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Review

Valorization of Food Waste to Produce Value-Added Products Based on Its Bioactive Compounds

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Abstract: The rapid growth of the global population and changes in lifestyle have led to a significant increase in food waste from various industrial, agricultural, and household sources. Nearly one-third of the food produced annually is wasted, resulting in severe resource depletion. Food waste contains rich organic matter, which, if not managed properly, can pose a serious threat to the environment and human health, making the proper disposal of food waste an urgent global issue. However, various types of food waste, such as waste from fruit, vegetables, grains, and other food production and processing, contain important bioactive compounds, such as polyphenols, dietary fiber, proteins, lipids, vitamins, organic acids, and minerals, some of which are found in greater quantities in the discarded parts than in the parts accepted by the market. These bioactive compounds offer the potential to convert food waste into value-added products, and fields including nutritional foods, bioplastics, bioenergy, biosurfactants, biofertilizers, and single cell proteins have welcomed food waste as a novel source. This review reveals the latest insights into the various sources of food waste and the potential of utilizing bioactive compounds to convert it into value-added products, thus enhancing people's confidence in better utilizing and managing food waste.

Keywords: food waste; value-added product; waste to wealth; bioactive compound

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1. Introduction

Food is a fundamental component necessary for the survival and sustenance of life. The continuously growing global population demands more food, while also producing significant amounts of agricultural and food waste (FW). According to the definition of the Food and Agriculture Organization of the United Nations (FAO), FW refers to the reduction in the quantity or quality of food resulting from the decisions and actions of retailers, food service providers, and consumers. The generation of FW is also associated with significant losses of other resources, such as water, land, energy, and labor. As reported by the FAO in 2019 [1], around 14% of the world's food, worth US$400 billion annually, is lost after harvest and before reaching stores. Additionally, the Food Waste Index report by the United Nations Environment Programme shows that an extra 17% of food is wasted at retail and by consumers, particularly households. It is estimated that roughly one-third of total food production is generated as FW annually, which could potentially feed 1.26 billion undernourished individuals [2].

Improper handling and disposal of food waste can result in significant environmental damage. Ineffectual management of FW and food loss is responsible for the discharge of approximately 3.3 billion tons of carbon dioxide equivalent or 4.4 kilotons of carbon dioxide equivalent each year, amounting to approximately 8% of the total anthropogenic greenhouse gas emissions into the environment [3]. The valorization of FW through the production of value-added products based on its bioactive compounds is a pioneering solution for reducing waste and generating new economic possibilities (Figure 1). These bioactive compounds, such as polyphenols, vitamins, minerals, and prebiotics, bring numerous health benefits and increase the value of the products [4]. To harness the potential of FW in extracting these compounds, it is possible to create high-quality and functional food ingredients, cosmetic products, and dietary supplements. This approach aims not only to reduce FW but also to create new sources of income and support the creation of a circular economy. To ensure the environmental and economic sustainability of future FW valorization, it is essential to consider the availability of this waste over time, its techno-economic potential, and the environmental assessment of benefits and burdens based on its life cycle [5]. The aim of this review is to provide a detailed summary of the common sources of FW and the interesting bioactive substances they contain. The potential applications and feasible approaches for the conversion of FW into value-added products are addressed for these mentioned bioactive substances. This review also intends to stimulate interest in the conversion and recycling of FW and provides directions and recommendations for future research to improve the management and utilization of FW.

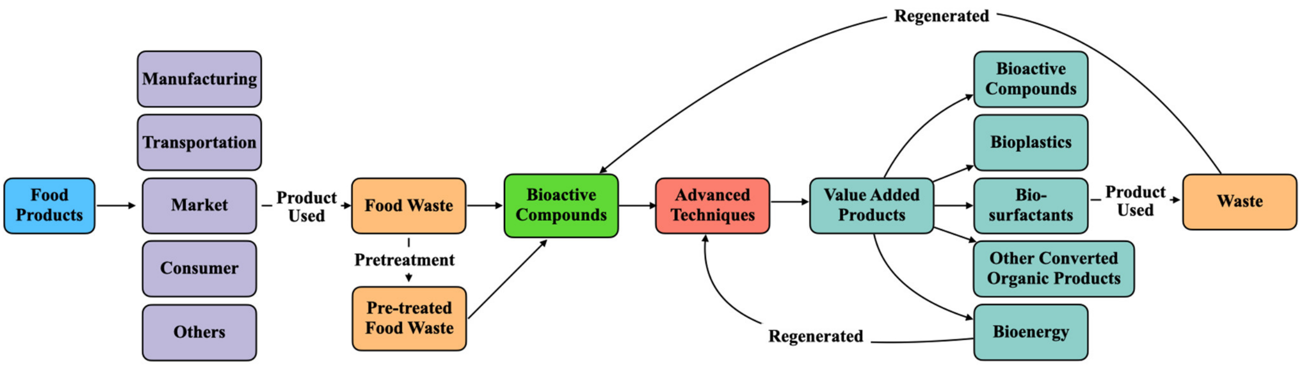


Figure 1. Sources of food waste and opportunities for its conversion into value-added products.

2. Food Waste Generation Sources

2.1. Cereals and Pulses

Cereals, including rice, sorghum, barley, wheat, millet, corn, and buckwheat, are essential energy sources in the human diet, comprising a significant proportion of the food pyramid. According to the online database [6], global cereal production reached 2998.11 million tons in 2020 (Figure 2). In the same year, worldwide production of pulses reached 89.82 million tons [7]. During processing, cereals and pulses yield various by-products such as germ and bran [8]. The malting process is a biochemical conversion of raw grains, such as barley, that transforms them into malt suitable for use in the production of beer, whiskey, and other spirits. This process involves the activation of enzymes that hydrolyze the starch present in the grain into simple sugars. The remaining cereal residue is typically considered a byproduct of the process and is commonly discarded as waste [9]. The husks from the pulses processing can be recycled to produce high-end products. Additionally, stems, leaves, and husks from crops, such as wheat, maize, rice, and barley, are conventionally used to produce handicrafts and implements such as baskets, brooms, and hand fans. Rice husks have multiple uses, including fodder fiber, fertilizer, substrates for composting techniques, and the production of innovative building materials [10].

The processing by-product of barley contains a significantly higher amount of vitamin E (2.7 times more) compared to the whole barley grain. Moreover, it is a rich source of various bioactive compounds, including phytates, phenolics, and insoluble dietary fiber [9]. Hydrolyzing rice bran and rice husk using cellulase also results in the production of phenolic compounds [11]. The remaining shells after cocoa processing can be used to extract pectin, flat mushrooms, and livestock feed, thereby providing value-added products [12]. Additionally, second-generation bioethanol can be derived from coconut husk [13].

2.2. Fruits and Vegetables

Fruits and vegetables are abundant in essential nutrients and contain high levels of water, soluble carbohydrates, fiber, minerals, vitamins, polyphenols, and other bioactive compounds [14]. Despite this, they are often considered waste once they experience changes in color, undergo biochemical reactions, become infested with microbes, experience breakage or frostbite, are subjected to heat treatment, or reach levels of ripeness that make them unacceptable to consumers. This waste can occur at any point in the food supply chain, from the source to the end of the chain. In 2020, the latest data from the FAO [15] indicates that the world produced 2015 million tons of fruits and vegetables (Figure 2). China, as the world's largest producer of fruits and vegetables, accounting for 38% of global production, had a yield of 709 million tons in 2020 [6]. However, during the processes of harvesting, transportation, sales, and processing, nearly 30% of the fruits and vegetables produced were wasted [16]. These fruit and vegetable wastes are either composted, landfilled, incinerated, or repurposed as animal feed. Such disposal techniques have brought about severe environmental problems, including toxic or greenhouse gas emissions and microbial proliferation, owing to the high moisture and waste leachate content [17,18].

Reducing the wastage of fruits and vegetables can help alleviate the pressures caused by growing food consumption and enhance the overall efficiency of the supply chain [19]. Consequently, researchers have intensified their efforts to study FW to identify more effective ways of utilizing this abundant and sustainable resource. One promising avenue involves the hydrolysis of cellulose and starch present in fruit and vegetable waste to extract soluble sugars that can be fermented to produce ethanol and hydrogen [20]. Microbial processing provides novel treatment directions for discarded fruits and vegetables, including single cell proteins (*Saccharomyces* sp., *Candida utilis*, *Endomycopsis fibuligera*, and *Pichia burtonii*), single cell oils, fermented beverages (fenny, vinegar), biopigments (carotenoids), polyphenols, dietary fibers, food additives, enzymes (cellulase, amylase, protease, phytase), biofuels [14,21–25]. Fruit and vegetable wastes can also be fermented to produce lactic acid [26] and succinic acid [18].

