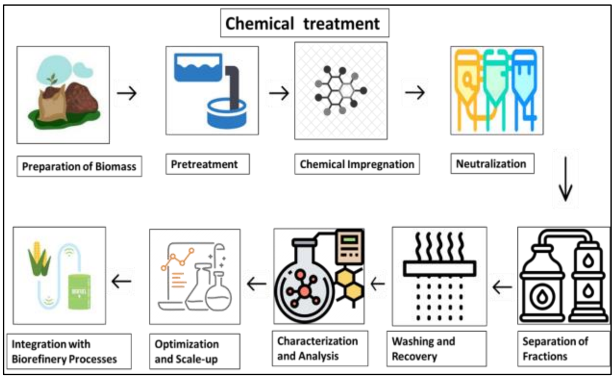

Fig. 2. Chemical treatment method

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

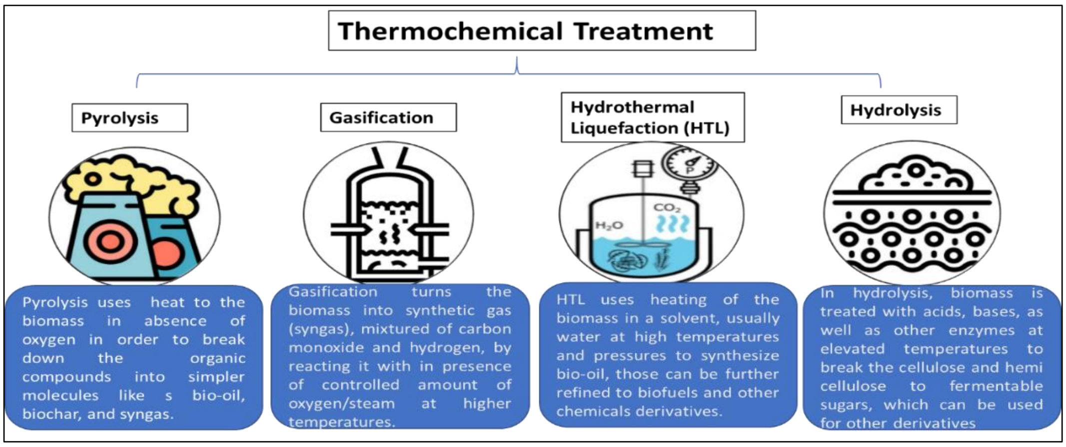

Fig 3. Thermochemical treatment method

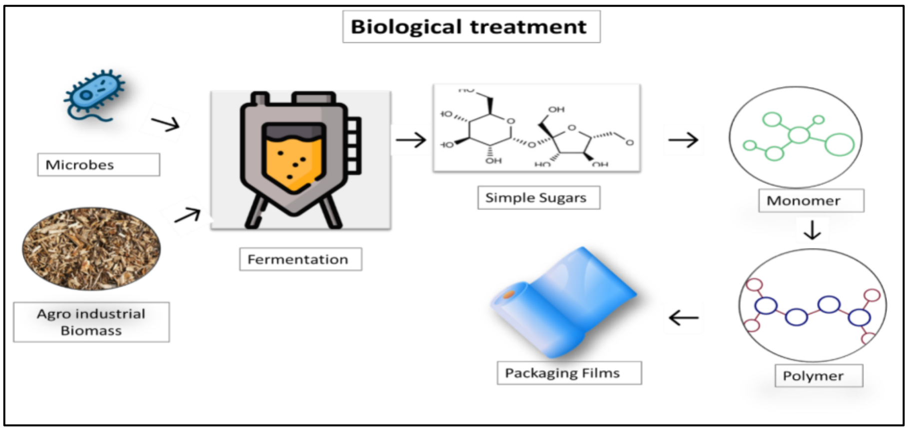

Fig. 4. Biological treatment method

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).

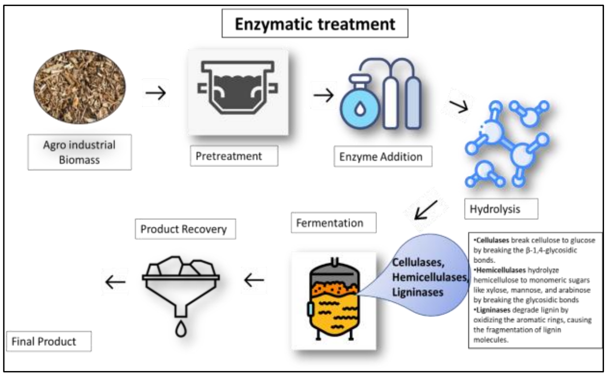

Fig. 5. Enzymatic treatment method

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].

