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Valorization of fruit waste for bio-refinery approach

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The magnitude of food waste across the food supply chain is intricate and can exert a substantial influence on various domains, including agriculture, food security, economics, waste utilization and management, environmental preservation, and human health. The crucial factor in effectively utilizing and managing fruit waste is the development of suitable environmentally sustainable reprocessing technologies. These technologies should be capable of converting all the valuable constituents found in the trash into valuable products, while simultaneously minimizing the quantity of waste destined for landfill disposal. A biorefinery can effectively utilize the variations in biomass components and intermediates by diversifying its product portfolio, so optimizing the value obtained from the biomass feedstock, and minimizing waste generation.

Keywords: Fruit waste valorization, bio-refinery, bioactive compounds, phenolic compounds

INTRODUCTION

Globally, fruit discards pose a major challenge due to their environmental, economic, and social impacts. Researchers are actively exploring methods to manage this waste. Food loss, distinct from food waste, refers to the decline in the quality and quantity of food caused by choices made within the supply chain before it reaches retailers. Food waste, in contrast, happens at the retail, food service, and consumer levels. Rapid population growth and our consumption habits are key drivers of both food loss and waste. Food loss exacerbates the environmental burden associated with food production within the food system. Data from the Food and Agriculture Organization (FAO) shows a critical situation: 15% of people in developing countries face hunger. This paradox highlights the global problem of food waste (FW). A significant amount of food that could be consumed is lost or discarded, throughout the food supply chain. Food waste isn't just a resource issue; it presents environmental, economic, and ethical challenges for modern society. FW occurs at every stage of the food lifecycle, from farms to processing facilities, retailers, and even in our homes. In lower-income countries, fruit waste is most prevalent during processing, with losses ranging from 15% to 20%. While at the consumption stage, only 4% to 10% of fruits go to waste. Interestingly, global fruit waste reached nearly 50% in 2011, a significant increase compared to 16 years prior [1].

Many scientific studies explore replacing fossil fuels with biomass resources, a concept known as biorefining. The food industry, encompassing agriculture and processing, is a prime candidate for biorefineries due to the potential utilization of its leftover materials. The initial step in utilizing these synergies involves identifying, measuring, and understanding the characteristics of these food processing residues. Due to the potential health benefits found in fruit waste (nutraceutical properties), there's a growing emphasis on finding ways to utilize it effectively (fruit valorization) [2]. One promising strategy is to use this waste as a starting material in bio-refineries. Bio-refineries are facilities that convert biomass, like fruit waste, into a range of valuable products. This can include things like heat, fuels, power, and even useful chemicals – all from materials that would otherwise be discarded [3].

According to the report of FAO 2023, Eating healthy is too expensive for many people in 11 African countries, especially those with lower incomes. These families, particularly those in suburbs and rural areas, would need to spend way more than they currently do on groceries to afford a diet that meets all their nutritional needs. The recovery of bioactive compounds from fruit waste has gained significant interest [4, 5]. Researchers are exploring green solvent extraction techniques to harness valuable components from fruit peels, seeds, pulp, and other byproducts generated during processing. Extracting valuable nutrients from fruit

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leftovers can make healthy foods cheaper and more accessible to everyone [6, 7].

Food waste (FW) is a global issue since a sizable portion of food that should have been eaten along the food value chain ends up as waste. In addition to being a resource issue, this also poses environmental, economic, and moral challenges for contemporary society. The first step for using industrial synergy in the food processing industry is detection, quantification, and characterization of residue. The objective of this article is: (a) to review the literature concerning the possible use of FW for producing usable compounds that reduce the burden on main raw materials. (b) to search for a novel valorization method for FW which overcomes the limitations faced during large scale implementation (c) to present different analytical techniques available for qualitative screening of bioactive compounds.

LITERATURE SURVEY

The burgeoning field of biorefinery necessitates the exploration of efficient and environmentally friendly methods that will be utilized for the valorization of fruit waste. Biorefinery approaches are increasingly exploring fruit waste as a sustainable source of health- promoting bioactive compounds. Recent studies highlight the potent antioxidant activity found within fruit byproducts. In the past, research focused on solid-liquid extraction (SLE) as the primary method. This technique simply involves using a solvent to dissolve and extract the target compounds from the material. SLE encompasses traditional methods such as Soxhlet extraction (SE), maceration extraction (ME), and percolation. [8]. Despite the effectiveness of conventional solvent extraction (CSE) in extracting polyphenols from plant materials, including fruit waste, its limitations are well documented like high time and energy consumption, along with the use of potentially hazardous organic solvents, make it an expensive and environmentally unfriendly option. The scientific community has been actively investigating towards finding more sustainable and cost-efficient methods for extracting these valuable compounds [9-12]. Emerging as a sustainable alternative, non-conventional extraction methods address the limitations of traditional techniques. These "green" approaches prioritize efficiency and selectivity while minimizing environmental impact. They achieve this through shorter processing times, reduced solvent use, and lower energy consumption [13].

Fruit waste valorization through biorefinery approaches can benefit from environmentally friendly extraction techniques. These methods, like microwave, enzyme, ultrasound, supercritical fluid, and pulsed electric field extraction, often utilize renewable resources and generate products that decompose naturally, minimizing the creation of harmful waste [14]. These methods champion several key principles: (i) Use sustainable source materials by utilizing fruit waste (FW) as a renewable resource. (ii) Apply alternative solvents by replacing traditional, often toxic, solvents with safer options, although limitations like high viscosity might exist. (iii) Reduced energy consumption by lowering the environmental footprint of the extraction process. (iv) Generation of coproduct by finding valuable uses for byproducts alongside the target compounds. (v) Ensure minimal environmental impact from the extracted biodegradable and pure extracts. (vi) Minimize the number of steps required for extraction streamlining the processes [15-18]. It's important to note that solvent selection, process design, and the type of fruit waste being processed all play a role in the final extraction yield. Additionally, to enhance the extraction process novel techniques can be employed as pretreatment with alternative solvents [19].

Table 1 indicates a different conventional method their advantages and disadvantages with the potential to extract bio-active compounds.

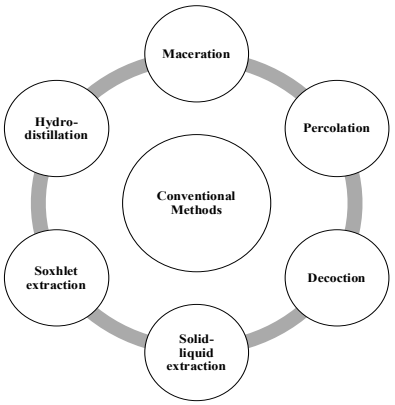

Fig. 1. Graphical representation of conventional methods of valorization.