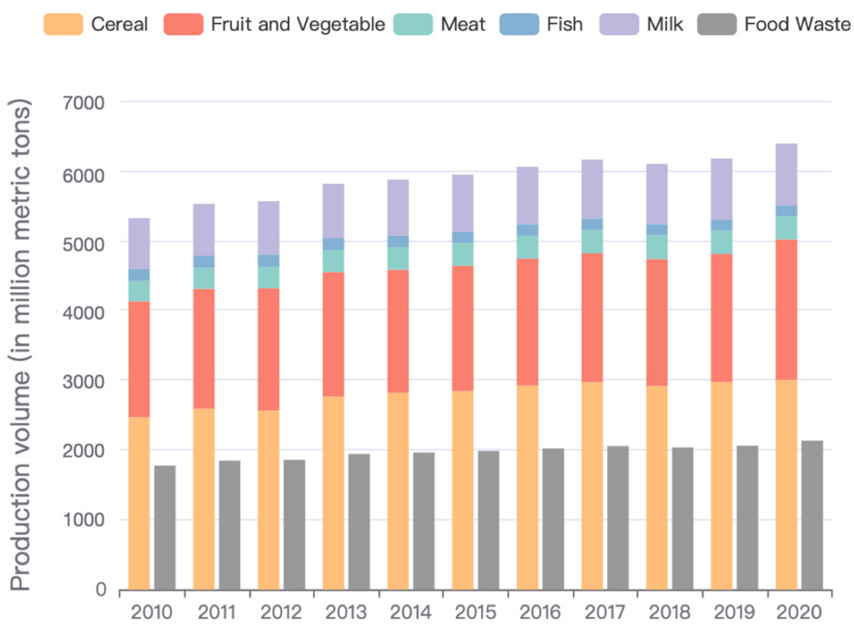


Figure 2. Total global production of several major food sources between 2010 and 2020, and estimated volume of food waste in the same year. Data were obtained from an online database [2,27–29].

2.3. Dairy

Recent research by The Guardian indicates that approximately one-sixth of the total milk production worldwide is lost or wasted, resulting in a staggering annual wastage of around 128 million tons of milk [30]. The dairy industry generates waste due to factors such as processing, microbial spoilage, and inadequate handling [18]. The dairy products' complex organic composition includes proteins, fats, sugars, and a small quantity of food additives [31]. Given their rich composition and absorption potential, they are some of the most susceptible products to perish. Fungal contamination can also contribute to observable or undetectable defects in dairy products, such as unfavorable flavor and spoilage.

India is the world's largest milk producer, generating up to three times the amount of waste for every unit of processed milk, which results in 11.217 million m^3 of waste per year. In cheese production, 9 kg of whey are discarded for every kilogram of cheese produced [32]. The total nitrogen concentration in milk processing wastewater is approximately 14–830 mg/L [33] and this wastewater contains significant amounts of carbohydrates, lipids, and proteins. For instance, nucleic acids, urea, proteins, and NO^{-2}, NO^{-3}, NH^{+4} can be produced by dissociating milk proteins [33]. One of the causes of methemoglobinemia is the elevated concentration of NO^{-3} (>40 mg/L) in groundwater [34].

Due to the substantial quantities of organic matter found in dairy waste, it is possible to obtain various value-added products through microbial-assisted waste conversion techniques [35]. For example, this dairy waste is a suitable substrate for ethanol production through enzymatic digestion using brewer's yeast [32]. Filamentous fungi also produce several enzymes that can break down complex carbohydrates present in dairy waste into monosaccharides. This process helps in producing high-quality biomass that is utilized as animal feed and as single-cell protein, which has Generally Recognized as Safe (GRAS) status for human consumption [36].

2.4. Edible Oil

The edible oil processing industry generates waste at each step in the refining process, including degumming, neutralization, bleaching, and deodorization [37]. Oxidative or hydrolytic rancidity is one of the primary reasons why edible oils deteriorate and become waste. This rancidity is attributed to the influence of oxygen, water, light, heat, and microorganisms, gradual hydrolysis or oxidation, neutral grease decomposition into glycerol and greasy acid, or breaking the unsaturated chain in the fatty acid to form peroxide, and then decomposing into low-grade fatty acid, aldehydes, ketones, and other substances [38]. It could result in odors and unpleasant smells; some rancidity products also have a carcinogenic effect [38]. The formation of polar molecules in waste cooking oil, such as free short-chain fatty acids, mono- and diglycerides, aldehydes, ketones, polymers, cyclic and aromatic compounds, makes it unsuitable for human consumption after undergoing multiple deep-frying processes. Oilseed cake and oilseed meal, by-products of the edible oil industry, are abundant sources of protein, with an annual production of 350.9 million tons [39]. These wastes are pre-treated and utilized to produce food, animal feed, and fertilizer [39].

Historically, the oil processing industry has discharged its effluents into the soil and groundwater, resulting in the formation of oily films on aquatic surfaces. This has posed a significant threat to the survival of marine animals and led to blockages of sewage and drains due to organic matter emulsification, as well as oil methanization, exacerbating the greenhouse effect [37]. However, innovative techniques now exist which utilize microbial cells for the biodegradation of organic matter in effluents, resulting in the production of a range of premium products, such as biobased zwitterionic biosurfactants. For instance, *Pseudomonas aeruginosa* has been shown to produce biosurfactants, including rhamnolipid and sophorolipid, as well as biodiesel generation through lipase and liquid hydrocarbon biofuels [40,41]. Waste from the edible oil industry, such as tocopherols, sterols, and squalene, are now extracted and used as raw materials in various industries, including the production of single-cell oil/protein for food [42], as well as in medicinal formulations and cosmetics in the form of soap stalk [43].

2.5. Meat, Poultry, and Eggs

The meat, poultry, and egg processing industries constitute a considerable portion of the food supply chain. According to recent data from an online database [44] the worldwide production of meat, including beef, poultry, sheep, and pork, has risen to 345.17 million tons in 2022, compared to almost 330.51 million tons in 2018 (as shown in Figure 2). Consequently, these industries generate large quantities of animal by-products, slaughterhouse waste, and wastewater [45], with cattle contributing 49%, sheep and lambs 47%, pigs 44%, and chickens 37% [46].

Feathers, hair, skin, horns, hooves, soft tissue, deboning remnants, and bones are among the most prevalent industrial waste materials. Additionally, slaughterhouse effluent comprises blood residue, animal fat (lard and tallow), detergent residues, protein, and a substantial quantity of organic matter. The rendering industry manufactures meat and bone meal, hydrolyzed feather meals, blood meals, fish meals, and animal fats (lard and butter) [47]. An encouraging approach is to utilize slaughterhouse waste is to generate lactic acid bacteria that can be employed in probiotic products [48]. Slaughterhouse waste is a fertile source of nutrients that can be utilized to generate various value-added products such as biogas, blood for food and non-food applications, biomass, and methane. These products include fish feed [47], fertilizers, binders [49], blood sausages, blood cakes, blood puddings, blood clots, and a clean energy alternative produced from the anaerobic digestion of wastewater [45]. Biodiesel has been produced from pork fat waste through fermentation with *Staphylococcus xylosus*, chicken manure biochar via pseudo-catalytic transesterification reactions, and eggshells via homogeneous catalysts for transesterification of triglycerides with methanol [50]. It has significant potential in the development of pharmaceutical and cosmetic products.

2.6. Seafoods and Aquatic Life

Marine ecosystems serve a vital role in the global food supply, providing approximately 20% of the world's food for human consumption, and as a result, are integral to supporting the needs of the planet's growing population [31]. Global fish production reached 174.6 million metric tons in 2020 [51] (Figure 2). In general, 50–70% of raw seafood is wasted annually [52]. The available quality of marine animals is relatively low, with only 40% of the total mass of protein accessible from crab and only 75% of the fillets from tuna attainable [31]. Consequently, a large amount of waste is produced, including inedible fractions such as shrimp shells, crab shells, prawn waste, fish scales, and endoskeleton shells of crustaceans. Globally, about six to eight million tons of crab, shrimp, and lobster shells are produced, with Southeast Asia accounting for 1.5 million tons. The shells and scales are rich in valuable chemicals such as proteins, chitin, and calcium carbonate. Dried shrimp and crab consist of roughly 50% chitin and can be sold for $100 to $120 per ton as animal feed additives, bait, or fertilizers [53]. Seafood waste contains pathogenic microorganisms, carcinogens, aflatoxins, and other health risks that may result from the bioaccumulation of these contaminants [31].

