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REVIEW PAPER

Novel extraction methods and potential applications of polyphenols in fruit waste: a review

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Abstract

During fruit waste processing, bioactive compounds can be lost along with waste, and thus it is necessary to recover these bioactive compounds. Recently, the extraction of polyphenols from fruit waste and the stabilization and integration of these compounds into food substances has become a valuable research field. Polyphenols have strong antioxidant, anti-inflammatory, and antibacterial activity and are the main active components of fruit waste. Their extraction from fruit waste is of great commercial and scientific significance. The extraction of polyphenols from fruit waste, the stabilization of their bioactivities, and their integration into the food matrix have become increasingly interesting topics. In this review, the novel extraction methods and potential applications of fruit waste polyphenols were summarized to inform the recovery and utilization of polyphenols in fruit waste. The comprehensive utilization of byproducts from food industry is beneficial to the reduction of food costs, the alleviation of environmental contamination, and the realization of food industry sustainability.

Keywords Fruit waste · Polyphenol · Bioactivity · Extraction · Shelf life

Introduction

Food processing waste is defined as the components of food products with little value or that are treated as waste due to loss of original value as a result of processing [1, 2]. The tremendous waste from fruit processing has led to significant resource waste and environmental contamination [3, 4]. Fruit waste typically contains high contents of moisture and organic matter, as well as many types of unsaturated fatty acids. Hence, fruit waste perishes and deteriorates easily, which can produce bad odors and create an environment suitable for the breeding of mosquitoes and bacteria, thus ultimately contaminating the environment [5]. At present, processing methods for fruit waste include landfills, incineration for power generation, and biorefining [6–9].

During fruit waste processing, bioactive compounds can be lost along with waste, and thus it is necessary to recover these bioactive compounds [10]. The most representative bioactive compounds in fruit waste are polyphenolic compounds. Polyphenolic compounds are plant compounds that contain several phenolic hydroxyl groups in their molecular structure. They exist in different compound formats in fruit waste, such as flavonoids, tannins, phenolic acids, and anthocyanins [11]. As universally-existing bioactive compounds in fruit waste, polyphenols have antioxidative effects and can strengthen blood vessel walls, facilitate gastrointestinal digestion, reduce blood lipid levels, increase body immunity, and prevent arteriosclerosis and thrombus. Additionally, bioactive compounds have diuretic effects and can relieve hypertension and inhibit bacteria and cancer cell growth. Hence, the research of bioactive compounds has become a pertinent research topic [12–14].

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Recently, the extraction of polyphenols from fruit waste and the stabilization and integration of these compounds into food substances have become valuable research field. Traditional extraction technologies include solid–liquid extraction, liquid–liquid extraction, and other solvent-based extraction methods [15]. Novel exaction technologies include ultrasound/microwave/enzyme-assisted extraction and membrane separation. These technologies present their own advantages and disadvantages. Hence, when selecting the processing technology, the nature of the fruit waste, the characteristics of the bioactive compounds, and the extraction rate and process must be considered.

Table 1 lists the major polyphenols in different fruit waste types and the processing methods. Although fruit waste contains many different types of polyphenols, most fruit waste is processed into landfills, resulting in tremendous resource wastage [16]. To reduce waste, protect the environment, and promote the recovery of fruit waste polyphenols, this article systematically discusses different technologies for recycling polyphenols from fruit waste, as well as their advantages and disadvantages. This article also provides insights into the application of fruit waste polyphenols in modern food development.

Polyphenol-extraction technologies from fruit waste

Traditional extraction technologies

Solid–liquid extraction

Solid–liquid extraction is the most commonly used technology for the extraction of polyphenolic compounds from fruit waste [39, 40]. Solid–liquid extraction, includes methods such as dipping extraction, alcohol extraction, and Soxhlet extraction. Solid–liquid extraction, as a well-developed industrial extraction technology, presents advantages such as simple equipment and low cost. Hence, it has been widely used to recycle fruit waste. Ethanolic solid–liquid extraction is employed to recover polyphenolic antioxidants from grape marc. The content of total polyphenols determined by HPLC is 4.00 g/L ± 0.05, and it has strong antioxidant capacity in human endothelial cells [41]. Another study optimized the conditions for the recovery of phenolic compounds from olive seeds and found that at an extraction temperature of 40 °C and extraction time of 89.49 min, with methanol as the solvent, resulted in a total polyphenol content of as high as 210.00 ± 0.28 mg GAE/kg dry substance [42]. However, although solid–liquid extraction is easy to operate, the large energy and solvent consumption raises energy and environmental concerns.