Supercritical fluid extraction (SFE)

This method that uses a highly compressed fluid to separate a desired substance from a mixture. This mixture can be solid or even liquid. While supercritical fluid extraction (SFE) utilizes a gas-like solvent, its effectiveness improves compared to traditional liquid organic solvents. This is due to a unique combination of properties:

SFE utilizes a solvent in a state where it possesses both liquid and gas-like properties. This solvent, often referred to as the SFE solvent, has a reduced

viscosity. In simpler terms, it is thinner than a typical liquid.

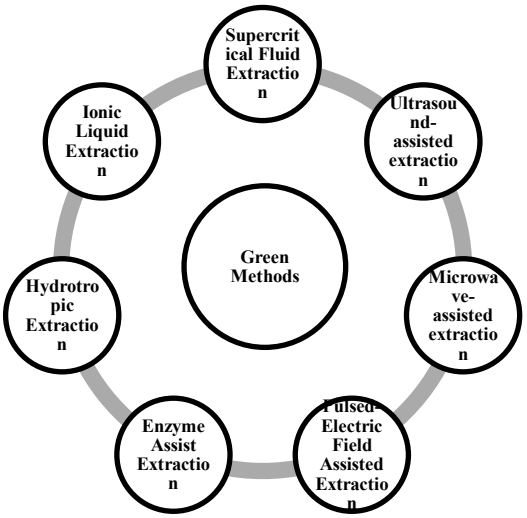

Fig. 2. Graphical representation of green methods of valorization

Table 1. Different conventional methods, their advantages and disadvantages with potential to extract bio-active compounds:

Techniques	Advantages	Disadvantages	Bio-active compound	Ref.
Maceration	● Maceration is a suitable method for extracting thermolabile components, meaning those that can degrade at high temperatures. ● Since it operates at room temperature, it minimizes the risk of damaging these delicate compounds. ● Maceration is a relatively cheap method compared to other extraction techniques. It requires minimal equipment and can be performed at ambient temperature, reducing energy consumption.	While maceration is a simple technique, it can be less efficient than other methods of extracting desired compounds from a material. ● Maceration often requires extended steeping times, which can be a drawback if faster processing is needed. Compared to some other techniques, maceration necessitates a larger amount of solvent to ensure proper submersion and adequate extraction.	Polyphenols, anthocyanins, flavonoids, and essential oils	[20-22]
Percolation	● Percolation offers greater efficiency than maceration in extracting desired compounds.	● Percolation exhibits lower extraction efficiency compared to some alternative methods. ● Percolation is characterized by extended extraction times.	Alkaloids, sterols, flavonoids, glycosides, saponins,	[23,24]
			phenols, lignin, sterols, and tannins	
Decoction	● Decoction is a highly economical method due to its reliance on water, a readily available solvent. ● Decoction utilizes only water as a solvent, eliminating the need for expensive and potentially hazardous organic solvents. By using water as the solvent, decoction minimizes environmental impact compared to methods that require harsh chemicals.	● A decoction is best suited for extracting compounds that can withstand high temperatures without degrading. ● Light-sensitive compounds can be damaged during the boiling process. A decoction may not be the ideal method for these materials. ● The efficiency of extracting desired compounds through decoction is heavily influenced by how well heat and the target compounds move throughout the	Antioxidants and Polyphenol	[25,26]

		solution.		
Solid- liquid extraction	● This method is efficient, using less solvent to achieve the desired extraction. ● Compared to other techniques, this method boasts a shorter extraction time. ● This method is straightforward to implement in a laboratory setting.	● These methods are not recommended for extracting volatile compounds. ● They are also not suitable for heat- sensitive compounds.	Essential oils, flavonoids, and polyphenols	[27,28]
Soxhlet extraction	● The Soxhlet extraction method offers a highly efficient way to extract target compounds from solid materials. Soxhlet extraction is a relatively low-cost technique, making it accessible for a wider range of research budgets. ● The underlying principles of Soxhlet extraction are fundamental, allowing for a straightforward understanding of the process. The Soxhlet extractor itself is a user-friendly apparatus, requiring minimal technical expertise to operate.	● The method is not ideal for extracting volatile and heat-sensitive compounds. Soxhlet extraction requires relatively large volumes of solvent. Sample preparation for Soxhlet extraction can be time- consuming.	Phenolics, antioxidants, essential oils, and flavonoids	[29,30]
Hydro-distillation	● Hydro-distillation is a time-tested and straightforward technique, making it one of the oldest and simplest methods for extracting bioactive compounds. This versatile process can be further classified into different methods, including steam distillation, water disstillation, and hydro-diffusion distillation.	Hydro-distillation is not ideal for extracting bioactive compounds from heat- sensitive components, as the high temperatures can degrade their delicate chemical structures. While a well-established technique, hydro- distillation can be time-consuming, requiring longer processing times.	Essential oils and phenolics.	[31,32]
	● Due to its relative simplicity, hydro- distillation remains a popular choice for small-scale bioactive compound production. ● For extraction of bioactive compounds, this method utilizes water as a solvent.	compared to some alternative methods. The process of hydro-distillation can be energy-intensive, as it relies on boiling large volumes of water to generate steam for extraction.		

The thinness allows for better penetration into the fruit waste, ensuring good contact with the target compounds [33]. SFE solvents also exhibit lower surface tension. Surface tension is a property that can hinder the interaction between a liquid and a solidThe lower surface tension of the SFE solvent allows for superior contact between the solvent and the desired compounds within the fruit waste, promoting efficient extraction. SFE provides unmatched tunable extraction power. By adjusting the operating pressure and temperature of the SFE process, researchers can precisely target specific compounds for extraction. This level of control allows for the selective extraction of high-value components from the fruit waste. Carbon dioxide in its supercritical state is often the preferred choice because it reaches its critical point at relatively mild conditions (31.1 °C and 73.8 MPa), is non- toxic, and doesn't react easily with other chemicals [34]. The utilization of supercritical CO2 in extraction processes yields purer extracts compared to conventional extraction methods. Supercritical fluid extraction has several advantages, including comparable solvating capabilities to liquid organic solvents, enhanced solute diffusivities, reduced viscosity, decreased surface tension, and the ability to modify solvating power by pressure or temperature adjustments [35]. It is a popular method applied to extract a wide range of materials, from insecticides and environmental samples to food ingredients like flavorings and essential oils, as well as polymers and other natural products. Despite its versatility, SFE faces two main challenges hindering its widespread commercial use. First, the technology can be expensive to implement. Second, SFE has traditionally been developed as a standalone process, not considering how it would integrate with other processing steps needed to create a final product. This lack of integration adds complexity and cost, further limiting commercial adoption [36].