Traditional methods of seafood waste disposal, such as ocean disposal, incineration, landfills, and discharge of seafood processing industry wastewater, can potentially lead to eutrophication and oxygen depletion in the receiving waters, thereby causing environmental harm [53]. Additionally, chitin, which is insoluble in water and inert in most chemicals, can contribute to biological and environmental pollution. Therefore, proper biological treatment of this waste is considered a necessary step towards environmental protection and a sustainable way to generate revenue in the bioeconomy [52,53]. Astaxanthin, a pigment similar to lutein and known as 3,3′-dihydroxy-carotene-4,4′-dione, is found in crustacean waste and can be extracted by oxidizing β-carotene or zeaxanthin that the feed microalgae consumed. This substance is derived from the waste generated by the shrimp processing industry [54]. Chitosan, a biopolymer derived from crustacean waste, has been found to possess important antibacterial properties, as it exhibits activity against several bacterial strains including *Enterococcus faecalis*, *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans* [55]. Glycosaminoglycans extracted from marine animal waste are of better quality than terrestrial organisms [56]. Furthermore, waste from the seafood processing industry has the potential to yield functional and bioactive compounds through hydrolysis mediated by enzymes.

2.7. Agricultural Waste

The laws outlined in the Waste Framework Directive 2008/98/EC define waste as "any substance or object which the holder discards or intends or is required to discard." [57]. Agricultural waste encompasses a variety of materials, such as straw, bagasse, molasses, spent grains, husks (rice, maize, and wheat), shells (walnut, coconut, and groundnut), skins (banana, avocado), plant debris, and animal and poultry manure [58]. According to a report by the FAO [59], approximately 250 million tons of inedible plant waste from different crop processing methods were generated as agricultural waste [60]. In 2013, China, the world's largest food producer, produced 1.75×10^9 tons of agricultural waste, which included 9.93×10^8 tons of crop residues, 4.52×10^8 tons of livestock manure, and 3.03×10^8 tons of forest residues [58]. It is noteworthy that Asia alone generates 4.4 billion tons of solid waste annually, with India contributing over 350 million tons of agricultural waste from various sources each year [61].

Conventional methods of disposing of agricultural waste typically involve either incineration or allowing the waste to decompose in fields, which can result in significant air pollution and contribute to the contamination of soil, water, and food. Such disposal methods release harmful gases, such as N_2O, SO_2, and CH_4, as well as smoke and greenhouse gases. Additionally, they release other harmful chemicals such as dioxins, furans, and polycyclic aromatic hydrocarbons into the air. Exposure to these hazardous chemicals can result in severe developmental damage for fetuses, infants, children, and adults alike [62].

Agricultural wastes are biodegradable organic wastes containing various nutrients such as polysaccharides (starch, cellulose, hemicellulose), proteins, lignin, fiber, minerals, vitamins, and others [61]. These wastes have a porous and loose structure that contains carboxyl, hydroxyl, and other reactive groups. As a result, agricultural biomass can serve as an adsorbent material for wastewater remediation, allowing for 'waste reduction by waste' [58]. Furthermore, agricultural waste could be utilized as a low-cost and natural alternative to produce a wide range of high-value products. Microorganisms can use fruit peels, seeds, oilseed cakes, field residues, and bran to generate a variety of high-end products, such as pigments, phytochemicals, antibiotics, and various enzymes, including endoglucanase, β-glucosidase, amylase, and glycosylase. [63–65]. Xanthan gum, an extracellular polysaccharide employed as a food additive in the food industry, could also be produced by *Xanthomonas* spp. using agricultural waste as a substrate. Mushrooms are ecological and economic balance crops generated by the mushroom fungi *Lentinula edodes* and *Pleurotus* sp. from lignocellulosic (waste wheat, rice, banana leaves, cotton straw) [66]. It has been found that agricultural wastes are effective carriers for enzyme immobilization and solid-state fermentation [67]. Additionally, the plentiful chemical composition of agricultural waste allows it to be a versatile candidate with the potential to synthesize a variety of products, such as bioplastics from plant parts, including leaves, stems, and the outer cuticle of flowers [60].

3. Bioactive Compounds in Food Waste

Bioactive compounds are powerful substances found in food and other natural sources that have the potential to positively influence health. FW, for example, may contain polyphenols, fiber, vitamins, minerals, and other substances that are well-known for their health-promoting properties [4]. By screening and isolating these bioactive compounds, we can create novel functional ingredients and dietary supplements, all while reducing waste and promoting sustainability. (Figure 3).

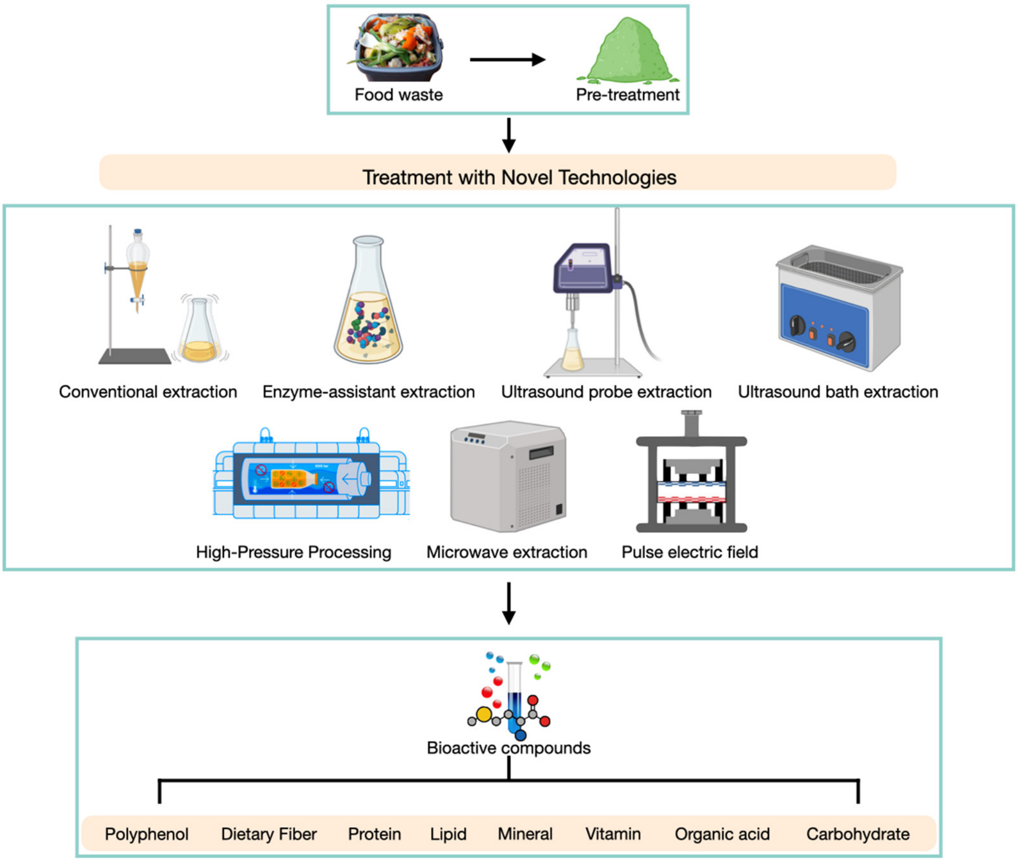


Figure 3. Extraction of bioactive substances from food waste using various novel methods.

3.1. Polyphenols

Polyphenols are a multifaceted assortment of compounds obtained from plants that have gained noteworthy consideration for their potential to boost health. These compounds are extensively distributed in the plant kingdom and can be found in various foods. Consequently, FW encompasses a considerable quantity of these health-promoting polyphenols [68] (Table 1). The existence of polyphenols in FW provides an exclusive opportunity to extract valuable, health-enhancing substances from what would otherwise be rejected material.

The fruit industry generates substantial quantities of fruit waste, with apple pomace being a significant contributor, amounting to up to 12 million tons worldwide annually [69]. The flavonoid content of apple peel is approximately three to six times higher than that of the flesh, containing unique flavonoids such as quercetin glycosides which are not found in apple flesh [70]. Extracts derived from apple peel have significant antioxidant activity. The principal polyphenols, including phloridzin, chlorogenic acid, and quercetin, have been identified in apple pomace fractions. These antioxidant activities exhibited values comparable to ascorbic acid [71]. The utilization of deep eutectic solvents has been shown to be an effective method for dissolving and desugaring quercetin derivatives from apple pomace [72]. In addition, pressurized liquid extraction, which involves the use of high pressure and temperature to enhance extraction efficiency, has been successfully combined with solid phase extraction to concurrently extract and isolate phenolic compounds from apple pomace [73]. Carrots contain high levels of anthocyanins [74], a type of polyphenol that gives fruits and vegetables red, blue, and purple pigments. These compounds have strong antioxidant properties and have been shown to have potential health benefits, including reducing the risk of cardiovascular disease and improving gut health [75]. A substantial commercial plant for carrot processing has the potential to generate as much as 175,000 tons of carrot waste annually. The unpressed carrot waste was found to contain a total phenolic content of 57.54 ± 5.14 mg of gallic acid equivalent per 100 g. [76]. Ultrasound-assisted extraction (UAE) represents a promising method for extracting anthocyanins from carrot waste due to its ability to break down cell walls and increase pigment solubility. Combining UAE with thermal treatment can lead to a synergistic effect, resulting in improved polyphenol yields [77]. As a by-product of pomelo consumption, pomelo peel is abundant in various nutrients and functional compounds. Pomelo peel is rich in polyphenols, mainly including flavonoids and phenolic acids, with contents ranging from 1799.04 mg/100 g to 5364.00 mg/100 g [78].