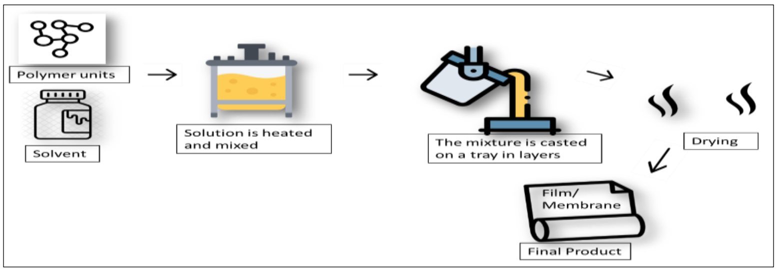

Fig. 6. Solvent casting

Tape casting

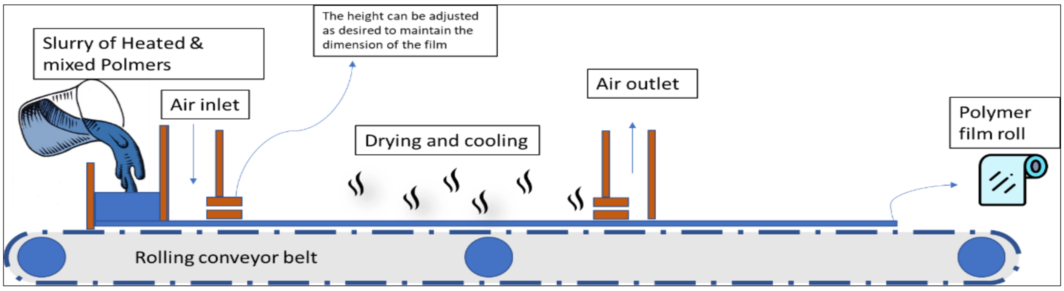

Fig. 7. Tape casting

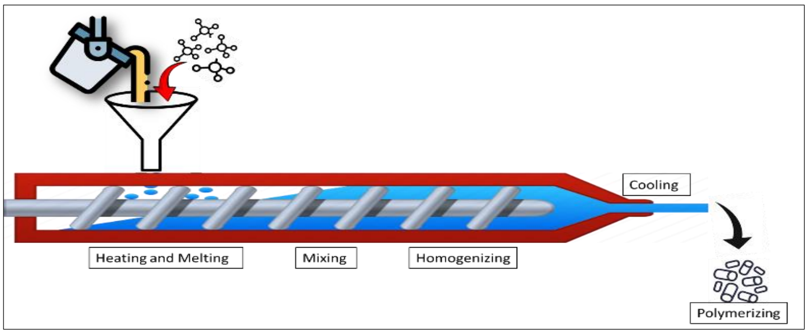

Fig. 8. Melt extrusion

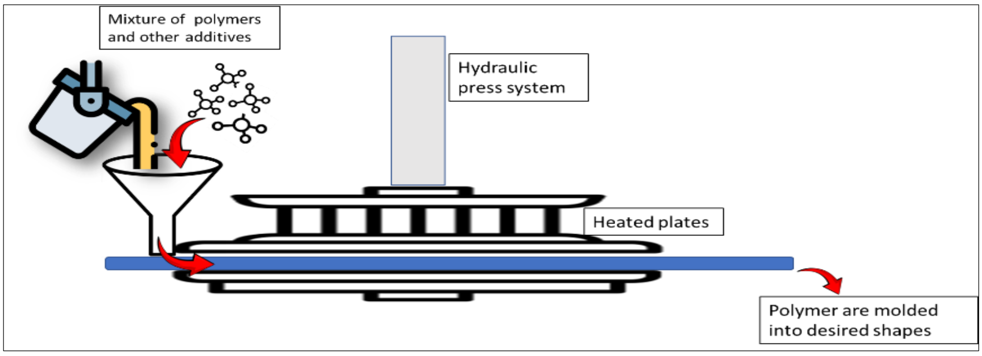

Fig. 9. Thermopressing

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].

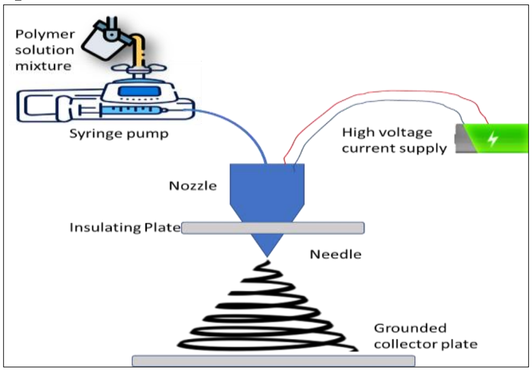

Fig. 10. Electrospinning

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.

Acknowledgement: *The authors would like to thank Vellore Institute of Technology, Vellore, Tamil Nadu, India, for providing access to the facilities, infrastructure, and financial support to carry out the work.*

Conflict of interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

Authorship contribution statement: *Juli Das, Diptanu De: conceptualization and writing. Aanchal Mittal (corresponding author): supervision, conceptualization, and visualization. Virangna Jamwal, Amit Dhaundiyal: rewriting and review. Kunwar Pal: editing and reviewing. Sangeeta Garg, Mario Guimarães Junior, Rameshpathy Manian, Vidisha Tomer, Jeevitha G C, Ramalingam C: editing and reviewing.*

REFERENCES

1. S. Bala, D. Garg, K. Sridhar, B.S. Inbaraj, R. Singh, S. Kamma, M. Tripathi, M, Sharma M Transformation of Agro-Waste into Value-Added Bioproducts and Bioactive Compounds: Micro/Nano Formulations and Application in the Agri-Food-Pharma Sector, Bioengineering, 10(2) (2023) 152.
2. J. Ranja, R. Sahni, Post harvest losses of fruits and vegetables in India. Ropan, (2023). 41-43.
3. S. A. Varghese, H. Pulikkalparambil, K. Promhuad, A. Srisa, Y. Laorenza , L. Jarupan, T. Nampitch, V. Chonhenchob, N. Harnkarnsujarit, Renovation of Agro-Waste for Sustainable Food Packaging: A Review, Polymers, 15(3) (2023) 648.
4. A. Astudillo, O. Rubilar, G. Briceño, M.C. Diez, H. Schalchli, Advances in Agroindustrial Waste as a Substrate for Obtaining Eco-Friendly Microbial Products. Sustainability, 15(4) (2023) 3467.
5. I.F. Olawuyi, W.Y. Lee, Development and Characterization of Biocomposite Films Based on Polysaccharides Derived from Okra Plant Waste for Food Packaging Application. Polymers, 14(22) (2022) 4884.
6. U. Choudhary, B.K. Bhinchhar, V.K. Paswan, S. Kharkwal, S.P. Yadav, P. Singh, Utilization of Agro-Industrial Wastes as Edible Coating and Films for Food Packaging Materials. In A Glance at Food Processing Applications, (2022).