Ultrasound-assisted extraction (UAE):

It is a method employed for bioactive compound recovery like antioxidants, essential oils, steroids, and lipids, from various plant sources [37]. Sound waves, characterized by frequencies over 20kHz, propagate across various mediums and encompass cycles of expansion and compression.

During green solvent extraction, manipulating pressure plays a crucial role. Expansion forces molecule During green solvent extraction, manipulating pressure plays a crucial role. Expansion forces molecules apart, while compression brings them closer together. Liquid expansion can lead to the formation and collapse of bubbles, which can be harnessed to improve mass transfer between the solvent and the fruit waste. Near a solid barrier, these collapsing bubbles create an asymmetrical effect. High-speed jets of liquid shoot out, potentially impacting and disrupting the fruit material, aiding in the extraction processes apart, while compression brings them closer together. Liquid expansion can lead to the formation and collapse of bubbles, which can be harnessed to improve mass transfer between the solvent and the fruit waste. Near a solid barrier, these collapsing bubbles create an asymmetrical effect. High-speed jets of liquid shoot out, potentially impacting and disrupting the fruit material, aiding in the extraction process. Ultrasound waves enhance solvent penetration into the cellular material of the fruit, facilitating increased mass transfer of target compounds into the solvent. Additionally, ultrasound can disrupt biological cell walls, promoting the release of valuable cellular contents. Notably, the effectiveness of ultrasound in this process depends on the frequency used. The optimal frequency will vary based on the specific characteristics of the fruit material being extracted [38].

Compared to traditional methods, ultrasound-assisted extraction offers a more efficient approach to fruit waste valorizations within the biorefinery framework. This technology drastically reduces the high temperature and pressure requirement, leading to faster processing and potentially higher yields of valuable bioproducts. Additionally, the equipment for ultrasound-assisted extraction is generally less expensive compared to microwave-assisted extraction [39]. Ultrasound-assisted extraction offers many benefits, but there are some limitations to consider. One issue is that sound waves travel less effectively (attenuate) when there are solid particles mixed in with the liquid (dispersed phase). This can happen with fruit waste, which may not be completely homogenized. Another challenge is the difference in how readily the particles and liquid heat up and compress (compressibility and heat capacity) and how quickly heat moves between them (thermal diffusion). These differences can make it harder to extract all the desired compounds [40] efficiently. Finally, the effectiveness of ultrasound weakens the farther you get from the source (emitter) inside the extractor. This means that some areas of fruit waste may not be exposed to the same level of sound energy. Ultrasound allows for extraction at lower temperatures and pressures than traditional methods. The efficiency of ultrasound-assisted extraction (yield and kinetics) depends heavily on both the frequency used and the specific properties of the plant material being processed [41].

Microwave-assisted extraction (MAE)

Microwaves are a type of electromagnetic radiation characterized by the presence of both electric and magnetic fields. Microwave technology presents a viable alternative to the conventional solid-liquid extraction method for the extraction of nutraceuticals from plants due to its ability to significantly reduce extraction time and solvent use, while also enhancing extraction yields. [42] Microwaves offer a promising avenue for solvent-free or reduced- solvent extractions. Unlike traditional heating methods, microwaves directly interact with the material at a molecular level, leading to faster and more uniform heating. This translates to quicker extraction times, minimized thermal degradation, and potentially lower energy consumption, making it an attractive green technology [43]. Biorefinery processes for fruit waste valorization require the development of techniques to extract heat-sensitive compounds. Vacuum microwave-assisted extraction is a valuable tool, employing a vacuum environment for efficient extraction under mild conditions.

Microwaves utilize a specific type of energy to heat. They work by rapidly changing electric and magnetic fields that interact with certain molecules in food. This interaction is most effective with molecules that have a positive and negative end, like tiny magnets. These "polar" molecules are more likely to absorb the microwave energy, which makes them vibrate and heat up. This targeted heating is what allows microwaves to cook food quickly and efficiently. This technique relies on the fact that microwaves interact differently with materials based on their electrical properties. Materials with high polarity, like water in fruit waste, absorb microwave energy more readily. This internal heating disrupts plant cell walls, releasing the trapped chemicals and making them easier to collect [44,45]. Conventional

solid-liquid extraction methods for nutraceuticals from plants often require large volumes of solvents and lengthy processing times. This raises concerns about environmental impact and cost-effectiveness. Microwave technology offers a greener alternative [46].

Microwave technology significantly reduces extraction time and solvent use compared to traditional methods. This translates to a more environmentally friendly process. Additionally, it can enhance the yield of extracted nutraceuticals. Microwave-assisted extraction shares some advantages with supercritical fluid extraction, such as process simplicity and cost-effectiveness. However, it's generally less expensive than ultrasound-assisted extraction. Researchers have developed various microwave extraction techniques, including methods suitable for extracting heat-sensitive compounds under milder conditions. These methods offer several advantages over traditional solvent extraction, such as reduced environmental impact and improved efficiency. Vacuum Microwave-Assisted Extraction: This approach utilizes a vacuum to gently draw out the desired compounds from the fruit material. This is particularly beneficial for heat-sensitive molecules [43].

Nitrogen-protected microwave-assisted extraction: In this extraction method nitrogen gas is used to create a pressurized environment within the extraction vessel. This technique is particularly well-suited for the biorefinery approach as it protects oxygen-sensitive compounds abundant in fruits. Ultrasonic Microwave-Assisted Extraction: This method combines the power of microwaves with ultrasonic waves. The ultrasonic waves create microscopic vibrations that disrupt plant cell walls, allowing for a more efficient release of valuable compounds.

Pulsed-electric field assisted extraction (PEFE)

Pulsed electric field has garnered significant interest in the food sector as a promising developing technique to enhance mass transfer operations. The process of electroporation involves subjecting cell material to brief applications of strong external electric fields, typically ranging from 1 to 50 kV/cm, for a duration of microseconds to milliseconds. This results in the permeabilization of cell membranes [47]. The utilization of pulsed-electric field (PEF) presents numerous advantages in comparison to alternative methodologies, including elevated temperatures and enzymatic treatments. The PEF process offers the advantage of reduced energy costs.

Pulsed electric field (PEF) treatment weakens the cell wall, making it easier for valuable bioactive compounds to escape. This significantly increases the amount of these compounds extracted from the fruit waste. PEF offers several advantages over traditional methods like heat or enzymes. Unlike these methods, PEF uses less energy and keeps temperatures low. This is important because high temperatures can damage cell membranes, releasing unwanted molecules and destroying heat-sensitive bioactive compounds. PEF avoids this by creating small, temporary pores in the cell wall, allowing the desired compounds to pass through without harming the cell or the valuable molecules inside [48].