Grape skins and seeds contain high levels of resveratrol, a type of polyphenol that is well known for its antioxidant properties and potential health benefits. Although it is found in more than 70 plants, grapes are still the primary dietary source of resveratrol [79]. The trans-resveratrol content ranged from 1.11 to 12.3 mg/100 g dry weight in grape skins, 8.64 ± 4.5 mg/100 g dry weight in white grape skins, and 1.42 ± 0.18 mg/100 g dry weight in white grape seeds [80]. Although a certain level of resveratrol in the grapes was transferred to the wine during the maceration process, a significant amount remained in the grape marc. Cranberry pomace, a by-product of cranberry processing, consists of the seeds, skins, and stems of the fruit. Despite containing beneficial polyphenols such as proanthocyanidins and anthocyanins, it is typically discarded due to their unpalatability. Co-drying cranberry pomace extract with a protein-rich food matrix, such as soy protein isolate (SPI), has been shown to enhance the stability of polyphenols during the extraction process [81]. The interaction between polyphenols and proteins is thought to be responsible for this increased stability. In fact, cranberry pomace-SPI powder was found to contain up to 10% total polyphenols and was highly stable at 37 °C, as evidenced by the retention of proanthocyanidins, anthocyanins, and total polyphenols [81]. These findings suggest that co-drying cranberry pomace extract with a protein-rich food matrix could be a promising approach for the utilization of cranberry pomace and the production of value-added products. The handling and processing of fresh blueberries result in the production of considerable quantities of inferior or second-rate fresh blueberries, as well as by-products that are discarded [82]. These by-products, consisting of peels, pulp remnants, seeds, and stems, account for 15–55% of the original mass of the entire berry and exhibit elevated levels of inherent anthocyanins and other phenolic compounds when compared to the pulp [83]. The utilization of pulsed electric field technology has been employed to enhance the efficiency of polyphenol extraction from blueberry pomace, owing to its ability to disrupt the cell membrane and thus promote the diffusion of intracellular compounds. The most optimal yield of anthocyanins (1757.32 μg/g of dry weight) and flavanols (297.86 μg/g of dry weight) was achieved using a methanol-based solvent [84].

Coffee waste generated from the production of soluble coffee contains around 6% and 4% of total polyphenols and tannins, respectively [85]. The total phenolic content of 17.75 mg gallic acid equivalent/g was extracted from waste coffee grounds and 21.56 mg gallic acid equivalent/g from coffee capsules discharged from automatic espresso machines [86]. Discarded tea leaves are a valuable source of polyphenols, particularly catechins, and theaflavins. Catechins are present in high concentrations in green tea leaves, whereas black tea leaves contain high levels of theaflavins [87]. In fact, the antioxidant activity of tea leaves and black spent tea leaves was almost identical, with % DPPH activity reduction of 57.83–59.27% [88].

Table 1. Important polyphenols isolated from common fruit and vegetable waste.

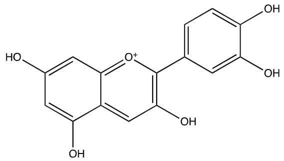
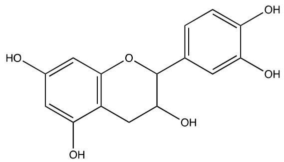
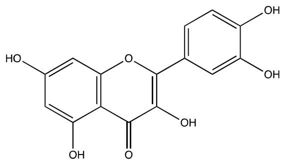
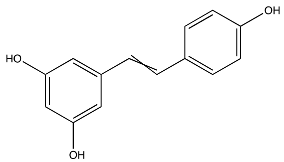
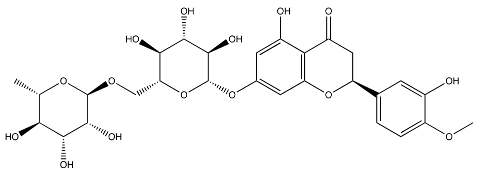
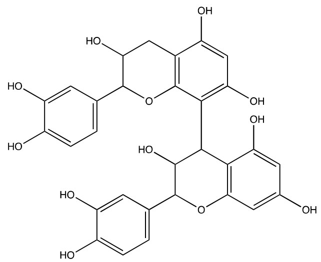
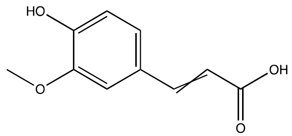
Compound Name	Classification	Structure	Molecular Formula	Source	Extraction Method	References
Cyanidin	Anthocyanidin		$C_{15}H_{11}O_6{}^+$	Grape seed, blueberry waste, cranberry pomace, carrot waste, apple peel	Chemical extraction, Supercritical CO_2 extraction, pulsed electric field, UAE, SPI co-drying, Spray-drying	Agcam, Akyıldız and Balasubramaniam [77], Roopchand, Krueger, Moskal, Fridlender, Lila and Raskin [81], Lončarić, Celeiro, Jozinović, Jelinić, Kovač, Jokić, Babić, Moslavac, Zavadlav and Lores [84]
Catechin/Epicatechin	Catechin, flavan-3-ol		$C_{15}H_{14}O_6$	Citrus peel, grape skin, spent tea leaves	Chemical extraction, microwave-assisted extraction, UAE, Supercritical CO_2 extraction	Vuong, et al. [89], M'hiri, et al. [90]
Quercetin	Flavonol		$C_{15}H_{10}O_7$	Grape skin, apple pomace, tomato waste	Chemical extraction, deep eutectic solvents, pressurized liquid extraction	Yu and Bulone [72], da Silva, Souza, Sumere, Silva, da Cunha, Barbero, Bezerra and Rostagno [73]
Resveratrol	Fitoalexin stilbene		$C_{14}H_{12}O_3$	Grape marc, peanuts waste	Chemical extraction, CO_2 extraction, microwave-assisted extraction	Kammerer, Claus, Carle and Schieber [80], Sales and Resurreccion [91], Casas, et al. [92]
Hesperidin	Flavonoid		$C_{28}H_{34}O_{15}$	Orange waste, orange peel	Chemical extraction	Victor, et al. [93]

Table 1. *Cont.*

Compound Name	Classification	Structure	Molecular Formula	Source	Extraction Method	References
Proanthocyanidin	Proanthocyanidin		$C_{30}H_{26}O_{12}$	Cranberry pomace, grape seed	Chemical extraction, SPI co-drying, UAE	Roopchand, Krueger, Moskal, Fridlender, Lila and Raskin [81], Unusan [94]
Ferulic acid	Catechin		$C_{10}H_{10}O_4$	Citrus peel, beetroot waste	Chemical extraction	Ozturk, et al. [95], Aarabi, et al. [96]

3.2. Proteins

Proteins are vital macromolecules that play critical roles in various biological processes such as tissue growth and repair, metabolic regulation, and maintenance. These indispensable compounds are abundant in food and constitute a significant component of many FW products. In fact, FW can be a rich source of protein, containing high-quality proteins akin to those present in foods such as meat, dairy, and eggs [97]. For instance, substantial amounts of muscle tissue, a rich protein source, can be found in poultry and meat processing waste. Similarly, whey, a prime source of high-quality protein, could be present in dairy processing waste.

The protein sources in FW can be categorized into animal and plant-based sources, depending on the availability of crude protein and nutritional value. Several plant-derived by-products are deemed essential protein sources, owing to their significant nutritional value. Wheat bran, which contains 13% to 18% protein, can be considered a viable source for protein extraction, given its high lysine and arginine content [98]. Bran also contains significant levels of tryptophan, tyrosine, and cysteine [99]. Moreover, due to its remarkable protein content of up to 50%, oilseed meal, primarily derived from seeds and other oilseed plants after pressing, is also regarded as a valuable source of extracted protein [100].

Similarly, tofu residue containing 27% active protein has been identified as a high-quality protein source [101]. Among the major plant-based FW protein sources, mushroom and beet flake proteins contain 40% of essential amino acids and are considered viable feed ingredients [102]. Spent tea leaves are also a good source of protein (18–35% of crude protein) and contain many amino acids, but the potential use of waste tea proteins in human food supplements remains untapped [103]. A potential technique for extracting protein from waste tea involves using a semi-permeable membrane with a relative molecular mass of 1,000,000 Da to separate the soluble and insoluble components of the waste tea. Following an alkali extraction membrane filtration, the protein content can increase by about 7% [104].