7. A. Chiralt, C. Menzel, E. Hernandez-García, S. Collazo, C. Gonzalez-Martinez, Use of by-products in edible coatings and biodegradable packaging materials for food preservation. In Sustainability of the Food System (2020) 101–127.
8. S. Birania, S. Kumar, N. Kumar, A.K. Attkan, A. Panghal, P. Rohilla, R. Kumar, Advances in development of biodegradable food packaging material from agricultural and agro-industry waste. Journal of Food Process Engineering, (2022) 45(1).
9. .D. Carnaval, A.K. Jaiswal, S. Jaiswal, Agro-Food Waste Valorization for Sustainable Bio-Based Packaging. Journal of Composites Science, 8(2) (2024) 4.
10. L.K. Ncube, A.U. Ude, E.N. Ogunmuyiwa, R. Zulkifli, I.N. Beas, Environmental Impact of Food Packaging Materials: A Review of Contemporary Development from Conventional Plastics to Polylactic Acid Based Materials. Materials, 13(21) (2020) 4994.
11. M. Alexandri, J.P. López-Gómez, A. Olszewska-Widdrat, J. Venus, Valorising Agro-industrial Wastes within the Circular Bioeconomy Concept: the Case of Defatted Rice Bran with Emphasis on Bioconversion Strategies. Fermentation, 6(2) (2020) 42.
12. C.C. Ogbu, S.N. Okey, Agro-Industrial Waste Management: The Circular and Bioeconomic Perspective. In Agricultural Waste - New Insights, (2023).
13. [L.C. Freitas, J.R. Barbosa, A.L. da Costa, F.W. Bezerra, R.H. Pinto, R.N. de Carvalho Junior , From waste to sustainable industry: How can agro-industrial wastes help in the development of new products? Resources, Conservation and Recycling, 169 (2021) 105466.
14. B. Naik, V. Kumar, S. Rizwanuddin, M. Chauhan, A.K. Gupta, S. Rustagi, V. Kumar, S.Gupta, Agro-industrial waste: a cost-effective and eco-friendly substrate to produce amylase. Food Production, Processing and Nutrition, 5(1) (2023) 30.
15. H.T. Duguma, P. Khule, A. McArdle, K. Fennell, E. Almenar, Turning agricultural waste into packages for food: A literature review from origin to end-of-life. Food Packaging and Shelf Life, 40 (2023) 101166.
16. N. Ibarra-Díaz, J.F. Castañón-Rodríguez, J. Gómez-Rodríguez, M.G. Aguilar-Uscanga MG, Optimization of peroxide-alkaline pretreatment and enzymatic hydrolysis of barley straw (Hordeum vulgare L.) to produce fermentable sugars using a