Enzyme assisted extraction (EAE): Enzymes offer a promising method to extract valuable bioactive compounds from fruit waste in biorefineries. By employing enzymes, either alone or combined, this green technique disrupts the cell wall, enhancing permeability. This translates to increased extraction yields of various target compounds like polysaccharides, oils, natural colors, flavors, antioxidants, and medicinal components, all without resorting to harsh chemicals [49]. In the domain of green extraction, enzyme-assisted extraction (EAE) leverages enzymes derived from various eco-friendly sources like bacteria, fungi, plant extracts, and even byproducts from animal sources. Optimizing factors like processing time, temperature, pH, and the enzyme to substrate ratio is crucial to maximize the yield of target compounds while minimizing environmental impact [50].

Enzyme-assisted extraction (EAE) offers an environmentally friendly solution. Specific enzymes, like pectinases, cellulases, and hemicelluloses, act like microscopic scissors, snipping apart the components of fruit cell walls. This increases cell wall permeability, allowing researchers to extract more of the desired compounds – from polysaccharides and oils to natural colors, flavors, antioxidants, and even medicinal components. The beauty of EAE lies in its versatility. Enzymes can be derived from various sources, including bacteria, fungi, animal organs, and even plants themselves. To maximize extraction yields, researchers can fine-tune the process by adjusting factors like time, temperature, pH, and the amount of enzyme used compared to the amount of fruit waste (enzyme to substrate ratio). This technique utilizes enzymes at the beginning of the processing line to achieve several advantages. It can significantly reduce extraction times, minimize the amount of solvent required, and ultimately improve the yield and quality of the extracted products. However, enzyme-assisted extraction does face

some technical limitations. A primary concern is the cost associated with processing large volumes of fruit waste. Enzymes can be expensive, and their large-scale application can translate to high overall processing costs. Our current enzyme cocktails lack the complete power to break down all components of plant cell walls. This limits the potential yield of extracted compounds [49]. Scaling up enzyme-assisted extraction for industrial applications remains a hurdle. Enzymes are sensitive to their environment, and their effectiveness can change significantly based on factors like oxygen levels, temperature, and nutrient presence.

HYDROTROPIC EXTRACTION (HE)

Hydrotropes are molecules readily water-soluble and contain a single negatively charged group with a water-repelling aromatic ring structure. Fruit waste valorization is significantly enhanced by employing hydrotropes. This approach overcomes the challenge of extracting poorly water-soluble compounds, leading to improved efficiency in recovering valuable chemicals from fruit discards [51]. Examples of these non-toxic hydrotropes include substances derived from common sources like fruits (polyhydroxy benzene) and fermentation processes (sodium salts of lower alkanols), along with naturally occurring aromatic compounds like cumene, toluene, and xylene [52]. Hydrotrope separation of active chemicals is the simplest but most important step. Hydrotropes lower interface surface forces during extraction, improving cell wall wettability and allowing hydrotrope molecules to penetrate phytochemical cellulose structures [53]. Limonin can be successfully extracted from citrus fruit waste using a range of eco-friendly solvents, such as sodium benzoate, niacinamide, sodium salicylate, sodium acetate, urea, and sodium citrate [54].

Ionic Liquid Extraction (ILE)

Fruit waste valorization can benefit from ionic liquids (ILs), unique salts that are liquid at room temperature (below 100 °C). These ILs are typically composed of a large organic molecule (cation) paired with another molecule, either organic or inorganic (anion). These compounds are sometimes referred to as "designer solvents" due to their unique characteristic of being customizable [55]. Ionic liquids (ILs) offer a unique set of advantages for extracting valuable compounds from fruit waste. These designer solvents boast exceptional stability under heat and resist burning. Additionally, ILs conduct electricity efficiently and can operate within a broad range of electrical conditions. Furthermore, their ionic nature translates to high density and minimal evaporation, simplifying the process of isolating the extracted organic materials [56]. Table 2 indicates a literature survey on different novel valorization methods

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Table 2. Literature survey on different novel valorization methods**.**

Fruit waste	Method	Optimum condition	Product extracted	Reference
Banana peel (*Musa Paradisiaca Cv. Tanduk*)	Supercritical water extraction	Temperature: 140 °C Time: 5 min Solvent: Water Particle size: 1.18 mm	Pectin yield: 4.23 %	[57]
Mango kernel (*Mangifera. Indica cv.*)	Solvent extraction	Weight: 0.5 gm Solvent: 25 ml Me-OH: water ratio: 3:2 (v/v)	Total polyphenols: 72.05 mg GAE/g DM	[58]
Litchi seeds (*Litchi chinensis Sonn*)	Solvent extraction	Solid to liquid ratio: 1:20 ethanol concentration: 41% Temperature: 51°C Time:139 min	Extraction yield: 8.9 mg/ 100g DW Extraction of phenolic compound: 967 mg GAE/ 100g DW	[59]
Longan seeds (*Dimocarpus longan*)	Solvent extraction	Solid to liquid ratio: 1:20 Ethanol concentration: 53% Temperature: 58°C Time: 220 min	Extraction yield: 14.2 mg/100g DW Extraction of Phenolic compound: 6144 mg GAE/100g DW	[60]
Jackfruit (*Artocarpus heterophyllus*)	Acid extraction	Solid to liquid ratio: 1:29 (w/v) Temperature: 80 °C PH: 2.0 Solvent:1 M H_2SO_4 Extraction time: 105 min	% Yield of Pectine : Core: 35.13 Tandem: 28.21 Peel: 25.35	[60]
Mango kernel (*Mangifera. Indica cv. Nam Dokmai*)	Supercritical CO extraction 2	Pressure: 50 Mpa Temperature: 40 °C Flowrate: 30 g/min	Polar lipid yield: 3.28%	[61]