Waste from food preparation or processing, including meat, fish, and dairy, has notable quantities of protein. For example, dairy waste can contain whey protein, which is a high-quality, complete protein used frequently in food and dietary supplements [33]. Fish waste biomass constitutes a plentiful reservoir of valuable biomolecules, such as enzymes, functional proteins, bioactive peptides, and oils that are abundant in omega-3 fatty acids [105]. The crude protein content of fishmeal extracted from fish waste amounts to 58% [106]. To extract the proteins, alkaline enzymes were used at a specific concentration through enzymatic digestion. Subsequently, the fish protein hydrolysate was dried using a spray dryer to acquire protein powder, which yielded the maximum amount of whole fish protein. Using whole fish waste (all parts collectively) during fish processing to extract protein eliminates the need to separate the waste [107]. Poultry by-products are derived from the remains of slaughtered poultry, typically consisting of clean meat, skins, heads, and feet, but not feathers and intestines. This residual material provides a sustainable source of animal protein, containing substantial amounts of protein, essential amino acids, and minerals, notably lysine, methionine, and phosphorus [108]. Similarly, this type of waste can be hydrolyzed with immobilized alkaline enzymes to produce a high-protein hydrolysate [109].

It is imperative to underscore that the extraction and utilization of protein from FW must be carried out safely, with no risk to human health. This may necessitate the development of novel processing technologies and the implementation of good manufacturing practices to ensure the safety and quality of the extracted protein.

3.3. Dietary Fiber

Dietary fiber refers to the indigestible portion of plant material that includes cellulose, noncellulosic polysaccharides such as hemicellulose, pectic substances, gums, mucilages, and the non-carbohydrate component lignin [110]. It is a crucial component of many foods and is vital for preserving human health. In FW, fiber can be discovered in discarded fruits, vegetables, and grains as well as the by-products of food processing, such as peels, skins, and stems. There are two primary types of fiber: soluble and insoluble [110]. Soluble fiber dissolves in water, forming a gel-like substance that slows down digestion and helps to regulate blood sugar levels. Insoluble fiber does not dissolve in water and promotes regular bowel movements by adding bulk to the stool. Both fiber types are critical for maintaining digestive health and preventing chronic illnesses [111].

FW can contain a considerable amount of fiber, which varies depending on the type of food and the discarded portion. Banana peel, for instance, contains high levels of insoluble dietary fiber that exhibit desirable properties, including water-holding, oil-holding, and glucose adsorption abilities [112]. It is noteworthy that banana peels are also an excellent source of xyloolygosaccharides, and hydrogen peroxide-dissolved residues from banana peels can yield up to 54% xyloolygosaccharides after enzymatic digestion. Additionally, guava pomegranate pomace and orange pomace can also serve as sources for extracting xyloolygosaccharides [113]. Jerusalem Artichoke residues are typically discarded as waste, resulting in environmental pollution and resource waste. However, these residues hold potential for the extraction of high-purity, high-performance soluble dietary fiber with promising applications in the food packaging industry [114]. On the other hand, despite its high dietary fiber content of approximately 70%, garlic peel is often disposed of as industrial waste. Unfortunately, the soluble dietary fiber content of garlic peel is only 5.3%, which is below the required minimum of 10% to qualify as a high-quality dietary fiber. A balanced modification of the composition of garlic peel-derived dietary fiber may have the potential to enhance its solubility and make it a better source of soluble dietary fiber [115]. Fructooligosaccharides, naturally occurring oligosaccharides found in plants such as the above-discussed banana peel, Jerusalem artichokes, garlic, and cassava waste, rice bran, apple pomace, beet peel, among others, are excellent sources of this soluble dietary fiber [116]. While pure enzymatic treatment of banana peels produces low yields of fructooligosaccharides, the combination of alkaline and enzymatic methods can improve both yield and purity [117].

Pearlings derived from the pearling process of barley are a plentiful source of insoluble dietary fiber. Barley middlings, which result from milling barley to produce flour, have an elevated fiber content, specifically a high concentration of β-glucan. The oat bran fraction is another copious source of β-glucan and dietary fiber, containing no less than 5.5% dry weight β-glucan and 16.0% dry weight dietary fiber, at least a third of which is soluble [9].

Pectins are polysaccharides that are commonly found in plants [118]. They are present in the cell walls located in the thin middle layer as well as in primary and secondary cell walls. Different sources, locations in the plant, and extraction methods result in a heterogeneous chemical structure of pectins. Due to their rheological properties and non-toxic nature, pectins were wide applications in the food industry as a stabilizer, texturizer, thickener, and emulsifier. In addition, pectin can also be utilized in pharmaceutical applications as a drug carrier and has been demonstrated to reduce blood cholesterol under various experimental conditions and influencing factors [118]. FW has been a source of interest for pectin, and different types of FW are rich in pectin [119]. Judith et al. found that the pectin yield of orange peel was extremely high, reaching 247 mg/g dry weight, making it an ideal source of dietary fiber. The study also indicated that by-products of the apple processing industry are the second largest source of pectin after citrus fruits. A certain amount of pectin could be extracted from whole apples discarded from fresh consumption, apple cakes from the fruit processing industry, and apple pomace [119].

3.4. Vitamins and Minerals

Vitamins are essential micronutrients required in small amounts for normal growth and development. Several types of vitamins include fat-soluble vitamins (A, D, E, and K) and water-soluble vitamins (B-complex vitamins and vitamin C). Fruits and vegetables discarded due to overproduction or cosmetic defects are still rich in vitamins, particularly vitamins C and B-complex [120]. Carrot and pumpkin processing produces bark and peel as by-products containing carotenoids, precursors of vitamin A [121].

Carotenoids are a group of pigments that are widely distributed in the plant kingdom. They have important health benefits and are also used commercially in various industries. Carotenoids can be found in various FW sources, such as vegetables and fruits that were directly discarded. Common carotenoids in FW include β-carotene, lycopene, lutein, and zeaxanthin [122]. In tomato peel by-products, the lycopene content is equivalent to 90% of the total carotenoids; β-carotene is the main carotenoid in the seeds [123]. Most of the published data support the fact that tomato waste has the highest carotenoid content. Tomato skins usually contain the highest lycopene content on a dry weight basis (about 377 μg/g) [123]. Shrimp, which is the most important crustacean commodity traded internationally, generates a significant amount of solid waste during processing, accounting for 50–60% of total waste, including heads, tails, and crusts. These byproducts, along with those from other crustaceans, are similar to tomato pomace in that they contain high levels of astaxanthin, a commercially important carotenoid [124]. The extraction of astaxanthin from shrimp waste using ethanol at high temperature and pressure is an efficient and environmentally sustainable method, achieving yields of about 24 mg/kg of shrimp waste [125]. Astaxanthin offers various health benefits, such as potent antioxidant and anti-inflammatory properties, and supports heart health, brain function, and skin health. Besides its nutritional benefits, astaxanthin has significant economic value due to its increasing use as an ingredient in various products, including dietary supplements, functional foods and beverages, cosmetics, and animal feed [126].

Recovering vitamins from FW could have significant benefits in reducing waste and utilizing these nutrients in other applications, such as fortifying foods or producing dietary supplements. Nonetheless, additional research is required to fully grasp the possible nutritional benefits of vitamins in FW and devise effective extraction and application techniques. However, further research is needed to comprehensively understand the potential nutritional value of vitamins in FW and to develop efficient methods for their extraction and utilization.

Minerals are essential nutrients that play a vital role in maintaining human health. They are involved in many physiological processes, such as regulating fluid balance, metabolism, muscle function, and bone health. Different minerals can be found in FW, including calcium, sodium, iron, magnesium, potassium, and zinc. These minerals can be found in various FW streams, such as fruits and vegetables, grains, dairy, and meat products. For instance, in the fruit and vegetable waste stream, minerals such as calcium and potassium can be found in high amounts in the skins and peels [127,128]. Meanwhile, magnesium and zinc can be found in the seeds and cores of these plants [129,130]. In the dairy waste stream, minerals such as calcium and phosphorus are present in high amounts in cheese and yogurt [131,132]. Meat waste is also a valuable source of minerals, with phosphorus, potassium, and calcium being among the most abundant [133].

4. Value-Added Products Obtained by Converting Bioactive Compounds in Food Waste

The potential for conversion of FW into value-added products using an appropriate approach is extremely promising. This review summarizes the common sources of FW and the relatively mature conversion methods available so far (shown in Table 2), providing confidence and direction for better management and utilization of FW in the future.

Table 2. Value-added products and bioactive compounds from different food waste sources.