Table 1 The treatment methods of fruit waste and the typical polyphenols

Fruit waste	Polyphenols	Treatment methods	References
Citrus peel	Caffeic acid, erucic acid, naringin, hesperidin, lysimachin	Landfill, extraction of active substances, biological fermentation	[17, 18]
Apple pomace	Anthocyanin, chlorogenic acid, protocatechuic acid, catechin, hydroxycinnamate	Landfill, making feed, compost	[19, 20]
Bagasse	Chlorogenic acid, caffeic acid, erucic acid, butyric acid, vanillin, orientin, vitexin	Papermaking, compost, biofuels	[21–23]
Grape pomace	(+)-Catechin, (−)-epicatechin, anthocyanin, quercetin, gallic acid	Extraction of active substances, functional component	[24–26]
Pomegranate peel	Tannin, ellagic acid	Landfill, making feed, oil extraction	[27]
Mango pomace	Mangiferin, allic acid, ellagic acid, quercetin, kaempferol, anthocyanin	Landfill, compost, biological fermentation	[28]
Banana peel	Protocatechuic acid, catechin, chlorogenic acid	Landfill, compost, biological fermentation	[29, 30]
Pomelo peel	Gallic acid, naringin, hesperidin	Landfill, biomass materials	[31, 32]
Kiwi peel	Gallic acid, coumaric acid, catechin	Landfill, extraction of active substances	[33, 34]
Hawthorn skin	Chlorogenic acid, epicatechin, rutin	Landfill, extraction of active substances	[35, 36]
Longan nucleus	Gallic acid, ellagic acid	Landfill, biomass material	[37]
Cranberry dregs	Procyanidins, anthocyanins	Landfill, extraction of active substances	[38]

Solid-phase extraction

Solid phase extraction, as a novel technology, utilizes a solid adsorbent to adsorb the target compound from a liquid sample [43]. Four resins, including Amberlite XAD7 and XAD16, IRA96, and Isolute ENV, as the solid phase were used to efficiently recover phenolic compounds from olive factory wastewater [43]. Other recent studies used solid phase microextraction to extract apple peel polyphenols from 12 traditional and eight commercial apple varieties. The results indicated that the major phenolic compounds and their levels in traditional and commercial apple were non-flavonoids (28.6%) and flavanols (46.2%), respectively [44]. Compared with solid–liquid extraction, solid phase extraction possesses various advantages, such as a high extraction rate, short processing time, and more applicable scenarios. However, its high cost prevents the large-scale applications.

Liquid–liquid extraction

Liquid–liquid extraction leverages the solubility or partition coefficient difference of a substance in two immiscible (or slightly soluble) solvents and commonly used solvents are ethanol, methanol, hexane, and other organic solvents. However, those solvents with toxic side effects are less frequently used in the extraction of polyphenols from fruit waste [45, 46].

Nowadays, rather than simply using traditional solvent extraction, researchers are more inclined to combine solvent extraction with emerging technologies such as ultrasound-assisted and microwave-assisted extraction to benefit from the advantages of the different techniques. The combinational usage of different techniques provides the possibility of reducing extraction time, enhancing extraction efficiency, and optimizing extraction steps.

Novel extraction technologies

Ultrasound-assisted extraction

Compared with traditional extraction technologies, ultrasound-assisted extraction has several advantages, including rapid extraction process, high extraction rate, reduced solvent use, and simple operation [43, 47]. It is thus recognized as a simple and effective technology for the extraction of bioactive compounds. Ultrasound-assisted extraction has been widely used in the extraction and separation of various effective compounds from natural plants achieving good results [48]. During the extraction, the active ingredient quickly enters the solvent under the action of ultrasound, thereby improving mass transfer, destroying the cell wall, and promoting the release of bioactive compounds.

When extracting flavonoids from grapefruit residue under the same conditions, the total polyphenol content and total antioxidant activity of ultrasound-assisted extraction extracts were about 1.7 times that of conventional solid–liquid extraction extracts [49]. Sally et al. combined infrared pretreatment with ultrasound-assisted extraction and compared the combined technology with traditional solid–liquid extraction. They found that ultrasound increased the extraction rate of polyphenols from untreated peels by 62.5% [50]. Tania et al. found that using a 60% ethanol–40% acetone mixture combined with ultrasound-assisted extraction significantly improved the recovery rate of phenolic compounds [51]. Ultrasound-assisted extraction has become a well-developed technology for polyphenol extraction from fruit waste [52]. Additionally, combining ultrasound-assisted technology with other extraction technologies is another research hotpot and may achieve further advantages.

Microwave-assisted extraction

Microwave-assisted extraction is a novel extraction technology that combines microwave and traditional solvent extraction. Compared with other extraction technologies, this technology has advantages such as short extraction time, high extraction rate, low labor demand, high extraction selectivity, and low cost [53]. Compared with traditional extraction methods and ultrasound-assisted extraction, microwave-assisted extraction can extract plant metabolites in a short time interval [54, 55].