Apple seed (*Malus pumila*)	Supercritical CO extraction 2	Pressure: 24 Mpa, Temperature: 40 °C Flowrate:1 L/h Time:140 min	Linoleic acid content: 63.76 g/100 g Phloridzin content: 2.96 µg/g	[62]
Citrus peel (*Satsuma Mandarin*)	Pulsed electric field extraction + Subcritical water extraction	For Hesperidin: PEF treatment time: 120 sec	Hesperidin extraction yield: 46.96% Narirutin extraction yield: 8.76%	[63]
		SWE at 150 °C for 15 min, For Narirutin, PEF treatment time: 120 sec SWE at 190 °C for 5 min		
Lemon peels (*Citrus limon*)	Microwave-assisted extraction	Solvent: ethanol Concentration: 80% (v/v) Liquid to solid ratio: 1:10 Temp: 80°C Time: 50 min	Essential oil yield: 2% Pigment yield: 6%	[64]
Watermelon rind (*Citrullus lanatus*)	Microwave-assisted extraction	Solvent: 0.5 N sulfuric acid Time: 15 min Solid to liquid ratio: 1:08 Microwave power: 39.9 W	Pectin yield: 11.25%	[65]
Mango peel (*Mangifera. Indica cv.*)	Microwave-assisted extraction	Microwave power: 700 W Time: 3 min HCl concentration: 2 M pH: 1.5	Pectin yield: 13.85%	[66]
Mango peel (*Mangifera Indica cv.*)	Microwave-assisted extraction	Microwave power: 500 W Time: 20 min HCl concentration: 1 M pH: 1.5	Pectin yield: 10.33%	[67]
Banana peel (*Musa acuminata x Musa balbisiana)*	Microwave-assisted extraction	Microwave power: 1000 W Time: 60 s Temperature: 195°C pH: 3.0	Pectin yield: 14.2%	[68]
Dragon fruit peels (*Hylocereus polyrhizus*)	Microwave-assisted extraction	Microwave power: 600 W Extraction time: 65 s pH: 2.07 Solid to liquid ratio: 66.57	Extraction yield: 17.2% Pectin yield: 69.68%	[69]
Jackfruit peel (*Artocarpus heterophyllus*)	Ultrasound-assisted extraction	Solvent: Citric acid Frequency: 2450 MHz Ultrasound power: 500 W	Pectin yield: 21.5%	[70]
		Time: 29 min Temperature: 86°C pH: 2.0		
Acerola residue (*Malpighia emarginata*)	Ultrasound-assisted extraction	pH: 2 Ethanol to residue ratio: 8.7 mL/g Temperature: 30 °C Time: 49.3 min	Anthocyanin: 2.00 to 11.16 mg TA/100 g	[71]
Dragon fruit peel (*Hylocereus undatus*)	Ultrasound-assisted extraction	Solvent: 80% acetone Ultrasound time: 15 min Temperature: 100°C	Betalains: 101.04 mg/100g Carotenoids: 1.58 µg βCE/g	[72]
Pineapple peel (*Ananas comosus*)	Ultrasound-assisted extraction	Temperature: 70.83°C pH: 1.0 Liquid to Solid ratio: 15.20 mL/g Sonication time: 21.88 min	Pectin yield: 16.24%	[73]
Pomegranate peel (*Punica granatum*)	Ultrasound-assisted extraction	Solvent: Sunflower and Soy oil Time: 30 min Peels to solvent ratio: 0.10 Temperature: 51.5 °C	Sunflower oil: 0.6134mg carotenoids/100g of DW Soy oil: 0.6715 mg carotenoids/100g of DW	[74]
Banana peel (*Musa acuminata x balbisiana*)	Enzyme-assisted extraction	Temperature: 55 °C Time:120 min Pectinase: 0.103 g/mL pH: 5.0 Enzyme: *Aspergillus niger*	Pectin Yield: 10.8%	[75]
Watermelon seeds (*Citrullus lanatus*)	Enzyme-assisted extraction	Temperature: 47.13 °C pH: 7.89 Enzyme: Protex 6L Enzyme dose: 2.63% Time: 7.8 h	Acid yield 97.92%	[76]
Banana peel (*Musa Paradisiaca Cv. Tanduk*)	Enzyme-assisted extraction	Types of enzymes: Viscozyme L, cellulose, pectinase Enzyme concentration: 1.0% Extraction time: 9 hr	TPC: 25.37 mg GAE/g DM TFC: 13.99 mg QE/g DM, DPPH: 81.59%, ABTS: 88.25%,	[77]

		Extraction temperature: 55°C Solute:liquid ratio: 1:25	α-glucosidase inhibitory effect: 74.67%	
Litchi (*Litchichinensis cv. Bombai*)	Enzyme-assisted extraction	Enzyme concentration: 1.0%, Extraction temperature: 55°C pH: 4 Incubation time: 1 h	TPC: Peel: 40.78 mg GAE/g DM Seed: 5.04 mg GAE/g DM TFC: Peel: 9.31 mg QE/g DM Seed: 0.13 mg QE /g DM	[78]
Litchi (*Litchichinensis cv. Bombai*)	Pressurized hot water extraction	Solid to liquid ratio: 1:20 Pressure: 20 psi. Temperature: 120°C Time: 30 min	TPC: Peel: 103.57 mg GAE/g DM Seed: 75.64 mg GAE/g DM TFC: Peel: 13.64 mg QE/g DM Seed: 8.96 mg QE /g DM	[78]
Lemon seed (*Citrus limon*)	Hydrotropic Extraction	Temperature: 44°C Time: 4 hr Hydrotropic solution: Sodium Salicylate(Na-Sal) Hydrotrope concentration: 1.65 M 8.08% of raw material loading.	Limonin: 6.41 mg/g	[79]
Sour orange seed (*Citrus aurantium L.*)	Hydrotropic Extraction	Temperature: 45°C Solid loading:10% Hydrotropic solution: Sodium Salicylate (NaSal) Sodium Cumene sulphonate (Na-CuS) Concentration: 2 M	Using Na-CuS: Limonin yield: 0.65 mg/g Using Na-Sal: Limonin yield: 0.46 mg/g	[80]
Mangosteen pericarp (*Garcinia mangostana L*)	Hydrotropic Extraction	Hydrotrope concentration: 2M Temperature: 40°C Solid loading: 3%	Xanthones yield: 4.69 mg/g	[81]
		Hydrotropic solution: Sodium Salicylate (Na-Sal)		
Jackfruit rind (*Artocarpus heterophyllus*)	Pulsed electric field extraction + Microwave treatment	Microwave power density: 647.30 W/g Pulsed-field strength: 11.99 kV/cm Time of exposure: 5 min	Pectin yield: 18.24%	[82]
Mangosteen pericarp (*Garcinia mangostana L*)	Pulsed electric field extraction	Hydrotrope concentration: 2 M Temperature: 40°C Solid loading: 3%	Xanthones yield: 4.69 mg/g	[83]
Watermelon Rind (*Citrullus lanatus*)	Ionic liquid-based ultrasound-assisted extraction	Ionic liquid concentration: 1.5 M Solid to liquid ratio: 1:40 Salt concentration: 35% Ultrasound Power: 100 W Ultrasonic time: 15 min	Amino acid recovery: 90.45%	[84]
Orange peel (*Citrus sinensis*)	Ionic liquid-based ultrasound-assisted extraction	Sample Weight: 5.0 g Ultrasound power: 200 W Frequency: 20 kHz Amplitude: 80% Time: 5 min Solid-liquid ratio: 1:3	Carotenoids yield: 39.99 µg/g	[85]

QUALITATIVE METHODS

A. Determination of total phenolic compounds (TPC)

Plant secondary metabolites, known as phenolic compounds, encompass a diverse array of molecules characterized by the presence of an aromatic benzene ring substituted with one or more hydroxyl moieties. These compounds exhibit various functionalities due to the existence of derivatives such as glycosides, esters, and methyl esters. Fruit and vegetable processing byproducts serve as a plentiful source of these phenolic constituents.