Food Waste Category	Main Source	Processing Method	Value-Added Products and Bioactive Compounds	References
Barley by-product	Cereal and pulses industry	Chemical extraction	Vitamin E, phytates, insoluble dietary fiber, and phenolic compounds	Papageorgiou and Skendi [9]
Rice bran and husk	Cereal and pulses industry	Enzymolysis	Phenolic compounds, γ-Oryzanol, and tocopherols	Wanyo, Meeso and Siriamornpun [11]
Wheat	Cereal and pulses industry	Chemical extraction, fermentation	Carbohydrates, lipid soluble vitamins, folic acid, phytosterols, amino acids, oligosaccharides, phenolic compounds, and peptides	Balandrán-Quintana, et al. [134]
Legumes	Cereal and pulses industry	Chemical extraction, fermentation	Activated carbon, proteins, lipids, fatty acids, vitamins, minerals, and phenolic compounds	Kiran, et al. [135], Ben-Othman, et al. [136]
Grape by-products	Fruits processing industry	Chemical extraction, fermentation, anaerobic digestion, gasification, pyrolysis distillation, producing single cell protein	Ethanol, flavanols, anthocyanins, procyanidins, tartaric acid, dietary fibre, grape seed oil, pomace oil, oleanolic acid, malates, citric acid, single cell protein.	Muhlack, et al. [137], Schieber [14]
Apple juice by-product	Fruits processing industry	Enzymolysis, chemical extraction	Pectin, lactic acid, citric acid, aroma compounds, butanol, fructooligosaccharides, and pectinases	Schieber [14], Kiran, Trzcinski, Ng and Liu [135]
Citrus processing industry	Fruits processing industry	Chemical extraction, distillation	Phenolics, pectin, essential oil (limonene), antioxidants, ethanol, and organic acids,	Matharu, de Melo, and Houghton [19], Schieber [14]
Avocado by-products	Fruits processing industry	Chemical extraction, homogenized, grinding	Phenolic compounds, acetogenins, phytosterols, carotenoids, alkaloids, starch, edible protein, and animal feed	Salazar-López, et al. [138]
Tomato waste	Vegetable processing industry	Supercritical fluid extraction using CO_2, chemical extraction	Trans-lycopene, lycopene, and pectin	Nobre, et al. [139]
Potato and sweet potato	Vegetable processing industry	Hydrolysis, chemical extraction, pulsed electric fields, fermentation	Lysine, protein, adsorption dyes, starch, steroidal alkaloids, β-carotene, α-tocopherol cellulolytic enzymes, and biopolymer films	Lappalainen, et al. [140], OKUNO, et al. [141], Matharu, de Melo and Houghton [19]
Onions	Vegetable processing industry	Chemical extraction, macroporous resin adsorption	Dietary fiber, fructans, phenolic compounds	Kühn, et al. [142], Kiassos, et al. [143], Benítez, et al. [144]
Milk	Dairy industry	Transglycosidation, enzymolysis, fermentation, fractionation	Prebiotics, biodiesel, ethanol, whey protein, lactose, galactooligosaccharides, baker's yeast, and minerals	Hua, et al. [145], Lappa, et al. [146]
Cheese, casein, yogurt	Dairy industry	Fractionation, producing single cell protein, fermentation, enzymolysis	Ethanol, single cell protein, animal feed, whey protein, lactose	Hua, Yang, Zhang, Fei, Jin and Jiang [145], Lappa, Papadaki, Kachrimanidou, Terpou, Koulougliotis, Eriotou and Kopsahelis [146]
Waste cooking oil	Family kitchen or commercial kitchen	Hydrolysis, esterification, producing single cell protein, fermentation	Biosurfactants and glycolipids, biodiesel, sterols, squalene, tocopherols and single cell protein	Henkel, et al. [147], Vescovi, et al. [148]
Olives	Edible oil industry	Combustion, chemical extraction	Phenolic compounds, carotenoids, squalene, dietary fiber and phytosterols	Pattara, et al. [149], Rodríguez, et al. [150]
Meat and poultry	Meat processing industry	Fermentation, anaerobic digestion, transesterification	Fertilizer, feather meal, lactic acid, animal feed, blood meal, meat and bone meal and probiotics	Yaakob, Mohamed, Al-Gheethi, Tiey and Kassim [47], Marques, Paz, Duval, Corrêa and Corrêa [50], Ashayerizadeh, Dastar, Samadi, Khomeiri, Yamchi and Zerehdaran [48]
Crabs, lobster and shrimps	Seafood processing industry	Grinding, destructive, fermentation	Chitin, calcium carbonate, protein, astaxanthin, and chitinase	Yan and Chen [53], Kumar, Kumar, George, Sharma and Gupta [52], Prameela, Venkatesh, Immandi, Kasturi, Krishna and Mohan [54]

4.1. Nutraceuticals

Nutraceuticals are a group of bioactive compounds derived from food that have pharmaceutical-like properties and are intended to improve health, prevent chronic diseases, extend life expectancy, or support bodily function and structure [151]. These compounds provide additional nutritional and health benefits beyond the basic nutritional value of food, and are known for their antioxidant, cardio-protective, anti-cancer, anti-inflammatory, immunomodulatory, and antimicrobial properties. Therefore, they are an excellent source for the production of nutraceuticals. Bioactive compounds have been shown to be effective in reducing the risk of chronic diseases, such as diabetes, cancer, cataracts, Alzheimer's disease, Parkinson's disease, hypercholesterolemia, hypolipidemia, and cardiovascular disease. Plants are considered a valuable source of bioactive compounds, which are composed of chemically balanced formulations and efficient and minimally harmful compounds compared to synthetic drugs [31,152]. Plant-derived FW offers excellent opportunities for the food industry to synthesize alternatives to synthetic chemicals using natural resources.

Wineries produce large quantities of grape skins rich in resveratrol (3,5,4′-trihydrostilbene) [153]. This antioxidant has multiple effects; it enhances the anti-inflammatory reaction of NF-κβ cells, thereby reducing the inflammatory response, scavenging free radicals, enhancing cytochrome P-450 enzyme activity, and helping to detoxify the liver. Resveratrol also further reduces genomic mutations, cell damage, and cartilage dysfunction [153,154]. Mango skin contains phenolic compounds, carotenoids, vitamin C, and dietary fiber. These compounds contribute to a reduced risk of cancer, cataracts, Alzheimer's disease, and Parkinson's disease [155]. Caffeine was extracted from waste tea leaves of black, white, green, and dark black tea using dichloromethane as the solvent, and the highest caffeine content was found in green tea (60 mg/100 g) and the lowest in black tea (3 mg/100 g) [156].

Fucose, galactose, rhamnose, and arabinose were found in FW [157]. These types of monosaccharides have anti-clotting, anti-HIV, and antioxidant effects. Green, red, and brown algae contain sulfate-polysaccharides. Fucoidan and alginate from brown algae suppress IL-4, IL-5, and IL-13, creating an anti-allergic response in airway hypersensitivity reactions and reducing eosinophil numbers in bronchoalveolar lavage and serum IgE production [158]. Xyloolygosaccharides are oligosaccharides that consist of xylose units, derived from guava pomegranate pomace, banana peels, and orange pomace [113]. These saccharides can serve as prebiotics, selectively promoting the growth of advantageous bacteria, such as bifidobacteria and lactobacilli, in the digestive tract [159]. Galactooligosaccharides are oligosaccharides comprised of galactose units, synthesized via lactose hydrolysis or transfer reactions. Currently, research is increasingly being conducted on utilizing dairy by-products, such as whey and whey permeate, as potential sources of these oligosaccharides, and even on the direct isolation of galactooligosaccharides from milk itself [160]. These prebiotics can enhance the number and activity of favorable bacteria, including bifidobacteria and lactobacilli, in the intestinal tract [161]. Fructooligosaccharides are oligosaccharides composed of fructose units, which could be extracted from sugar cane bagasse, cassava waste, rice straw, apple pomace, and banana peels among many others. These dietary fibers can also function as prebiotics, facilitating the proliferation and metabolism of beneficial bacteria, such as *Bifidobacterium* and *Lactobacillus*, in the intestinal tract [116]. The consumption of these dietary fibers can lead to positive health outcomes, such as better blood sugar control [162], improved immune function, antioxidative effects, prevention of constipation, and inhibition of carcinogens [116].

Potato peel, a by-product of potato processing, contains a plethora of bioactive substances, chiefly including chlorogenic, cryptochlorogenic, neochlorogenic, caffeic, ferulic, gallic, and *p*-coumaric acids, flavonoids such as flavonols, flavanols, and anthocyanins, and minor quantities of syringic, vanillic, sinapic, and salicylic acids. Among these, caffeic acid, chlorogenic acids, and quercetin exhibit mild inhibitory effects against parasites [163,164]. The bioactive compounds present in bananas have shown potential in treating Leishmaniasis, another protozoan-associated disease. Banana alcohol extracts possess anti-leishmanial properties [152].