Box–Behnken design. Biomass Conversion and Biorefinery, 12(7) (2022) 2389–2398.
17. L. Copeland, J. Blazek, H. Salman, M.C. Tang MC, Form and functionality of starch. Food Hydrocolloids, 23(6) (2009) 1527–1534.
18. D. Elieh-Ali-Komi, M.R. Hamblin, Chitin and chitosan: production and application of versatile biomedical nanomaterials. International journal of advanced research, 4(3)(2016) 411.
19. E.G. Maxwell, N.J. Belshaw, K.W. Waldron, V.J. Morris, Pectin – An emerging new bioactive food polysaccharide. Trends in Food Science & Technology, 24(2) (2012) 64–73.
20. D.M. Rein, R.Khalfin, Y. Cohen, Cellulose as a novel amphiphilic coating for oil-in-water and water-in-oil dispersions. Journal of Colloid and Interface Science, 386(1) (2012) 456–463.
21. C.G. Grotto, C.J. Colares, D.R. Lima, D.H. Pereira, A.T. do Vale, Energy potential of biomass from two types of genetically improved rice husks in Brazil: A theoretical-experimental study. Biomass and Bioenergy, 142 (2020) 105816.
22. T. Tufail, F. Saeed, M. Afzaal, H.B. Ain, S.A. Gilani, M. Hussain, F.M. Anjum, Wheat straw: A natural remedy against different maladies. Food Science & Nutrition, 9(4) (2021) 2335–2344.
23. K. Shaker, Y. Nawab, Wood and Agriculture Waste Fibers, (2022) 45–55.
24. M.G. Gomes, L.V. Gurgel, M.A. Baffi, D. Pasquini D, Pretreatment of sugarcane bagasse using citric acid and its use in enzymatic hydrolysis. Renewable Energy, 157 (2020) 332–341.
25. X. Song, X. Wang, K. Kito, Effects of Heating Temperature on the Properties of Bio-Board Manufactured by Using Soybean Straw. Materials, 13(3) (2020) 662.
26. N.H. Metwally, A.S. Owis, Recycling and chemistry of the lignocellulosic biomass for cotton stalks to primer value-added products. Egyptian Journal of Chemistry, (2023).
27. I.N. Mohammad, C.M. Ongkudon, M. Misson, Physicochemical Properties and Lignin Degradation of Thermal-Pretreated Oil Palm Empty Fruit Bunch. Energies, 13(22) (2020) 5966.
28. G. Moreno, K. Ramirez, M. Esquivel, G. Jimenez, Isolation and Characterization of Nanocellulose Obtained from Industrial Crop Waste Resources by Using Mild Acid Hydrolysis. Journal of Renewable Materials, 6(4) (2018) 362–369.
29. I. Gómez-Cruz, I. Romero, M.D. Contreras, J. Labidi, F. Hernández-Ramos, L.B. Roseiro, L.C. Duarte, E. Castro, F. Carvalheiro, Combined Extraction and Ethanol Organosolv Fractionation of Exhausted Olive Pomace for Bioactive Compounds. Advanced Sustainable Systems, 6(4) (2022).
30. B.M. Gonçalves, M.D. Camillo, M.P. Oliveira, L.G. Carreira, J.C. Moulin, H Fantuzzi Neto, B.F. de Oliveira, A.C. Pereira, S.N. Monteiro, Surface Treatments of Coffee Husk Fiber Waste for Effective Incorporation into Polymer Biocomposites. Polymers, 13(19) (2021) 3428.
31. Y. Fu, H. Gao, H. Yu, Q. Yang, H. Peng, P. Liu, Y. Li, Z. Hu, R. Zhang, J. Li, Z. Qi, Specific lignin and cellulose depolymerization of sugarcane bagasse for maximum bioethanol production under optimal chemical fertilizer pretreatment with hemicellulose retention and liquid recycling. Renewable Energy, 200 (2022) 1371–1381.
32. O. Akatwijuka, M.A.H. Gepreel, A. Abdel-Mawgood, M. Yamamoto, Y. Saito, A.H. Hassanin, Overview of banana cellulosic fibers: agro-biomass potential, fiber extraction, properties, and sustainable applications. Biomass Conversion and Biorefinery, 14(6) (2024) 7449–7465.
33. S.O. Dahunsi, Liquefaction of pineapple peel: Pretreatment and process optimization. Energy, 185, (2019) 1017–1031.
34. [M.S. Ganewatta, H.N. Lokupitiya, C. Tang, Lignin Biopolymers in the Age of Controlled Polymerization. Polymers, 11(7) (2019) 1176.
35. S.A. Nemes, K. Szabo, D.C. Vodnar, Applicability of Agro-Industrial By-Products in Intelligent Food Packaging. Coatings, 10(6) (2020) 550.
36. J. Baranwal, B. Barse, A. Fais, G.L. Delogu, A. Kumar, Biopolymer: A Sustainable Material for Food and Medical Applications. Polymers, 14(5) (2022) 983.
37. I.S. Bayer, S. Guzman-Puyol, J.A. Heredia-Guerrero, L. Ceseracciu, F. Pignatelli, R. Ruffilli, R. Cingolani, A. Athanassiou, Direct Transformation of Edible Vegetable Waste into Bioplastics. Macromolecules, 47(15) (2014) 5135–5143.
38. M. Castillo, M.J. de Guzman, J.M. Aberilla, Environmental sustainability assessment of banana waste utilization into food packaging and liquid fertilizer. Sustainable Production and Consumption, 37 (2023) 356-368.
39. S.P. Singh, V. Chonhenchob, J. Singh, Life cycle inventory and analysis of re-usable plastic containers and display-ready corrugated containers used for packaging fresh fruits and vegetables. Packaging Technology and Science: An International Journal, 19(5) (2006) 279-293.
40. S. Ramesh, P. Radhakrishnan, Cellulose nanoparticles from agro-industrial waste for the development of active packaging. Applied Surface Science, 484 (2019) 1274-1281.
41. P.P. Singh, S.V. Singh, S.J. Dutta, (2022) Role of Agro-Wastes in Economical Food Packaging Material Synthesis. In Biodegradable Polymer-Based Food Packaging (2022) 135-153. Singapore: Springer Nature Singapore.
42. I. Bose, R. Singh, S. Negi, K. Tiwari, Utilization of edible film and coating material obtained from fruits and vegetables residue: A review. 020015 (2023).
43. S.M. Amaraweera, C. Gunathilake, O.H. Gunawardene, N.M. Fernando, D.B. Wanninayaka, R.S. Dassanayake, S.M. Rajapaksha, A. Manamperi, C.A. Fernando, A.K. Kulatunga, A. Manipura, Development of Starch-Based Materials Using Current Modification Techniques and Their Applications: A Review. Molecules, 26(22) (2021)