Similar to ultrasound-assisted extraction, microwave-assisted extraction has been reported for the extraction of polyphenols from fruit waste. Casazza et al. used microwave-assisted extraction to extract polyphenols from the from apple skins for the formulation of new antioxidant products (dietary supplements, cosmetics, drugs) [56]. Ana et al. studied the dynamics of microwave-assisted extraction on grape pomace, aiming to facilitate the large-scale application of microwave-assisted extraction in industry [57]. Additionally, compared with traditional solvent extraction, it was reported that the total phenol content of grape skins extracted by microwave-assisted extraction was 73.68 mg GAE/100 g DW, which was a nearly 200% increase [58]. When the methods of microwave, ultrasound, and accelerated solvent extraction were compared for the extraction of polyphenols from orange peels, microwave-assisted extraction was found to be better than the other methods [59]. It can be seen that microwave-assisted extraction has certain advantages in the recovery of polyphenols from fruit waste. Further in-depth research and development are thus necessary.

Enzyme-assisted extraction

The cell wall of fruit waste tissue is a barrier preventing the release of polyphenols from the cell. Enzymes such as cellulase, β-glucosidase, xylanase, and pectinase can degrade cell wall structure and facilitate the release of internal substances [60]. Due to these features, enzyme-assisted extraction [61] can be used as a pre-treatment technology in combination with other extraction technologies, or as a major extraction technology with the use of multiple enzymes to extract the target compound (Fig. 1).

Enzyme-assisted extraction also has unique advantages in the extraction of polyphenols from fruit waste. Compared with mechanical treatment, it damages the cell wall more effectively and can reduce the loss of active compounds [62]. Mushtaq et al. introduced a 3.8% cocktail enzyme to pretreat pomegranate peels at pH 6.7 and 41 °C for 85 min, and the extraction efficiency was three times higher than that of traditional solvent extraction [63]. Compared with ultrasound-assisted extraction of polyphenols from citrus peels, it was discovered that the polyphenol productivity of the enzyme-assisted extraction was two times higher than that of the ultrasound-assisted extraction [64]. The above studies all showed that enzyme-assisted extraction is an effective supplemental method to traditional solvent extraction methods.

Membrane separation technique

Membrane separation is a technique that achieves the selective separation of molecules of different sizes at the molecular level through a semipermeable membrane. Membrane filtration separates phenolic compounds based on molecular weight, which is not achievable by other techniques. The semi-permeable membranes used in membrane separation generally include microfiltration membrane, ultrafiltration membrane, nanofiltration membrane, and reverse osmosis membrane. In recent years, membrane separation techniques have been applied to the treatment of wastewater from food industry [65].

Compared with traditional extraction techniques, membrane separation presents certain advantages such as low energy consumption, high efficiency, mild operation conditions, and scalability for the recovery of phenolic compounds from food waste [66, 67], as shown in Fig. 2. Compared with solvent extraction, membrane separation consumes less organic solvent. Compared with enzyme-assisted extraction, membrane separation is less susceptible to heat and acid, and hence is more stable. Compared with ultrasound-assisted extraction, membrane separation has better selectivity [68, 69].

Various methods have been developed for the extraction of polyphenols from fruit waste using membrane separation. Papaioannou et al. efficiently recovered pomegranate peel polyphenols (≥ 98%) using nanofiltration [74]. Conidi et al. recovered flavonoids (70%) and anthocyanins (89%) from citrus by-products through nanofiltration [75] (Fig. 3).

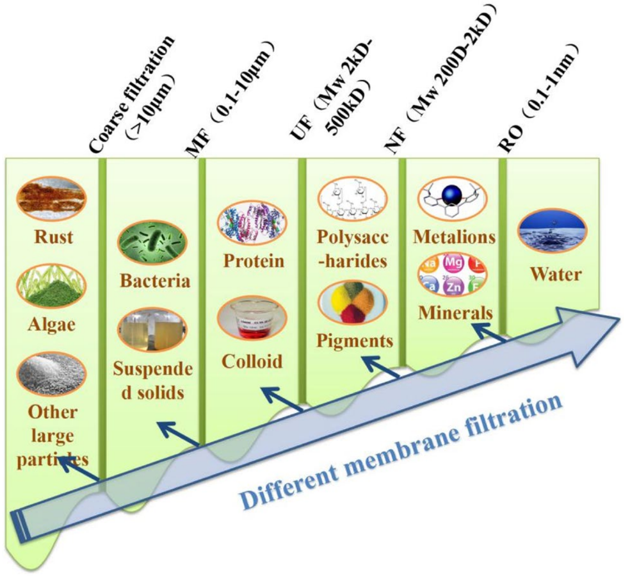
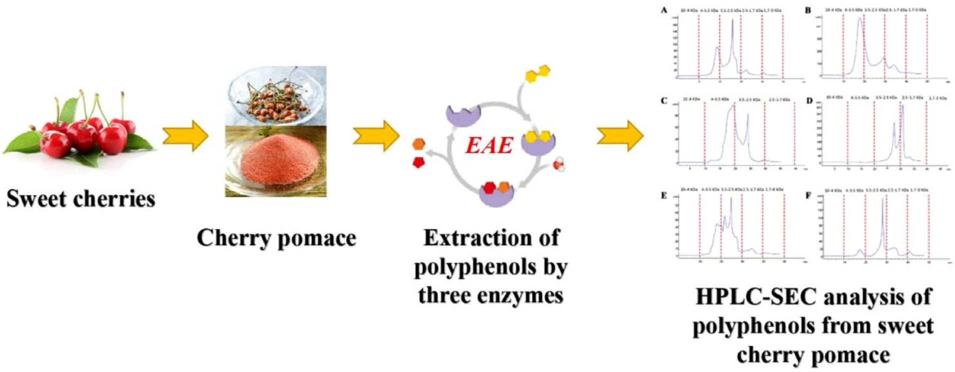