4.2. Food Additives

Food additives refer to substances added to food to improve its flavor, appearance, or other organoleptic qualities. Various by-products, such as overripe berries, unacceptable fruits, discarded peels, pomace, and seeds, can be valuable resources for novel antioxidant food additives. Recent studies have highlighted the potential of polyphenol-rich waste olive oil extract as a natural antioxidant in lamb patties, which can delay lipid and protein oxidation, preserve an admirable color, and extend the product's shelf life up to three days [165]. Additionally, apple peel extract has been found to inhibit protein and lipid oxidation in minced rainbow trout during refrigeration (4 °C), leading to a reduction in peroxides and thiobarbituric acid-reactive substances [166]. Enzymatic browning is a common issue that affects the quality and shelf life of fresh produce, leading to negative impacts on taste, flavor, color, and nutritional value. In this regard, strawberry tree extracts (leaves and twigs) and apple by-products have been shown to inhibit polyphenol oxidase and peroxidase, thereby preventing browning and increasing consumer acceptance of these products.

Various bioactive compounds found in food waste have been identified as potential natural antimicrobial agents for food preservation. These compounds mainly include terpenoids, peptides, polysaccharides, and phenolic compounds. Olive leaf extract, for example, has been demonstrated to reduce bacterial contamination in organic leafy greens and shrimps [167,168]. Moreover, adding bioactive compounds to meat products has been shown to improve their quality and extend their shelf life [169]. Studies have also demonstrated the ability of natural compounds to retard microbial spoilage of fish, including *E. coli*, *L. monocytogenes*, and *S. aureus*, leading to an extended shelf life under retail conditions [170]. Pomegranate peel extract has been reported to exhibit antibacterial activity against *S. aureus* and *B. cereus*, showing promising antibacterial effects in chicken products [171,172].

Many of the colorants used commercially are synthetic, although there are already some natural sources of colorants such as carotenoids and anthocyanins [173]. Incorporating FW as a new source of colorants could offer a way for the food industry to adopt more natural additives while remaining cost-effective. There are various sources of anthocyanins, including distillery by-products, red kale, black carrots, purple sweet potatoes, and berries [174]. Blackberry residues are a significant natural source of colorants and nutraceuticals, with 4.31 mg cyanidin-3-O-glucoside equivalent/g [175]. Citrus peel and pomace are also considered to be valuable sources of carotenoids [176,177]. These compounds could function as natural colorants in products and help to extend the shelf life of foods and beverages by preventing pathogens, contaminants, or unpleasant flavors.

Water-insoluble fibers, such as pectin, are classified as functional foods and are believed to be beneficial to intestinal microbiota health [176,178]. Citrus peels are an abundant source of pectin, making them an excellent choice for extracting pectin to be used as a gelling agent in bakery, confectionery, and meat products. Avocado production generates approximately 30% of waste products, including seeds, peels, and defatted pulp. The edible protein found in avocado by-products exhibits better water absorption, oil absorption, and free radical scavenging capacity than sorghum protein, though it has lower in vitro digestibility. Additionally, the protein from avocado by-products demonstrated superior emulsion stability (oil in water) compared to soy protein, offering potential applications in functional food [179]. Avocado seeds contain 15–16% straight-chain amylose with a gelation range of 56–74 °C, a water absorption of 22–24 g water/g starch, the solubility of 19–20%, swelling power of 28–30 g water/g starch, and a maximum viscosity of 380–390 BU, making them an ideal source of starch [180]. As such, they hold potential for use as a thickening and gelling agent, a carrier for pharmaceuticals, or a component of biodegradable food packaging materials [138].

4.3. Biosurfactants

Biosurfactants are surface-active compounds derived from microorganisms, including bacteria, fungi, and yeast [181,182]. The biosurfactant market was estimated to be worth over US$18 billion globally in 2016, with a current market value of US$30.64 billion [183]. Due to higher production costs, biosurfactants are generally more expensive than synthetic surfactants. However, utilizing FW as a substrate for the production of biosurfactants can be a sustainable and cost-effective way to reduce production costs and pollution. FW is abundant, inexpensive, and contains rich nutritional substances that can support microbial growth and biosynthesis. It has been shown that FW performs well in the production of rhamnolipid and sophorolipid biosurfactants (over 100 g/L) because of their easy degradation and high nutrient content [41]. Kopsahelis et al. carried out a life cycle assessment to examine the production of glycolipid biosurfactants using waste oil, with a comparison of the yields of rhamnolipids and sophorolipids. The study found that rhamnolipids had a 22.7% lower environmental impact than sophorolipids due to the former's lower energy requirements. Further analysis of the fermentation process that has the most significant environmental impact may be utilized to diminish its environmental impact by reducing energy consumption and other requirements during the fermentation process [184].

FW from livestock and various food industries can serve as a valuable substrate for biosurfactant production. Waste whey from the dairy industry is typically discharged into the environment without pretreatment, resulting in soil and water pollution. However, repurposing waste whey as a substrate for biosurfactant production can not only reduce waste but also increase productivity. For example, *Pseudomonas aeruginosa* SR17, an isolate from hydrocarbon-contaminated soil, produced 2.7 g/L of biosurfactant using waste whey as a substrate. By adding mineral salts and glucose, the yield was further increased to 4.8 g/L [185]. Used kitchen oil is another prominent source of FW. It is rich in protein and water, making it an excellent substrate for microbial growth, and a potential fermentation substrate for biosurfactant production by *Pseudomonas aeruginos* [40]. Soybean molasses is a byproduct generated during soybean processing. It lacks commercial value, although it is rich in protein, carbohydrates, and lipids [186]. Nonetheless, *Pseudomonas aeruginosa* ATCC 10145 strain was able to produce biosurfactants using soy molasses as the sole carbon source [187], with a yield of 11.7 g/L of glycolipid biosurfactant, utilizing 120 g of soy molasses as the fermentation substrate [188].

Olasanmi and Thring conducted a comprehensive review of the impact of biosurfactants on environmental sustainability. They identified the potential of using renewable by-products or waste, which would otherwise require further management, as a way to reduce costs and waste [189]. In the future, there is a need for a deeper understanding of FW composition and the complementary requirements of producers. Applicable FW pre-treatment and biosurfactant purification strategies must be developed, and the entire life cycle of biosurfactant production must be optimized. With the reduction of costs, the application of biosurfactants will be strengthened, which is crucial for environmental applications [41].

4.4. Single-Cell Protein

Single-cell protein (SCP) is a term used to describe the crude, refined, or edible protein derived from pure microbial cultures, as well as from dead or dried cell biomass. This protein source can serve as an ingredient or a substitute for protein-rich foods and is suitable for human consumption or animal feed. Utilizing SCP as a means of converting organic resources is a promising approach due to its numerous advantages over other protein sources. One key advantage is SCP's abundance of amino acids, with many essential amino acids surpassing those found in soybeans [190]. Additionally, microorganisms grow at an incredibly rapid rate and can accumulate large amounts of SCP in a short amount of time. Furthermore, microorganisms are not susceptible to environmental influences [191].

FW is a favorable fermentation substrate for SCP production. It is reported that a protein content of 38.8 ± 0.2% *w/w* biomass dry weight was achieved by *Yarrowia lipolytica* for FW utilization in the two-stage fermentation, which indicated FW could be efficiently converted to SCP [192]. The production of SCP by photosynthetic bacteria depends on the bioavailability of the carbon source, while plenty of volatile fatty acids in FW fermentation broth could be a potential alternative. It was shown that by regulating the level of carbon source, the production of SCP could be effectively increased (2088.4 mg/L) with a high carbon source conversion capacity (0.99 mg-biomass/mg-chemical oxygen demand). Photosynthetic bacteria preferred to utilize the volatile fatty acids in the FW fermentation broth [193].

Coffee processing generates a significant amount of wastewater that can be utilized as a substrate for bioconversion, yielding nutrient-rich extracts with abundant sugars, proteins, and salts [194]. Yeast has been found to efficiently assimilate glucose, mannose, and fructose from this substrate, resulting in SCP yields of up to 37.4% to 39%, which can serve as a cost-effective source of alternative protein for animal feed supplements [194]. Moreover, SCP obtained from fermented vegetable residues was incorporated into wheat flour bread without any adverse effects on the bread's organoleptic properties. This outcome highlights the possibility of using these by-products to generate SCP, which could be utilized to supplement other edible products [195].

4.5. Organic Fertilizers

Organic fertilizers have been considered an effective alternative to chemical fertilizers for increasing crop yields and reducing methane emissions for a long time. FW is utilized as a source of animal nutrition as well as an organic fertilizer that is manufactured through the processes of composting and vermicomposting [195]. When used as a substrate for mushroom cultivation [66], agricultural waste reduces the environmental burden while increasing crop productivity and changing the soil bacterial community. The biogas residue from FW could be used as an organic fertilizer or soil conditioner because it is rich in plant-growth-promoting nutrients (N, K, P, Ca, Mg) and trace minerals (Fe, Cu, Zn, Al) [196].