6880.
44. C.P. Jiménez-Gómez, J.A. Cecilia, Chitosan: A Natural Biopolymer with a Wide and Varied Range of Applications. Molecules, 25(17) (2020) 3981.
45. S. Riaz, K.Y. Rhee, S.J. Park, Polyhydroxyalkanoates (PHAs): Biopolymers for Biofuel and Biorefineries. Polymers, 13(2) (2021) 253.
46. J.T. McNamara, J.L. Morgan, J. Zimmer, A Molecular Description of Cellulose Biosynthesis. Annual Review of Biochemistry, 84(1) (2015) 895–921.
47. S. Janaswamy, M.P. Yadav, M. Hoque, S. Bhattarai, S. Ahmed, Cellulosic fraction from agricultural biomass as a viable alternative for plastics and plastic products. Industrial Crops and Products, 179 (2022) 114692.
48. W.G. Glasser, About Making Lignin Great Again—Some Lessons From the Past. Frontiers in Chemistry, 7 (2019).
49. S. Jayarathna, M. Andersson, R. Andersson, Recent Advances in Starch-Based Blends and Composites for Bioplastics Applications. Polymers, 14(21) (2022) 4557.
50. A.A. Vaidya, K.D. Murton, D.A. Smith, G. Dedual, A review on organosolv pretreatment of softwood with a focus on enzymatic hydrolysis of cellulose. Biomass Conversion and Biorefinery, 12(11) (2022) 5427–5442.
51. D. Elieh Ali Komi, L. Sharma, C.S. Dela Cruz, Chitin and Its Effects on Inflammatory and Immune Responses. Clinical Reviews in Allergy & Immunology, 54(2) (2018) 213–223.
52. R.A. Harmsen, T.R. Tuveng, S.G. Antonsen, V.G. Eijsink, M. Sørlie, Can we make Chitosan by Enzymatic Deacetylation of Chitin? Molecules, 24(21) (2019) 3862.
53. M. Guzik, T. Witko, A. Steinbüchel, M. Wojnarowska, M. Sołtysik, S. Wawak, What Has Been Trending in the Research of Polyhydroxyalkanoates? A Systematic Review. Frontiers in Bioengineering and Biotechnology, 8 (2020).
54. [54] Y. Fu, H. Gao, H. Yu, Q. Yang, H. Peng, P. Liu, Y. Li, Z. Hu, R. Zhang, J. Li, Z. Qi, Specific lignin and cellulose depolymerization of sugarcane bagasse for maximum bioethanol production under optimal chemical fertilizer pretreatment with hemicellulose retention and liquid recycling. Renewable Energy, 200 (2022) 1371–1381.
55. M. Abbasi, D. Pokhrel, E.R. Coats, N.M. Guho, A.G. McDonald, Effect of 3-Hydroxyvalerate Content on Thermal, Mechanical, and Rheological Properties of Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) Biopolymers Produced from Fermented Dairy Manure. Polymers, 14(19) (2022) 4140.
56. B.S. Gadgil, N. Killi, G.V. Rathna, Polyhydroxyalkanoates as biomaterials. MedChemComm, 8(9) (2017) 1774–1787.
57. V. Rana, S. Kamboj, R. Sharma, K. Singh, Modification of gums: synthesis techniques and pharmaceutical benefits. Handbook of polymers for pharmaceutical technologies: biodegradable polymers. 28 (2015) 3:299-364.
58. J. Patel, B. Maji, N.H. Moorthy, S. Maiti, Xanthan gum derivatives: review of synthesis, properties and diverse applications. RSC Advances, 10(45) (2020) 27103–27136.
59. B. Trica, C. Delattre, F. Gros, A.V. Ursu, T. Dobre, G. Djelveh, P. Michaud, F. Oancea, Extraction and Characterization of Alginate from an Edible Brown Seaweed (Cystoseira barbata) Harvested in the Romanian Black Sea. Marine Drugs, 17(7) (2019) 405.
60. C. Rodrigues, V.G. Souza, I. Coelhoso, A.L. Fernando, Bio-Based Sensors for Smart Food Packaging—Current Applications and Future Trends. Sensors, 21(6) (2021) 2148.
61. L. Gao, P. Liu, L. Liu, S. Li, Y. Zhao, J. Xie, H. Xu, κ-carrageenan-based pH-sensing films incorporated with anthocyanins or/and betacyanins extracted from purple sweet potatoes and peels of dragon fruits. Process Biochemistry, 121 (2022) 463-480.
62. M. Grimaldi, O. Pitirollo, P. Ornaghi, C. Corradini, A. Cavazza, Valorization of agro-industrial byproducts: Extraction and analytical characterization of valuable compounds for potential edible active packaging formulation. Food Packaging and Shelf Life, 33 (2022) 100900.
63. .N. Adilah, B. Jamilah, M.A. Noranizan, Z.N. Hanani, Utilization of mango peel extracts on the biodegradable films for active packaging. Food packaging and shelf life, 16 (2018) 1-7.
64. R.K. Khalil, M.R. Sharaby, D.S. Abdelrahim, Novel active edible food packaging films based entirely on citrus peel wastes. Food Hydrocolloids, 134 (2023) 107961.
65. T.J. Madera-Santana, Y. Freile-Pelegrín, J.C. Encinas, C.R. Ríos-Soberanis, P. Quintana-Owen, Biocomposites based on poly (lactic acid) and seaweed wastes from agar extraction: Evaluation of physicochemical properties. Journal of Applied Polymer Science, 132(31) (2015).
66. P. Di Donato, V. Taurisano, A. Poli, G.G. d'Ayala, B. Nicolaus, M. Malinconinco, G. Santagata, Vegetable wastes derived polysaccharides as natural eco-friendly plasticizers of sodium alginate. Carbohydrate Polymers, 229 (2020) 115427.
67. L.Z. Wang, L. Liu, J. Holmes, J.F. Kerry, J.P. Kerry, Assessment of film-forming potential and properties of protein and polysaccharide-based biopolymer films. International journal of food science & technology, 42(9) (2007) 1128-1138.
68. S. Marino-Cortegoso, M. Stanzione, M.A. Andrade, C. Restuccia, A.R. de Quirós, G.G. Buonocore, C.H. Barbosa, F. Vilarinho, A.S. Silva, F. Ramos, K. Khwaldia "Development of active films utilizing antioxidant compounds obtained from tomato and lemon by-products for use in food packaging." Food Control 140 (2022) 109128.
69. G.B. Kaynarca, D.D. Kamer, T. Gumus, O. Sagdıc, Characterization of Poly (vinyl alcohol)/gelatin films