The Folin-Ciocalteu (FC) method was employed to quantify the total phenolic content (TPC) of the extract. Briefly, the extract (0.5 ml) was reacted with FC reagent (2.5 ml, 10%) for 5 minutes, followed by the addition of sodium carbonate solution (2.5 ml, 7.5%). The mixture was incubated for 30 minutes at ambient temperature without light exposure. A blank, prepared without the extract, was included for comparison. Following incubation, the absorbance was measured at the maximum wavelength (λ_max= 765 nm) using a spectrophotometer. This procedure was replicated to obtain reliable data, and the mean absorbance was used for further analysis.

The calibration line was construed and the total phenolic content of extract was calculated using the equation presented in Eq (i).

$$\text{Total phenolic content (TPC)} = (C \times Ve)/M \quad \text{Eq(i)}$$

where C indicates the standard concentration

(gallic acid), Ve indicates extract volume, and M weight of the material.

Giri *et al.,* (2016) have applied Folin-Ciocalteu (FC) method for the quantitative analysis of total phenolic compounds for the ultrasound assisted phytochemical extraction of persimmon fruit peel. Ultrasonic power has the highest effect on total phenolic compound followed by temperature, solvent to solid ratio and solvent concentration. Combining solvent extraction with ultrasonication offers a significant advantage for extracting phenolic compounds from plant material. This technique utilizes acoustic cavitation, a process that creates microscopic bubbles within the solvent. The collapse of these bubbles generates high shear forces that effectively break down cell walls. This enhances solvent penetration into the cells, promoting the release and dissolution of the target phenolic compounds, ultimately leading to increased extraction yield [86]. Velderrain-Rodriguez *et al.* (2021) investigated the total phenolic content (TPC) of avocado peel and seed extracts using maceration with 80% ethanol. Maceration involved stirring the avocado material (solid) in the solvent at a 1:15 solid-to- solvent ratio for 20 hours at 40°C. The avocado peel extract exhibited a significantly higher TPC (142.23 mg gallic acid equivalents (GAE)/g) compared to the seed extract (63.19 mg GAE/g). This difference in TPC likely contributes to the higher antioxidant activity expected in the avocado peel extract. Phenolic compounds are well-documented for their antioxidant properties, and their abundance can influence the overall antioxidant capacity of a plant extract [87].

B. Determination of total flavonoid compounds (TFC)

Flavonoids represent a remarkably diverse and abundant class of secondary metabolites found within the plant kingdom. These polyphenolic compounds are ubiquitous throughout the plant world, with a presence in a vast array of edible plant species. They are recognized for their potential health benefits due to their possession of numerous biologically and physiologically active moieties. This widespread occurrence and structural diversity within flavonoids contribute significantly to their potential advantages for human health. The total flavonoid content of the extract was determined using a spectrophotometric method. Briefly, the extract was reacted with sodium nitrite and aluminium chloride, followed by the addition of sodium hydroxide. The resulting mixture's absorbance was measured at 510 nm using a UV spectrophotometer. A calibration curve was generated using known concentrations of quercetin (QE) standard solution, following the same reaction protocol. The total flavonoid content in the extract was then expressed as milligrams of quercetin equivalents (mg QE) per gram of dry weight.

$$Total\ Flavonoid\ content\ (TFC) = (Ce \times Ve \times D)/M \quad \text{Eq(ii)}$$

where Ce is the extract concentration (mg QE/mL) obtained from the calibration curve; Ve is the volume of extract; D is the dilution factor; M is the mass of the extract.

Da Silva Francischini *et al*., (2020) performed Homogenizer assisted extraction, Ultrasound assisted extraction and microwave assisted extraction on the passion fruit peels and HAE stand out as the one of the best extraction methods with better extraction yields and lowest energy consumption. 0.1 sample/solvent ratio, 70% solution of ethanol in water and 2 min of extraction time set as optimum parameter for HAE with highest recovery of 0.94, 1.11 and 0.34 mg/g for orientin, isoorientin and isovitexin, respectively, which is higher than UAE and MAE [88].

C. Determination of antioxidant activity

1. 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay

The antioxidant activity was measured using the DPPH (2,2-diphenyl-1- picrylhydrazyl) assay. It is based on reduction of 2,2-diphenyl-1-picrylhydrazyl radicals, which are scavenged by antioxidant compounds. This involved mixing 50 µL of the extract with 2 mL of DPPH ethanolic solution (20 µM) and measuring the absorbance after 960 s at 517 nm. Colour changes were observed indicating the reaction of the reactive antioxidant compound with the reagent. To calculate the antioxidant activity (%AA) the eq. (iii) is used:

$$\%AA = \left(\frac{(\text{AbsControl} - \text{AbsSample})}{\text{AbsControl}}\right) \times 100 \quad \text{Eq(iii)}$$

Solvent with extract used as a blank. DPPH with solvent used as negative control [89]. Catechin, ascorbic acid, and Trolox (6-hydroxy-2,5,7,8-tetramethylchroman-2- carboxylic acid) were used as pure standards. The effective concentrations necessary to scavenge 50% of DPPH radicals (EC50) were calculated for all analyzed samples and Trolox using graphical regression analysis and expressed as v/v% (relative to the volume of DPPH solution) [90].

2. Ferric reducing antioxidant power (FRAP) assay

The ferric reducing antioxidant power (FRAP) assay was employed to assess the reducing potential of the sample extracts. The reducing ability of the sample is determined by its capacity to convert ferric

tripyridyltriazine (Fe3+-TPTZ), a colorless complex, to its ferrous form (Fe2+-TPTZ), which exhibits a distinct blue color [91].

The difference in light absorption at 593 nm can be used to estimate the antioxidant potential of the extracted bioproducts. Methodology was established by Benzie and Strain (1996). A FRAP reagent was prepared by mixing a 300 mM sodium acetate buffer solution, 10 mM 2,4,6-tripyridyl-s-triazine (TPTZ) solution, and 20 mM ferric chloride solution in a 10:1:1 volume ratio. Samples (20 µL) were combined with freshly prepared FRAP reagent (280 µL) and incubated for 10 minutes at 37 °C. Following incubation, the light absorption of the samples was measured at a wavelength of 593 nm. To quantify the antioxidant activity, a calibration curve was constructed using known concentrations of ascorbic acid (0-50 µg/mL). The final results are expressed as milligrams of ascorbic acid equivalents (AAE) per gram of fresh sample weight. [92,93].