Fig. 2 Four separation membranes and the data was cited from the references [69–73]. MF, microfiltration; UF, ultrafiltration; NF, nanofiltration; RO, reverse osmosis

Fig. 1 Enzyme assisted extraction of polyphenols from sweet cherry [61]



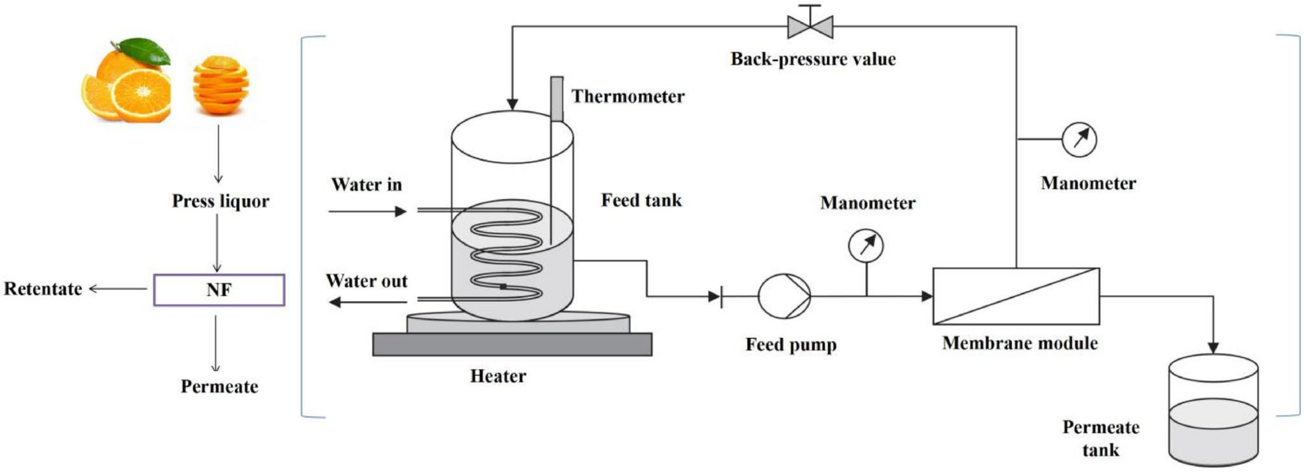


Fig. 3 Schematic diagram of the NF experimental setup [75]

It was also revealed the recovery of almost all polyphenols from olive processing wastewater using microfiltration and nanofiltration integrated membrane systems [76]. It can be concluded that membrane separation has its unique advantages in the recovery and separation of polyphenols from fruit waste. Membrane separation is thus an environmentally friendly technique with great application potential.

Pressurized liquid extraction

Pressurized liquid extraction is widely used to extract bioactive compounds from natural sources. The principle is to use an organic solvent as the extractant to obtain the target product through molecular diffusion, mass transfer, and vacuum evaporation. Compared with traditional solvent extraction, pressurized liquid extraction has higher extraction efficiency, lower extraction durations, and less organic solvent consumption [77]. Compared with ultrasound-assisted extraction and microwave-assisted extraction, it has characteristics such as non-thermal processing, energy saving, and low operation cost [78]. Pressurized liquid extraction has been applied to the extraction of polyphenols from fruit waste, and it is a technology that can be used in large-scale industrial manufacturing [79]. Mariotti-Celis et al. used high-pressure liquid extraction in combination with resins to purify grape pomace polyphenols, effectively obtaining purified polyphenol extracts free of hydroxylmethyl furfural and reduced sugars [80]. Pressurized liquid extraction has also been used to recover and characterize polyphenols in apple peel [81]. Pressurized liquid extraction, as a suitable technique for large-scale industrial applications, presents great potential in recycling and recovering food waste. With further research and development, it could be advantageous in many different aspects.