made with winery solid by-product (vinasse) extract. Food Packaging and Shelf Life, 35 (2023) 101013.

70. M. Armghan Khalid, B. Niaz, F. Saeed, M. Afzaal, F. Islam, M. Hussain, Mahwish, H. Muhammad Salman Khalid, A. Siddeeg, A. Al-Farga, "Edible coatings for enhancing safety and quality attributes of fresh produce: A comprehensive review." International Journal of Food Properties 25 (2022) no. 1: 1817-1847.
71. A.A. Mohammed, A.A. Omran, Z. Hasan, R.A. Ilyas, S.M. Sapuan, Wheat biocomposite extraction, structure, properties and characterization: A review. Polymers, 13(21) (2021) 3624.
72. M.M. Tosif, A. Najda, A. Bains, G. Zawiślak, G. Maj, P. Chawla, Starch–mucilage composite films: An inclusive on physicochemical and biological perspective. Polymers, 13(16) (2021) 2588.
73. A. Kafashan, H. Joze-Majidi, S. Kazemi-Pasarvi, A. Babaei, S.M. Jafari, Nanocomposites of soluble soybean polysaccharides with grape skin anthocyanins and graphene oxide as an efficient halochromic smart packaging. Sustainable Materials and Technologies, 38 (2023) e00755.
74. H.M. Akhtar, A. Riaz, Y.S. Hamed, M. Abdin, G. Chen, P. Wan, X. Zeng, Production and characterization of CMC-based antioxidant and antimicrobial films enriched with chickpea hull polysaccharides. International journal of biological macromolecules, 118 (2022) 469-477.
75. I.B. Basumatary, A. Mukherjee, V. Katiyar, S. Kumar, Biopolymer-based nanocomposite films and coatings: Recent advances in shelf-life improvement of fruits and vegetables. Critical Reviews in Food Science and Nutrition, 62(7) (2022) 1912-1935.
76. E. Tavassoli-Kafrani, M.V. Gamage, L.F. Dumée, L. Kong, S. Zhao, Edible films and coatings for shelf life extension of mango: A review. Critical Reviews in Food Science and Nutrition, 62(9) (2022) 2432-2459.
77. P.F. Muñoz-Gimena, V. Oliver-Cuenca, L. Peponi, D. López, A review on reinforcements and additives in starch-based composites for food packaging. Polymers, 15(13) (2023) 2972.
78. [S. Chavan, B. Yadav, A. Atmakuri, R.D. Tyagi, J.W. Wong, P. Drogui, Bioconversion of organic wastes into value-added products: A review. Bioresource Technology, 344 (2022) 126398.
79. M. Zhao, S. Zhang, R. Yin, C. Hu, M. Fan, and L. Li, "Active Antioxidant Packaging from Essential Oils Incorporated Thermoplastic Starch/Polylactic Acid/Poly(Butylene Adipate-Co-Terephthalate) (TPS/PLA/PBAT) for the Autolysis of Straw Mushroom (Volvariella Volvacea)," SSRN Electron. J., 2021
80. L.J. Jönsson, C. Martín, Pretreatment of lignocellulose: formation of inhibitory by-products and strategies for minimizing their effects. Bioresource technology, 199 (2016) 103-112.
81. K. Kucharska, P. Rybarczyk, I. Hołowacz, R. Łukajtis, Glinka M, M. Kamiński, Pretreatment of Lignocellulosic Materials as Substrates for Fermentation Processes. Molecules, 23(11) (2018) 2937.
82. [X. Li, Y. Shi, W. Kong, J. Wei, W. Song, S. Wang, Improving enzymatic hydrolysis of lignocellulosic biomass by bio-coordinated physicochemical pretreatment—A review. Energy Reports, 8 (2022) 696–709.
83. A.K. Kumar, S. Sharma, Recent updates on different methods of pretreatment of lignocellulosic feedstocks: a review. Bioresources and Bioprocessing, 4(1) (2017) 7.
84. L. Lajoie, A.S. Fabiano-Tixier, F. Chemat, Water as Green Solvent: Methods of Solubilisation and Extraction of Natural Products—Past, Present and Future Solutions. Pharmaceuticals, 15(12) (2022) 1507.
85. K.C. Badgujar, R. Dange, B.M. Bhanage, Recent advances of use of the supercritical carbon dioxide for the biomass pre-treatment and extraction: A mini-review. Journal of the Indian Chemical Society, 98(1) (2021) 100018.
86. S.K. Bhatia, S.S. Jagtap, A.A. Bedekar, R.K. Bhatia, A.K. Patel, D. Pant, J.R. Banu, C.V. Rao, Y.G. Kim, Y.H. Yang, Recent developments in pretreatment technologies on lignocellulosic biomass: Effect of key parameters, technological improvements, and challenges. Bioresource Technology, 300 (2020) 122724.
87. J. Dharmaraja, S. Shobana, S. Arvindnarayan, R.R. Francis, R.B. Jeyakumar, R.N HG. Saratale, Ashokkumar V, Bhatia SK, Kumar V, Kumar G, Lignocellulosic biomass conversion via greener pretreatment methods towards biorefinery applications. Bioresource Technology, 369 (2023) 128328.
88. P. Chakraborty, R. Kumar, S. Chakrabortty, S. Saha, S. Chattaraj, S. Roy, A. Banerjee, S.K. Tripathy, A.K. Ghosh, B.H. Jeon, Technological advancements in the pretreatment of lignocellulosic biomass for effective valorization: A review of challenges and prospects. Journal of Industrial and Engineering Chemistry (2024).
89. L. Kratky, T. Jirout, Biomass Size Reduction Machines for Enhancing Biogas Production. Chemical Engineering & Technology, 34(3) (2011) 391–399.
90. Y. Yu, J. Wu, X. Ren, A. Lau, H. Rezaei, M. Takada, X. Bi, S. Sokhansanj, Steam explosion of lignocellulosic biomass for multiple advanced bioenergy processes: A review. Renewable and Sustainable Energy Reviews, 154 (2022) 111871.
91. A. Fernandes, L. Cruz-Lopes, B. Esteves, D.V. Evtuguin, Microwaves and Ultrasound as Emerging Techniques for Lignocellulosic Materials. Materials, 16(23) (2023) 7351.
92. G. Chatel, K. De Oliveira Vigier, F. Jérôme, Sonochemistry: What Potential for Conversion of Lignocellulosic Biomass into Platform Chemicals? ChemSusChem, 7(10) (2014) 2774–2787.