3. 2,2′ -Azinobis(3-ethylbenzothiaziline-6-sulfonate) (ABTS) assay

The 2,2'-Azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical cation assay was employed to evaluate the antioxidant capacity of fruit waste extracts. Solutions of ABTS and potassium persulfate were prepared at concentrations commonly used in antioxidant activity assays. The ABTS concentration was 7.4 millimolar, and the potassium persulfate concentration was 2.6 millimolar. A working solution of ABTS radical cations was generated by mixing equal volumes of these stock solutions and incubating for 12 h at room temperature in the dark to allow for complete radical formation. The working solution was then adjusted to an absorbance of 1.1 units at 734 nm using a dilution with methanol (1:60, ABTS: methanol). Fresh ABTS working solution was prepared for each experiment to ensure consistent radical activity.

The antioxidant capacity of the extracts was determined by their ability to quench the ABTS radical cation. Fruit waste extracts (150 µL) were mixed with 2850 µL of the ABTS working solution and incubated for 2 hours under dark conditions. The reduction in absorbance at 734 nm was measured using a spectrophotometer, reflecting the extract's antioxidant potential. A Trolox standard curve (25-600 µM) was used for calibration, and results are expressed as micromolar Trolox equivalents (TE) per gram of fresh sample mass. To ensure reliable measurement of antioxidant activity (represented by the ABTS value), samples exceeding the standard curve's range required further dilution [94].

Marjanovic *et al.,* (2021) measured the antioxidant activity and polyphenolic content of eight berry species from Bosnia and Herzegovina. They found that the berries had significant antioxidant activity and high levels of polyphenolic compounds, with black chokeberry having the highest anthocyanin content [95]. Uuh-Narváez et al., (2023), reported that mango (*Mangifera indica L cv Ataulfo*) peels and seeds waste are a rich source of bioactive compounds and have significant antioxidant activity. Mango seed flour had the highest antioxidant activity (DPPH: 1.10 mg Trolox/g, FRAP: 1.30 mg Trolox/g) [96].

Bansod *et al*. (2023) investigated the microwave-assisted extraction (MAE) of bioactive compounds from pineapple peel waste. They optimized the extraction process using a Box-Behnken design (BBD) to identify the most favourable conditions for yield. The optimal parameters were found to be a solvent-to-substrate ratio of 20 mL/g, microwave power of 600 W, and extraction time of 40 minutes. Under these optimized conditions, the extract exhibited strong antioxidant activity, with a DPPH radical scavenging capacity of 75%. Additionally, the researchers quantified the proteolytic activity of bromelain, an enzyme present in pineapple peel, and determined it to be 1647.612 GDU/g concentrate [97].

Capeletto *et al*. (2016) investigated the effect of extraction method on the phenolic content and antioxidant activity of extracts from *Campomanesia xanthocarpa* seeds. They compared supercritical CO_2 extraction at 40 °C and 250 bar with n-butane extraction at 35 °C and 10 bar. Notably, n-butane extraction yielded a significantly higher amount of total phenolic compounds (17.18 mg/g) compared to supercritical CO_2 extraction (68.58 mg/g). Furthermore, n-butane extracts exhibited stronger antioxidant activity as measured by FRAP, DPPH, and deoxyribose assays. These findings suggest that n-butane extraction, despite yielding lower total phenolics, might be a more efficient method for obtaining antioxidants from *C. xanthocarpa* seeds [98].

D. Determination of carotenoids

Carotenoids, the preeminent naturally occurring pigments, have garnered significant interest in recent years owing to their advantageous attributes. These pigments boast low toxicity, exhibit a diverse structural landscape, and possess a ubiquitous presence. Notably, they are naturally sourced and contribute to physiologically important functions, thereby promoting human health. It is well-established that the concentration of carotenoids within foodstuffs is susceptible to a multitude of post-

harvest factors and processing techniques [100].

Lima *et al*., (2019) demonstrated method for quantification of total carotenoids content. Briefly, the isolated extracts were transferred to petroleum ether, a non-polar solvent suitable for carotenoid extraction. To disrupt cell walls and release bound carotenoids, saponification was performed using a 10% sodium hydroxide methanolic solution for 16 hours. Following saponification, the extracts were washed with ultrapure water to remove residual contaminants and then dried with sodium sulfate to eliminate water [100]. The absorbance of the final extracts was measured at a specific wavelength (λ = 470 nm) using a spectrophotometer. This absorbance value, along with established equations eq. (iv) and eq. (v), was used to calculate the total carotenoid content present in the original samples.

where x is the carotenoid concentration, A is the absorbance, v is the volume of the solution, w is the sample weight, $A^{1\%}_{1}$ is the absorption coefficient of the carotenoid in the solvent used ($A^{1\%}_{1}$ = 3450 for lycopene in petroleum ether).

Carotenoids were quantified using hyphenated techniques to minimize degradation from light and oxygen exposure. High-performance liquid chromatography (HPLC) with C30 columns provided selectivity for quantification of the major carotenoid stereoisomers (Z and E isomers). To definitively identify these isomers, the HPLC system was coupled online with two complementary techniques: atmospheric pressure chemical ionization mass spectrometry (APCI-MS) and nuclear magnetic resonance (NMR). While HPLC-APCI-MS differentiates between lutein and zeaxanthin, HPLC- NMR allows for the identification of all the major Z and E isomers present in the sample [101].

Boukroufa *et al*. (2015) reported recovery of carotenoid from the citrus peel waste using solvent free microwave assisted extraction, ultrasound assisted extraction and steam distillation. The best result was obtained in ultrasound assisted extraction. Effect of n-hexane as compared to limonene is quite negligible. But considering limonene as a green solvent combined with UAE make valorization process more environment friendly. At optimized conditions (ultrasound power, temperature and time were 208 W cm^{-2}, 20 °C and 5 min), 11.25 mg/L of carotenoid can be extracted. The ultrasonic probe-assisted extraction resulted in the greatest degradation of carotenoids [102]. This is likely due to the increased formation of free radicals caused by the high-intensity cavitation generated during the process. Cavitation is the phenomenon of rapid bubble formation and collapse in a liquid medium, and the high energy associated with this collapse can lead to the generation of reactive oxygen species (ROS) that can degrade carotenoids [103].

Mesquita *et al.* (2020), performed valorization of *bactris gasipaes* waste using ionic liquid assisted extraction technique. Maximum yield of carotenoids = 88.7 μg carotenoids/ g of dried waste was achieved at the optimum conditions of extraction time: 8.2 min; concentration 140 mM of IL, and Solid to liquid ratio of 0.15. Further Carotenoids were applied on chitosan -based film which is applicable in food industries for packaging purpose [104].