The process of anaerobic digestion involves mixing FW and organic matter under anoxic conditions in an anaerobic digester. Microorganisms then decompose the organic matter and convert it into biogas. Once the biogas has been produced and captured, the nutrient-rich residue left behind is called anaerobic digestate. This digestate can be used as a soil fertilizer and has been shown to increase ryegrass yield by 5–30% compared to mineral fertilizers [197]. However, it is important to note that FW digestate can be phytotoxic until it matures, which may reduce nutrient availability and germination [197]. Despite this, the digestate can still be used as a soil amendment, which can increase the dissolved organic matter in the soil, leading to the slow and fast release of nutrients while also improving the soil's water-holding capacity [198]. Additionally, kitchen waste can produce volatile fatty acids through anaerobic fermentation that can be used as soil cleaners for soils contaminated with vanadium and chromium [199]. Finally, compost made from FW could be effective in chelator-enhanced phytoremediation of toxic metal-contaminated soils, making it an effective soil remediation technique according to some studies. [200].

Organic fertilizers are prepared mainly by anaerobic digestion, aerobic composting by microorganisms, chemical hydrolysis (alkaline or acidic hydrolysis at 600–1000 °C), or in-situ degradation of natural organic matter. Different forms of fertilizers are produced, such as soil conditioners, composts, soluble bio-waste composts, degraded crops, and mineral and liquid organic fertilizers [201]. Liquid organic fertilizers are more advantageous to plant growth than other fertilizers since they are administered directly to the single root zone in the irrigation system. Besides that, they are quickly absorbed by plants and require less per plot, and the degradation process is relatively straightforward [202]. The efficacy of organic fertilizers could be further enhanced by incorporating methane-oxidizing bacteria [64]. Additionally, organic fertilizers promote the growth of microalgae. It could be used as a substitute nutritional media to cultivate Chlorella for biodiesel production [203].

4.6. Bioplastics

Bioplastics or biobased plastics, made from renewable resources such as starch, vegetable oils, and microorganisms, are promising alternatives to synthetic plastics due to their reduced environmental impact. In 2019, biobased plastics accounted for only 1% of total plastic production, with a global production of 3.8 million tons [157]. Substituting synthetic plastics with bioplastics could also mitigate global warming concerns, as the production of oil-based synthetic plastics requires more energy (77 MJ/kg) than bioplastics (57 MJ/kg) [204].

Bioconversion of FW to bioplastics is an effective waste treatment strategy. To produce bioplastics from FW, pretreatment is necessary to improve its biological and physicochemical properties. Physical hydrolysis, chemical hydrolysis, bio-hydrolysis, and enzymatic hydrolysis are common pretreatment strategies. Physical treatment processes such as heating, grinding, ultrasound, and microwaves are used to convert FW into fermentable organic compounds [205]. Biological treatments involve utilizing food waste as a fermentation substrate for microorganisms. The primary biodegradable polymers with significant market potential include polyhydroxyalkanoates (PHA), polyhydroxybutyrate (PHB), polybutylene succinate (PBS), starch blends, polyvinyl alcohol (PVA), and polylactic acid (PLA) [100,205–207].

Alcaligenes sp. *NCIM 5085* was reported to obtain 70.89% high molecular weight PHB with a productivity of 0.312 g/L/h by optimizing the fermentation process using sugarcane molasses [207]. Another strain, *Halomonas campaniensis strain LS21*, grown in FW, which is rich in cellulose, starch, fatty acids, and proteins, produced 70% PHB at 37 °C [205,208]. Lignocellulosic FW was converted into hemicellulose, cellulose, and lignin by enzymatic or chemical hydrolysis and it was further used to synthesize biopolymers. A range of biocomposites have been developed and are commercially available, such as (1) calcium acetate for the production of wound dressings and toothbrushes; (2) PLA for the manufacture of bone splints, surgical sutures; (3) PHB for the manufacture of compost bags, consumer bags, containers; and (4) polycaprolactone for the production of medical implants [209]. Despite the non-toxicity and biocompatibility advantages of biocomposites, they face challenges in the commercial field due to their high processing costs, lack of suitable raw materials, and inferior price competitiveness. Addressing these drawbacks is crucial for the future of FW research and the development of more competitive biocomposites [210].

4.7. Animal Feed

FW, as a viable raw material for animal feed formulations, presents an interesting alternative. Plant waste has a high-water content (usually more than 80%), requiring an additional drying process. The composition of this waste may change significantly throughout the year [211], requiring animal feed manufacturers to adapt their feed formulations regularly based on the changing composition. On average dried FW contains 65% carbohydrate, 13% crude fiber, 12% crude protein, 8% ash, and 2% ether extract [212]. Carbohydrates are the primary source of energy in pig metabolism, but a high concentration of fiber could diminish the digestibility and availability of energy in pig diets [212]. Consequently, diets containing vegetable waste may be utilized, but additional ingredients, including Cenchrus ciliaris hay [213], mineral mixture, and common salt [214], must be supplemented.

Currently, available processing technologies allow the conversion of FW into safe animal feed products with added value and high-quality nutrients [215]. FW processing includes cooking, dehydration, ensiling [216], extrusion, pelletizing, and probiotic treatment [217]. Among the above treatments, extrusion, pelletizing, and dehydration result in value-added FW products with a longer shelf life than cooking and ensiling [216]. Furthermore, the dehydration process could promote incorporating the generated FW products into existing swine feeding programmes [218].

Animal feed derived from fermented, heat-treated, and coupled hydrothermally treated FW has an adequate and balanced nutritional value. However, some unwanted substances, such as those originating from cattle and sheep, may remain in the feed products derived from raw FW and are difficult to eliminate through the feed conversion process. Nonetheless, these deficiencies can be mitigated or eliminated by limiting the application of the feed. For instance, feeding ruminants with feed made from FW should be prohibited [219].

Protein-rich FW has the potential to serve as a valuable raw material for the production of fish feed pellets, thereby reducing the amount of waste that is typically disposed of in landfills. In fact, FW derived from plant materials such as grains, fruits, and vegetables, when supplemented with yeast and a mixture of bromelain and papain, has been shown to enhance the growth performance of grass carp, with a relative weight gain of up to 63.6% and improved immunity [220].

5. Conclusions and Future Perspectives

Numerous bioactive compounds are derived from FW. Thus, the conversion of FW into other value-added products has been studied to reduce the burden of waste management, decrease resource and energy consumption, and safeguard the environment. The growing recognition of the importance of sustainable practices and the need to decrease FW have motivated the development of novel and innovative technologies to extract bioactive compounds from FW. The use of cutting-edge technologies provides various advantages, including reducing waste, creating new economic prospects, promoting a circular economy, and developing functional food ingredients, cosmetics, and dietary supplements. This review provides a comprehensive overview of the various sources of FW, highlights the bioactive compounds that have captured the attention of researchers, and presents extraction techniques for these substances. Furthermore, this review summarizes the current state of value-added product transformation and development based on the aforementioned bioactive compounds.

Despite the establishment of various conversion technologies for FW at the laboratory scale, the sustainable implementation of these technologies at the commercial level presents challenges and limitations, which require researchers to address these issues in future research. Most of the technologies discussed above are in the developmental stage, with excessive extraction costs due to expensive equipment, solvents, and energy being a significant obstacle. In addition, undesirable extraction rates, lower stability of natural active compounds than synthetic compounds, and difficulties in managing residues that may pose environmental or health risks if not properly disposed of or utilized, are some of the other issues that need to be addressed to ensure sustainable FW conversion at the commercial level. Hence, it is not yet possible to conclude that the utilization of these technologies alone will effectively resolve FW-related issues. One of the primary challenges for the future will be to improve the efficiency of the extraction processes and develop new methods that are more environmentally friendly. Additionally, more research will be required to determine the bioavailability and safety of the extracted compounds and to identify new applications for these products. Ultimately, the goal is to recycle and breathe new life into waste, with the background of the urgent problem of global FW production as a driving force. Balancing the costs of large-scale FW conversion with the benefits of the additional products obtained is also one of the factors that the researcher must consider and pursue.

In the coming years, it will be crucial to develop specific extraction methods for different FW sources or bioactive compounds of interest. To minimize environmental and human health impacts, it is important to use green solvents as much as possible. Given the lack of a uniform standard for FW sources, setting specific standards for value-added products resulting from FW conversion may prove difficult but worthwhile. Moreover, efforts should be made to bridge the gap between the quality of value-added products derived from FW and that of the original product. Exploring the possibility of substituting existing products with value-added products derived from FW is a promising avenue for research. Conduct more life cycle assessment studies of FW-derived products. Moving forward, studies on FW should not be limited to waste utilization and value discovery but should also aim to leverage FW as a cost-effective source of high-quality value-added products.

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