93. Y.L. Loow, T.Y. Wu, J. Md. Jahim, A.W. Mohammad, W.H. Teoh, Typical conversion of lignocellulosic biomass into reducing sugars using dilute acid hydrolysis and alkaline pretreatment. Cellulose, 23(3) (2016)1491–1520.
94. C. Zhao, Q. Shao, S.P. Chundawat, Recent advances on ammonia-based pretreatments of lignocellulosic biomass. Bioresource Technology, 2 98 (2020) 122446.
95. A. Fernandes, L. Cruz-Lopes, B. Esteves, D.V. Evtuguin, Improving the economy of lignocellulose-based biorefineries with organosolv pretreatment. Bioresource Technology, 299 (2020) 122695.
96. A. Lorenci Woiciechowski et al., “Lignocellulosic biomass: Acid and alkaline pretreatments and their effects on biomass recalcitrance – Conventional processing and recent advances,” Bioresour. Technol., vol. 304, p. 122848, May 2020,
97. T.R. Sarker, F. Pattnaik, S. Nanda, A.K. Dalai, V. Meda, S. Naik & S. Naik, Hydrothermal pretreatment technologies for lignocellulosic biomass: A review of steam explosion and subcritical water hydrolysis. Chemosphere, 284 (2021) 131372.
98. A.A. Houfani, N. Anders, A.C. Spiess, P. Baldrian, S. Benallaoua, Insights from enzymatic degradation of cellulose and hemicellulose to fermentable sugars– a review. Biomass and Bioenergy, 134 (2020)105481.
99. N. Nayan, A.S. Sonnenberg, W.H. Hendriks, J.W. Cone, Prospects and feasibility of fungal pretreatment of agricultural biomass for ruminant feeding. Animal Feed Science and Technology, 268 (2020) 114577.
100. E. Demir, S. Tappi, K. Dymek, P. Rocculi, F. Gomez-Galindo, Reversible electroporation caused by pulsed electric field – Opportunities and challenges for the food sector. Trends in Food Science & Technology, 139 (2023) 104120.
101. F.R. Amin, H. Khalid, H. Zhang, S.U. Rahman, R. Zhang, G. Liu, C. Chen, Pretreatment methods of lignocellulosic biomass for anaerobic digestion. AMB Express, 7(1) (2017) 72.
102. R. Ravindran, S.S. Hassan, G.A. Williams, A.K. Jaiswal, A Review on Bioconversion of Agro-Industrial Wastes to Industrially Important Enzymes. Bioengineering, 5(4) (2018) 93.
103. S. Sun, X. Cao, R. Sun , The role of pretreatment in improving the enzymatic hydrolysis of lignocellulosic materials. Bioresource Technology, 199 (2016) 49–58.
104. E.C. Bensah, M. Mensah, Chemical Pretreatment Methods for the Production of Cellulosic Ethanol: Technologies and Innovations. International Journal of Chemical Engineering, 2013 (2013) 1–21.
105. M.J. Taylor, H.A. Alabdrabalameer, V. Skoulou, Choosing Physical, Physicochemical and Chemical Methods of Pre-Treating Lignocellulosic Wastes to Repurpose into Solid Fuels. Sustainability, 11(13) (2019) 3604.
106. Y. Aryan, P. Yadav, S.R. Samadder, Life Cycle Assessment of the existing and proposed plastic waste management options in India: A case study. Journal of Cleaner Production, 211 (2019) 1268
107. C. Lamo, P.C. Bargale, S. Gangil, S. Chakraborty, M.K. Tripathi, N. Kotwaliwale, B. Modhera. High crystalline cellulose extracted from chickpea husk using alkali treatment. Biomass Conversion and Biorefinery, 14(1) (2024) 751-759.
108. A. Meraj, S.P. Singh, M. Jawaid, M.M. Nasef, T.S. Alomar, N. AlMasoud, A Review on Eco-friendly Isolation of Lignin by Natural Deep Eutectic Solvents from Agricultural Wastes. Journal of Polymers and the Environment, 31(8) (2023) 3283–3316.
109. H.V. Lee, S.B. Hamid, S.K. Zain, Conversion of Lignocellulosic Biomass to Nanocellulose: Structure and Chemical Process. The Scientific World Journal, 2014 (2014) 1–20.
110. M.Y. Alazaiza, A. Albahnasawi, M. Eyvaz, T. Al Maskari, D.E. Nassani, S.S. Abu Amr, M.S. Abujazar, M.J. Bashir, An Overview of Green Bioprocessing of Algae-Derived Biochar and Biopolymers: Synthesis, Preparation, and Potential Applications. Energies, 16(2) (2023) 791.
111. A.R. Gollakota, N. Kishore, S. Gu, A review on hydrothermal liquefaction of biomass. Renewable and Sustainable Energy Reviews, 81 (2018) 1378–1392.
112. A. Morales, J. Labidi, P. Gullón, G. Astray, Synthesis of advanced biobased green materials from renewable biopolymers. Current Opinion in Green and Sustainable Chemistry, 29 (2021) 100436.
113. C , Maraveas, Production of Sustainable and Biodegradable Polymers from Agricultural Waste. Polymers, 12(5) (2020) 1127.
114. F. Ortega, F. Versino, O.V. López, M.A. García, Biobased composites from agro-industrial wastes and by-products. Emergent Materials, 5(3) (2022) 873–921.
115. J.R. Mielenz, Small-Scale Approaches for Evaluating Biomass Bioconversion for Fuels and Chemicals. In Bioenergy (pp. 385–406) (2015).
116. S. Singh, I.J. Chaudhary, P. Kumar, Utilization of Low-cost Agricultural Waste for Removal of Toxic Metals from Environment A Review. International Journal of Scientific Research in Biological Sciences, 6(4) (2019).
117. T.G. Induchoodan, Haq I, A.S. Kalamdhad, Factors affecting anaerobic digestion for biogas production: a review. In Advanced Organic Waste Management (pp. 223–233) (2022).
118. P.N. Singh, T. Robinson, S. Dalel, Pre-treatment of Agro-Industrial Residues. In Biotechnology for Agro-Industrial Residues Utilisation (pp. 13–33) (2009) Springer Netherlands.
119. A. Procentese, F. Raganati, G. Olivieri, M. E. Russo, L. Rehmann, and A. Marzocchella, “Deep Eutectic Solvents pretreatment of agro-industrial food waste,” Biotechnol. Biofuels, vol. 11, no. 1, p. 37, Dec. 2018.
120. L. Zhao, K. Meng, P. Shi, Y. Bai, H. Luo, H. Huang, Y. Wang, P. Yang, B. Yao, A novel thermophilic

xylanase from Achaetomium sp. Xz-8 with high catalytic efficiency and application potentials in the brewing and other industries. Process Biochemistry, 48(12) (2013) 1879–1885.

121. P. Xu, L. Shu, Y. Li,S. Zhou, G. Zhang, Y. Wu, Z. Yang, Pretreatment and composting technology of agricultural organic waste for sustainable agricultural development. Heliyon, 9(5) (2023) e16311.

122. V. Bhardwaj, G. Degrassi, R.K. Bhardwaj, Bioconversion of cellulosic materials by the action of microbial cellulases. International Research Journal of Engineering and Technology, 4(8) (2017) 494-503.

123. B.C. Makhubela, J. Darkwa, The Role of Noble Metal Catalysts in Conversion of Biomass and Bio-derived Intermediates to Fuels and Chemicals. Johnson Matthey Technology Review, 62(1), 4–31 (2018).

124. R. Kumar, S. Singh, O.V. Singh, Bioconversion of lignocellulosic biomass: biochemical and molecular perspectives. Journal of Industrial Microbiology & Biotechnology, 35(5) (2008) 377–391.

125. S. Sarsan, R. Merugu, Role of Bioprocess Parameters to Improve Cellulase Production: Part II. In New and Future Developments in Microbial Biotechnology and Bioengineering (pp. 77–97) (2019).

126. R. Intasit, B. Cheirsilp, W. Suyotha, P. Boonsawang, Synergistic production of highly active enzymatic cocktails from lignocellulosic palm wastes by sequential solid state-submerged fermentation and co-cultivation of different filamentous fungi. Biochemical Engineering Journal, 173 (2021) 108086.