Supercritical fluid extraction

Supercritical fluid extraction is an environmentally friendly technology that uses supercritical fluid [e.g., carbon dioxide (CO_2)] as an extraction solvent to extract bioactive compounds from waste. Compared with traditional extraction technologies, supercritical fluid extraction has high selectivity and a short extraction time. Additionally, given that it is conducted in the absence of light and oxygen, supercritical fluid extraction significantly reduces compound oxidation [82]. It thus has great potential in the extraction of active compounds from food waste [83].

Carla et al. conducted a kinetic study on the superfluid extraction of grape seed polyphenols (Fig. 4), indicating that under a pressure of 80 bar, a CO_2 flow rate of 6 kg/h, and a co-solvent weight ratio of 20% (w/w), the extraction rate of total phenols reached its highest value [85]. Espinosa-Pardo et al. used supercritical CO_2 to extract phenolic compounds in dried fermented citrus pomace [86]. Other studies indicated that CO_2 supercritical fluid extraction is also suitable for the recovery of phenolic compounds from bayberry residue and blueberry residue [87, 88]. The above results demonstrated that the superfluid extraction of polyphenols from fruit waste is safe and environmentally friendly. However, the industrialization cost as a result of high pressure limits its large-scale application.

Pulsed electric field-assisted extraction

Pulsed electric field-assisted extraction, as a new technology for the extraction of bioactive compounds, has attracted increasing attention in recent years [89]. In a pulsed electric field-assisted extraction process, the food waste is placed in the strong electric field between two electrodes, which results in the formation of pores on the cell wall and

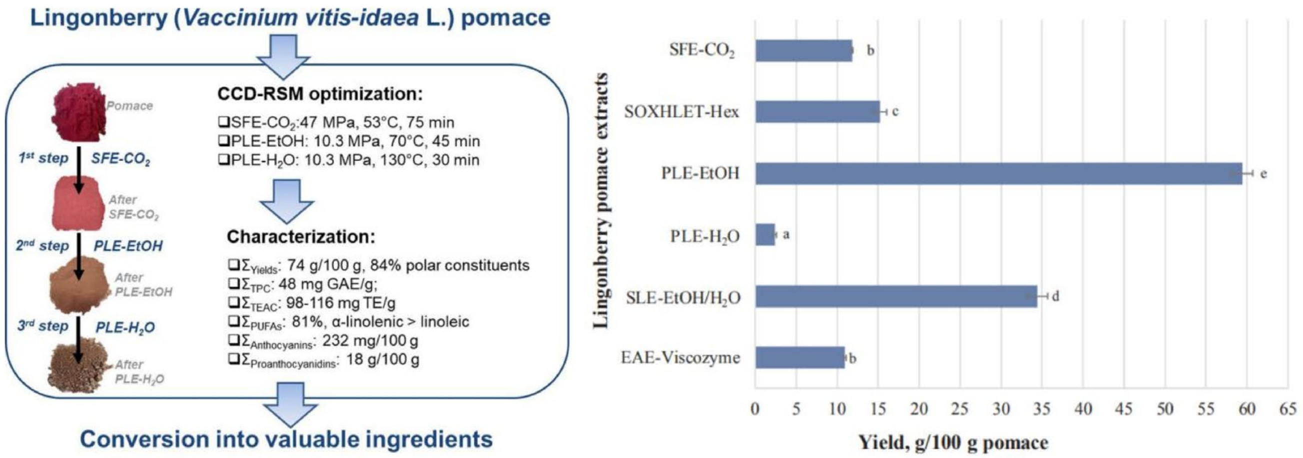


Fig. 4 Recovering polyphenols from grape seeds via supercritical fluid-assisted extraction [84]. *EAE* Enzyme-assisted extraction, *SLE* solid liquid extraction, *PLE* pressurized liquids extraction, *SFE* supercritical fluid extraction

promotes cell membrane permeability as a result of the polarization of transmembrane ions [90]. Compared with traditional extraction technologies, pulsed electric field-assisted extraction is environmentally friendly, low-cost, fast, and can enhance the extraction rate of bioactive compounds [91, 92].

The use of pulsed electric field treatment for fruit processing can significantly improve quality, juice yield, and polyphenol content in food industry [93, 94]. Sylène et al. optimized the parameters of the pulsed electric field to increase the content of total polyphenols and the extraction of anthocyanins in grape pomace [95]. Deng et al. showed that the "pin-ring" pulsed discharge is an effective and promising method for extracting polyphenols from grape pomace [96]. Luengo et al. proved that pulsed electric field extraction increased the extraction rate of total polyphenols and total flavonoids in orange peel by several times [97]. It can be revealed that pulsed electric field extraction, as an emerging low-energy-consumption technology, can increase the extraction rate of polyphenols from fruit waste. However, this technology is currently less widely used and requires further development.