Chutia and Mahanta (2021) investigated a novel green approach for extracting carotenoids from passion fruit peel waste. They employed ultrasound-assisted extraction (UAE) with olive oil as a solvent, achieving a high extraction yield of 91.4% under optimized conditions. These optimized conditions consisted of a treatment time of 39 minutes, a temperature of 47 °C, and a solid-to-liquid ratio of 0.30 g/mL. This study suggests that UAE with olive oil offers a promising green alternative to conventional solvent extraction methods for the recovery of valuable carotenoids from food byproducts [105].

E. Determination of dietary fibers.

Plant cell walls are reinforced by dietary fibers, which are complex carbohydrates like cellulose, hemicellulose, pectin, and lignin. These fibers provide structural stiffness to the plant. Additionally, dietary fibers can be classified into soluble and insoluble types based on their water solubility. Soluble dietary fibers, such as mucilage, gums, and pectin, dissolve easily in water. Insoluble dietary fibers, including lignin, cellulose, and hemicellulose, do not dissolve in water.

The analytical method for estimation of total dietary fibers was established by Lee et al., (1992). According to this method, add 4 volumes 95% EtOH (heated to 60°C) to digested samples (1 volume). Precipitate at room temperature (1 h). Transfer digestate through Celite bed on crucible. Wash residue with specific solvents under vacuum. Dry residue overnight (105°C), cool, and weigh. Subtract crucible and Celite weight. Analyze separate sample duplicates for protein and ash content using established methods [106].

Khanpit *et a*l., (2023) reported that extrusion improves the recovery of soluble dietary fibers as compared to Ultrasonication process from 22.27% to 24.28 % from orange peel waste. Also, extrusion has 1.5 kg CO_2 equivalent of Global warming potential, which is very low as compared to

Ultrasonication [107].

Kaur *et al.,* (2021) has reported comparative work on novel extraction techniques like enzymatic, ultrasound, and ultrasound-assisted enzymatic extraction for the extraction of dietary fibers from mango peels. Ultrasound waves assisted enzyme extraction significantly increased the yield (71%) of total dietary fibers. The optimal conditions for this process were found to be 25 °C temperature, 40% amplitude, a 1:50 solid-to-liquid ratio, and a 9-minute extraction time [108].

Dietary fiber concentrates used in bakery, meat, dairy snacks and pasta products [109, 110] Soluble dietary fibers are incorporated into beverages to manipulate their rheological properties (flow behavior) and enhance their colloidal stability. Upon hydration, these fibers interact with water molecules, forming a three-dimensional network that increases the beverage's viscosity. This thickening effect contributes to a desirable mouthfeel and prevents undesirable phenomena like sedimentation or phase separation of ingredients [111, 112].

F. Total anthocyanin content

The anthocyanin concentration in samples was determined using the pH differential method. A produced sample solution (0.5 mL) was combined with 0.025 M KCl buffer pH 1.0 (1.5 mL), whereas another portion (0.5 mL) of the same extract was combined with 0.4 M NaOAc buffer pH 4.5 (1.5 mL). Both mixes were aggressively stirred for 30 seconds and left for 15 minutes in the dark. The extinction coefficients of samples were determined at specified wavelengths using buffer as a reference solution. The total anthocyanins content (C), given in mg of cyanidin-3-O-glucoside (Cy3G) equivalents per L, was determined as follows.

$$C = ((A \times MW \times R \times 1000)/(\epsilon \times l) \quad \text{Eq(vi)}$$

Here, absorbance is denoted by A, cyanidin-3-O-glucoside's molecular weight (449.2 g/mol), dilution factor R, molar extinction coefficient (26900 L/(mol.cm)) for cyanidin- 3-O-glucoside, and route length are represented by l and ϵ, respectively. The final results were given as cyanidin-3-O-glucoside equivalents in milligrams per gram of dry matter (DM) [95]. Ivankovic *et al*., (2024) performed extraction using maceration process from berries pomace and reported anthocyanin content present in the blackberry, raspberry, strawberry, and chokeberry as 0.32, 0.09, 0.26, 0.68 cyanidin-3-O-glucoside equivalents in milligrams per gram of dry matter (DM) respectively. Excessive maceration can lead to anthocyanin degradation due to enzymatic activity or exposure to light and oxygen. Water-based solutions with mild acidity are often preferred as they effectively extract anthocyanins while minimizing degradation [114].

SUMMARY AND OUTLOOK

Throughout this review, an overview of the current status of fruit waste generation and valorization has been presented. Discarded fruit parts hold immense potential. They're packed with nutrients, functionality, and nutraceutical properties, making them ideal for various applications in food design. This approach can address economic, social, and environmental issues. To minimize natural resource depletion, environmental harm, and potential threats to food security, rigorous research is crucial in the realm of fruit waste valorization. These fruit residues can be directly incorporated into food products or used to extract valuable components like proteins, lipids, vitamins, and antioxidants. Additional biomolecules can be isolated using physical or chemical methods to create functional and nutritious food ingredients. Maintaining the safety and quality of biomaterials derived from fruit waste is crucial. Drying techniques are essential to prevent microbial growth and ensure the physicochemical and microbiological stability of these materials. We can delve deeper into the potential of emerging valorization techniques like microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), enzyme-assisted extraction (EAE), pulsed-electric field-assisted extraction (PEF), and supercritical CO_2 extraction by employing various optimization methods. The development of a bio-refinery concept for the recovery of value-added products from fruit waste has big opportunities over the landfilling and incineration methods of disposal. Researchers are finding success with solvents like ionic liquids and hydrotropes. Government support is needed to establish infrastructure and technologies for utilizing food waste and byproducts effectively in production and storage facilities. Further research is needed to develop new functional food formulations that are high-quality and appealing to consumers. Industries should explore ways to valorize their fruit waste byproducts by integrating them into novel products. This might involve redesigning processing steps to reincorporate waste streams into the original food product on an industrial scale. It's important to address other potential risks, such as the presence of toxins or antinutrients, in these materials. These solvents not only improve the overall yield of bioactive compounds but they are also considered Generally Recognized as Safe (GRAS) for consumption due to their low toxicity. Increased

public funding for research and development (R&D) can lead to breakthroughs in several areas. (a) Food production: Techniques like vertical farming or drought-resistant crops could increase food yields and improve nutrition. (b) Food processing: Innovations in food preservation and fortification could extend shelf life, reduce waste, and ensure essential vitamins and minerals reach consumers. (c) Distribution: Investments in infrastructure and logistics could connect remote areas to fresh produce markets and incentivize the sale of healthy options in underserved communities. (d) Consumer behavior: Research into food preferences and marketing strategies could nudge people towards healthier choices without sacrificing taste or convenience. By tackling these challenges, a future is created where healthy eating is an accessible and affordable option for everyone.

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