127. N. Bhati, Shreya, A.K. Sharma, Cost-effective cellulase production, improvement strategies, and future challenges. Journal of Food Process Engineering, 44(2) (2021)

128. G.B. Santos, Á. de Sousa Francisco Filho, J.R. da Silva Rodrigues, R.R. de Souza, Cellulase production by Aspergillus niger using urban lignocellulosic waste as substrate: Evaluation of different cultivation strategies. Journal of Environmental Management, 305 (2022)114431.

129. [L.W. Yoon, T.N. Ang, G.C. Ngoh, A.S. Chua, Fungal solid-state fermentation and various methods of enhancement in cellulase production. Biomass and Bioenergy, 67 (2014) 319–338.

130. S. Sindhu, M. Phour, S.R. Choudhary, D. Chaudhary, Phosphorus Cycling: Prospects of Using Rhizosphere Microorganisms for Improving Phosphorus Nutrition of Plants (pp. 199–237) (2014).

131. A. Surendran, Y. Siddiqui, H.M. Saud, N.S. Manickam, The antagonistic effect of phenolic compounds on ligninolytic and cellulolytic enzymes of Ganoderma boninense, causing basal stem rot in oil palm. (2017).

132. C.G. Liu, Y. Xiao, X.X. Xia, X.Q. Zhao, L. Peng, P. Srinophakun, F.W. Bai, Cellulosic ethanol production: Progress, challenges and strategies for solutions. Biotechnology Advances, 37(3) (2019) 491–

133. R.S. Abolore, S. Jaiswal, A.K. Jaiswal, Green and sustainable pretreatment methods for cellulose extraction from lignocellulosic biomass and its applications: A review. Carbohydrate Polymer Technologies and Applications, 7 (2024).

134. H. Zhang, S. Sablani, Biodegradable packaging reinforced with plant-based food waste and by-products. Current Opinion in Food Science, 42 (2021) 61–68.

135. M. Maki, K.T. Leung, W. Qin, The prospects of cellulase-producing bacteria for the bioconversion of lignocellulosic biomass. International Journal of Biological Sciences, 500–516 (2009).

136. A.K. Kumar, B.S. Parikh S.P., Singh, D. Shah, Use of combined UV and chemical mutagenesis treatment of Aspergillus terreus D34 for hyper-production of cellulose-degrading enzymes and enzymatic hydrolysis of mild-alkali pretreated rice straw. Bioresources and Bioprocessing, 2(1) (2015) 35.

137. I.S. Druzhinina, C.P. Kubicek, Genetic engineering of Trichoderma reesei cellulases and their production. Microbial Biotechnology, 10(6) (2017) 1485–1499.

138. M.D. Sanchez-Garcia, E. Gimenez, J.M. Lagaron, Morphology and barrier properties of solvent cast composites of thermoplastic biopolymers and purified cellulose fibers. Carbohydrate Polymers, 71(2) (2008) 235–244.

139. L.F. Ballesteros, M. Michelin, A.A. Vicente, J.A. Teixeira, M.Â. Cerqueira, Lignocellulosic Materials and Their Use in Bio-based Packaging. Springer International Publishing. (2018).

140. N.L. Cristofoli, A.R. Lima, R.D. Tchonkouang, A.C. Quintino, M.C. Vieira & Vieira, M. C Advances in the Food Packaging Production from Agri-Food Waste and By-Products: Market Trends for a Sustainable Development. Sustainability, 15(7) (2023) 6153.

141. D.F. Vogelsang, J.E. Perilla, G. Buitrago, N.A. Algecira. Preparation of biopolymer films by aqueous tape casting processing. Journal of Plastic Film & Sheeting, 30(4) (2014) 435–448.

142. X.T. Pham, F. Thibault, L.T. Lim, Modeling and simulation of stretch blow molding of polyethylene terephthalate. Polymer Engineering & Science, 44(8) (2004) 1460–1472.

143. V. Aguié-Béghin, G. Paës, M. Molinari, B. Chabbert, Films and coatings from lignocellulosic polymers. In Edible Films and Coatings (pp. 161-178) (2016) CRC Press.

144. K.J. Figueroa-Lopez, D. Enescu, S. Torres-Giner, L. Cabedo, M.A. Cerqueira, L Pastrana, L. Fuciños P, J.M. Lagaron, Development of electrospun active films of poly(3-hydroxybutyrate-co-3-hydroxyvalerate) by the incorporation of cyclodextrin inclusion complexes containing oregano essential oil. Food Hydrocolloids, 108 (2020) 106013.

145. M.C. Ignacio, K.N. Tumu, M. Munshi, K.L. Vorst, G.W. Curtzwiler, Suitability of MRF Recovered

Post-Consumer Polypropylene Applications in Extrusion Blow Molded Bottle Food Packaging. Polymers, 15(16) (2023) 3471.

146. P. Gupta, B, Toksha, M. Rahaman, A Review on Biodegradable Packaging Films from Vegetative and Food Waste. The Chemical Record (2022) 22(7).

147. G. Tassinari, Bassani, G. Spigno, C. Soregaroli, D. Drabik, Do biodegradable food packaging films from agro-food waste pay off? A cost-benefit analysis in the context of Europe. Science of The Total Environment, 856 (2023).

148. P.K. Sadh, S. Duhan, J.S. Duhan, Agro-industrial wastes and their utilization using solid state fermentation: a review. Bioresources and Bioprocessing, 5(1) (2018) 1.

149. A. Gomes, A. Borges, J.A. Peres, M.S. Lucas, Bioenergy Production from Agro-Industrial Wastewater Using Advanced Oxidation Processes as Pre-Treatment. Catalysts, 13(8) (2023) 1186.

150. G. Davis, J.H. Song, Biodegradable packaging based on raw materials from crops and their impact on waste management. Industrial Crops and Products, 23(2) (2006) 147–161.

151. V. Jamwal, A. Mittal, A. Dhaundiyal, "Valorization of agro-industrial waste in composite films for sustainable packaging applications." Materials Today: Proceedings (2023).

152. S. Pérocheau Arnaud, Valorisation of Brewer's Spent Grain: Lignocellulosic Fractionation and its Potential for Polymer and Composite Material Applications. Chemistry Africa. (2024).