Other techniques

Besides the above common methods used to extract polyphenols from fruit waste, other methods exist such as subcritical water extraction, pulsed arc electrohydraulic discharge extraction, and a combination of the various methods. Table 2 lists the extraction methods and outcomes for different fruit waste types. At present, solvent extraction still remains the most commonly used industrial method. However, the combination of ultrasound-assisted solvent extraction and microwave-assisted solvent extraction presents many advantages. Due to their various advantages, such as environmental-friendliness and easy operation, enzyme-assisted extraction and membrane separation are also expected to be used for large-scale industrial manufacturing in the future. However, due to the high cost, supercritical fluid extraction and pulsed electric field assisted extraction are still under development and consideration.

Potential applications

Polyphenols have great potential for the utilization in food formulations due to their nutritional and functional characteristics. Hence, the comprehensive utilization of fruit processing by-products or waste has become a new means of saving resources and energy. Polyphenols also have bioactive effects such as antioxidation, anti-inflammatory, and antibacterial activity. In recent years, polyphenols have been used in various applications, such as in extending food shelf-life, developing functional foods, and medical treatment (Fig. 5).

Extending food shelf-life

Fruit waste polyphenols rely on their antioxidative and antibacterial activities to extend food shelf life. As natural antioxidants and bacterial inhibitors, polyphenols have proven effective in inhibiting some pathogens and retaining product quality [111]. They are expected to become a substitute for synthetic antioxidants and preservatives.

Fruit waste polyphenols can be added to oil to prevent it from rancidity and nutrition loss. Olive residue polyphenol extracts can be added to the frying process to delay lipid oxidation [112]. Bouaziz et al. found that under accelerated oxidation conditions, the addition of polyphenol extracts in

Table 2 Extraction methods and performance of polyphenols from fruit waste

Fruit waste	Methods	Extraction condition and results	References
Mango leaves	MAE	Extraction for 5 min using water at microwave power of 272 W. The maximum extraction yield was 55 mg/g	[98]
Orange peel	SWE	Extraction at 150℃, 10 mL/min, hesperidin (188.74 ± 0.51 mg/g DW) and naringin (21.98 ± 1.39 mg/g DW) were obtained	[99]
Citrus peel	EAE and UAE	UAE: 70.89% amplitude, 40 ml/g solvent–solid ratio, 35 min extraction time EAE: 0.84% enzyme concentration, 30.94 mL/g solvent–solid ratio, 4.87 h extraction time	[64]
Citrus peel	UAE	80% methanol: 32.48 mg gallic acid equivalent (GAE)/g extract 80% ethyl acetate through the maceration technique: phenolics (8.64 mg GAE/g extract)	[100]
Orange pomace	SFE	15, 25 and 35 MPa,40, 50 and 60 °C, using pure ethanol and ethanol:water (9:1 v/v) as cosolvents The total extraction rate was increased by 2.01 to 2.62%, and total polyphenols (18–21.8 mg GAE/g dry extract)	[86]
Pomegranate peel	UAE	Extraction time of 25 min, ethanol concentration of 59%, solid to solvent ratio of 1:44, and extraction temperature of 80 °C Total polyphenols: 149.12 ± 7.46 mg/g dw	[101]
Pomegranate peel	MAE	50% aqueous ethanol; solvent/solid ratio, 60/1 mL/g; power, 600 W. The free radical scavenging activity of pomegranate glycoside (143.64 mg/g DW) was 94.91%	[102]
Pomegranate peel	EAE	3.8% of cocktail enzyme at 6.7 pH and 41℃ for 85 min produced a mass yield of 65.89 ± 2.64 g/100 g of crude extracts (threefold increase compared to conventional solvent extraction) Total phenols concentration of 277.93 ± 6.17 mg GAE/g dw	[63]
Blueberry pomace	NF	Both nanofiltration membranes (NF245 and NF270) showed complete rejection of phenolic compounds at good permeances, whereas crossflow mode of filtration was found to reduce membrane fouling considerably. After repeated filtrations followed by the cleaning protocol, the rejection performance was preserved unaltered and the relative permeance was recovered up to 73% for NF245 membrane and more than 99% for NF270 membrane	[103]
Blueberry pomace	PLE and SFE	PLE: temperature, pressure and solvent flow rate kept constant at 40 ℃, 20 MPa and 10 mL/min SFE: 90% carbon dioxide, 5% water and 5% ethanol	[104]
Apple pomace	UAE and UAMME	UAE and UAMME were prepared with ultrasonic bath InterSonic IS-3 (25 × 14.5 × 22.5 cm), frequency 50 ± 3 Hz, power 300 W The yield of conventional crops polyphenols by UAMME extracts was 349.65 mg/dm^3 and the value was seven times higher than obtained by UAE method	[105]
Grape pomace	EAE	The yield of soluble solids (20–45%) and phenols (25–65%) were significantly increased by the combination of three commercial enzymes	[106]
Grape pomace	UAE	UAE with a temperature of 56 °C, a solvent/solid ratio of 8 mL/g, an amplitude level of 34%, and a time of 20 min with 53% aqueous ethanol The yield of polyphenols was 48.76 ± 1.06 mg GAE/g dry grape pomace	[107]
Persimmon pomace	SLE	Solid–liquid ratio (V:W) 20:1,temperature 90℃, ethanol concentration 40%, time 4 h Total polyphenols was 21.402 mg/g	[108]
Red pitaya peel	MAE	Extraction time of 20.3 min, ratio of solvent to raw material 33.4:1 (mL:g), microwave power 497 W, extraction temperature 43.3 °C and ethanol concentration 64.9% The yield of polyphenols was (463.8 ± 1.1) mg gallic acid equivalents (GAE) per 100 g dw	[109]
Banana peel	MAE	Ethanol concentration was 50%, liquid ratio was 1:35, extracted for 100 s at the microwaves power of 380 W The extraction ratio of polyphenol reached 2. 16%	[110]

EAE enzyme-assisted extraction, *MAE* microwave-assisted extraction, *NF* nanofiltration, *SLE* solid liquid extraction, *PAED* pulsed arc electrohydraulic discharges, *PLE* pressurized liquids extraction, *SFE* supercritical fluid extraction, *SWE* subcritical water extraction, *UAE* ultrasound-assisted extraction, *UAMME* ultrasound-assisted micelle-mediated extraction

olive oil effectively delayed oxidation, which demonstrated that polyphenol extracts could strongly prevent oil oxidation [113].

Meat products, if not frozen or marinated timely, oxidize and deteriorate rapidly. Fruit waste polyphenols have positive effects on preventing microbial spoilage, lipid

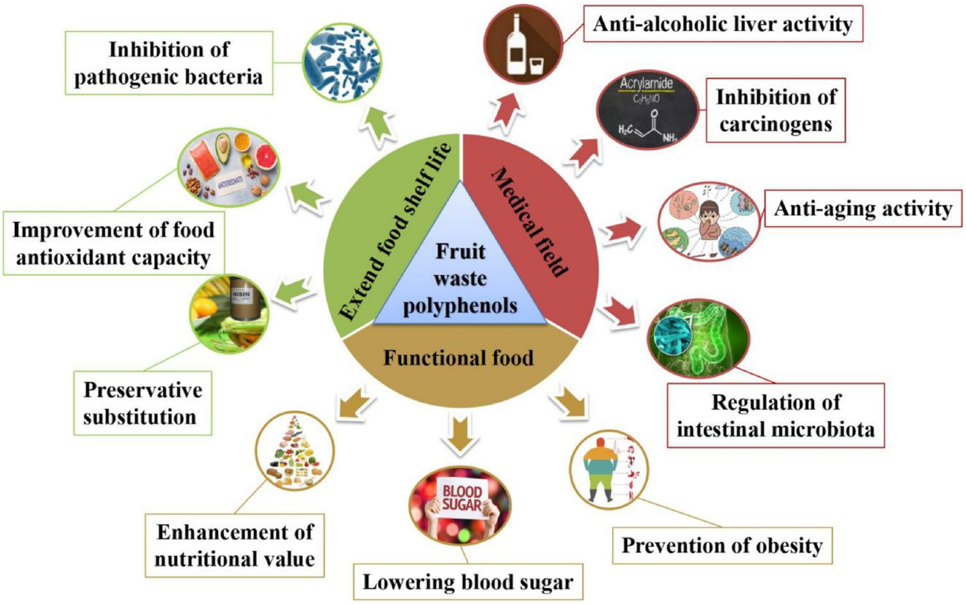


Fig. 5 Different applications of fruit waste polyphenols

oxidation, and quality deterioration [114]. Phenolic compounds extracted from cranberry pomace can effectively inhibit the formation of malondialdehyde in meat products, effectively inhibit the growth of pathogenic bacteria and spoilage bacteria, improve the oxidation stability of pork sauce and ham, and extend the shelf life of meat products [115]. Moreover, it was found that the addition of grape by-products (mainly skin and pomace) to chicken patties reduced TBARS content without affecting sensory characteristics (texture and color) or microbial quality [116].

Fruit waste polyphenol extracts can also improve the antioxidant performance of dairy products. Silva et al. studied the application of grape pomace phenolic extracts in cheese. Their findings indicated that polyphenol extracts increased the gel strength and antioxidant properties of cheese without affecting their physical quality [117]. Polyphenols can improve the antioxidant properties of dairy products, while dairy products can protect polyphenols. Carlos et al. found that dairy and egg products could protect polyphenols from degradation during the digestion process and improve their biological availability and antioxidant activity [118].

In addition to the above categories, fruit waste polyphenols can also be used in other food applications. Taticchi et al. reported the effect of olive polyphenol extracts on the preservation of tomato sauce, revealing that the phenolic extracts reduced the loss of carotenoids in tomato sauce during heating [119]. Kaderides et al. used polyphenols from orange juice by-products for biscuit fortification and found that the phenolic compounds still showed good antioxidant activity after baking and storage, and no side-effects were observed on the sensory quality of the biscuits [120].

Functional food

Polyphenol compounds present antioxidative effects and can strengthen blood vessel walls, facilitate gastrointestinal digestion, reduce blood lipids, and increase body immunity. Hence, they are the preferred healthy functional food ingredients [121]. A grape peel (*Syrah* var.) jam which has high content of bioactive components and antioxidant capacity has been developed and can be used as a source of natural antioxidants in a variety of food industry products [122]. Bijan et al. used pomegranate peel polyphenols in sponge cake controlling the human body glucose index, as pomegranate peel polyphenols have obvious inhibitory effects on α-amylase and α-glucosidase. Hence, the pomegranate peel polyphenols (1.5 g/100 g) reduced the glucose index by 44% [123]. Kan et al. found that the co-digestion of berry polyphenols and bread significantly reduced the starch digestion rate and degree, thus demonstrating their potential usage in reducing the glycemic index of starchy food [124].

Sarahí et al. demonstrated that polyphenols and dietary fibers in peach by-products could prevent obesity complications and lower blood glucose, and hence could be used as functional food ingredients [125]. Grape skin polyphenol extracts could more effectively inhibit the low-density lipoprotein cholesterol and triacylglycerol levels of Wistar rats, indicating that grape skin polyphenol extracts could be used in food and supplement industry. Grape skin polyphenols could be a cost-effective source of bioactive phenols to prevent coronary artery disease and other age-related issues [126]. Large amounts of fruit waste can be recovered and recycled as ingredients for next-generation functional goods. The great practical value and the products above will become the prioritized choices for a modern healthy and environmentally friendly lifestyle [84].

Medical field

The importance of polyphenols in human health has attracted increasing attention from the scientific community. Many recovered fruit polyphenols have been applied in medical and related fields. Alcohol abuse is extremely harmful to human physical and mental health. Studies have indicated that olive and grape polyphenol extract (resveratrol) has an anti-alcohol effect and can effectively offset the formation of free radicals as a result of long-term alcohol intake [127]. Various pomace polyphenol extracts have been used to reduce the formation of carcinogens [128]. Sabally et al. found that adding dried apple peel polyphenols into fried beef patties effectively inhibited the formation of heterocyclic amines and other carcinogens [129]. Nunzio et al. confirmed the therapeutic ability of olive pomace polyphenols in intestinal disease [130]. It was also revealed that the mangiferin and other hydrolysable polyphenols (ellagic acid, gallic acid) relieved the symptoms of gastrointestinal and respiratory tract infection in children [131]. Fruit waste polyphenol extracts have also been studied to protect the skin from ultraviolet rays and anti-aging [132].

Other applications

In addition to above applications, fruit waste polyphenols introduce developmental potential in many other fields. Studies have indicated that they have great application prospects in the encapsulation and delivery of active molecules, regulation of intestinal bacterial, and allergen desensitization [133–135]. Also. polyphenols can be used as packaging materials for food manufacturing to improve food stability, texture, and flavor [136]. Xiong et al. found that berry pomace polyphenols, in the form of protein polyphenol aggregate particles, were considerably stable during gastrointestinal digestion, maintaining high antioxidant and anti-inflammatory activity, and regulating intestinal bacterial [137]. Also, it has confirmed that polyphenolic compounds extracted from chestnut and olive processing wastewater were beneficial for improving serum immunity and antioxidant defense ability [138].

Conclusions

The comprehensive utilization of fruit waste has become an increasingly important issue in food industry. This article reviewed the different technologies for the extraction of polyphenols from fruit waste and briefly discussed their application potential. These recovered fruit waste polyphenols are expected to be used in industries such as medicine, health products, food, and cosmetics, providing a material foundation for human health. When selecting the extraction technology, it is critical to consider the nature and required amount of the extraction substance, the characteristics of the bioactive compounds, as well as the recovery rate. It is vital that novel and environmentally friendly extraction technologies are necessary and urgent. The comprehensive utilization of byproducts from food industry is beneficial to the reduction of food costs, the alleviation of environmental contamination, and the realization of food industry sustainability.

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Declarations

Conflict of interest All authors declare that they have no conflict of interest.

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