Research Progress on the Efficient Utilization of Citrus Fruit Pomace

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Abstract The citrus processing industry in China generates a large amount of pomace by-products every year, and its resource utilization has become a research hotspot in the fields of food science, agricultural product processing, and agroecology. Citrus pomace is rich in various high-value bioactive components such as pectin, polyphenols and flavonoids, carotenoids, and limonoids, and has functional properties including antioxidant, anti-inflammatory, and antibacterial activities. At present, the utilization of citrus pomace has formed three main pathways: direct crude utilization, extraction and utilization of active components, and microbial conversion utilization. Breakthroughs have also been made in emerging fields such as novel materials, asphalt modifiers, and active packaging films. However, core problems remain, including low comprehensive utilization efficiency, difficulties in industrializing processing techniques, poor stability of active components, low added value of products, and challenges in the collection, storage, and transportation of raw materials. Future research should focus on full-component cascade utilization, green and efficient processing technologies, stabilization techniques for active components, and the development of high value-added products, so as to promote the efficient transformation of citrus pomace from "waste" to "renewable resources" and support the green and sustainable development of the citrus industry.

Key words Citrus pomace; Pectin; Flavonoid; Resource utilization; Active component extraction; High value-added development

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Citrus is a general term for evergreen fruit trees of the genus *Citrus* in Rutaceae, covering varieties such as orange, tangerine, pomelo, lemon, and mandarin. It is one of the most widely cultivated and economically valuable fruit categories in the world[1]. China is the world's largest producer of citrus, and citrus is a pillar industry for agricultural development and increasing farmers' income in the main southern production regions[1]. In 2019, the national planting area of citrus reached 2.62 million hm^2, with a total output of 45.85 million t. While the industry continues to expand in scale, the citrus processing sector concurrently generates substantial amounts of fruit pomace. The resource utilization of this processing by-product has become a critical issue that urgently needs to be addressed for industrial development. Citrus pomace is the main by-product of citrus processing, accounting for 30% – 50% of the fresh fruit processing volume[2]. The pomace is rich in various high-value bioactive components, including flavonoids, pectin, dietary fiber, and essential oils[2]. Among these, the contents of total flavonoids and total polyphenols are significantly higher than those in citrus juice[3], endowing citrus pomace with multiple functions such as antioxidant, anti-inflammatory, and antibacterial activities. As a source of natural active ingredients, citrus pomace holds great potential for resource utilization in fields such as food processing and pharmaceutical development[2]. Relying on favorable climatic conditions, China's citrus industry has continued to maintain a vigorous development momentum. As a result, the annual output of citrus pomace has exceeded 13 million t[4]. Globally, the annual output of citrus by-products is approximately 15 million t, urgently calling for research on efficient treatment and resource utilization[6].

Fresh citrus pomace is mainly composed of peel, seeds, core, and residual pulp. If discarded directly, it is prone to mold and rot, causing water and soil pollution. If only simply dried and used as livestock feed, the potential value of its high-value components cannot be effectively exploited. For rotten citrus fruits caused by fungal infections such as green mold and sour rot after harvest, the traditional treatment method is sanitary landfill. This approach not only wastes biological resources, but also easily leads to secondary pollution[6]. With the advancement of the "dual carbon" strategy and the widespread adoption of green agriculture concepts, citrus pomace is no longer regarded as "waste", but has been redefined as an abundant renewable resource with excellent compositional properties. Its comprehensive utilization has become a research hotspot in the fields of food science, agricultural product processing, and agroecology[1].

This study focuses on the compositional characteristics, current utilization status, existing problems, and development directions of citrus pomace. The overall research framework is shown in Fig. 1.

Main Components and Functional Characteristics of Citrus Pomace

Citrus pomace is rich in various high-value active components

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such as pectin, flavonoids, and essential oils, and also contains macro- and micro-elements including potassium, calcium, and phosphorus, giving it a rich nutritional composition. Among them, pectin, as a natural plant polysaccharide, can regulate the intestinal microbiota of livestock and poultry and ameliorate inflammation through specific signaling pathways[7]. Flavonoids, with their phenolic hydroxyl structures, exhibit significant antioxidant activity, and can scavenge free radicals, regulate lipid metabolism, and help alleviate metabolic syndrome[7]. Essential oils, whose main active components are terpenes and limonoids, show inhibitory effects against various bacteria and fungi, helping to reduce the use of antibiotics[8]. The synergistic effects of these active components endow citrus pomace with multiple functions, including antioxidant, anti-inflammatory, and antibacterial activities.

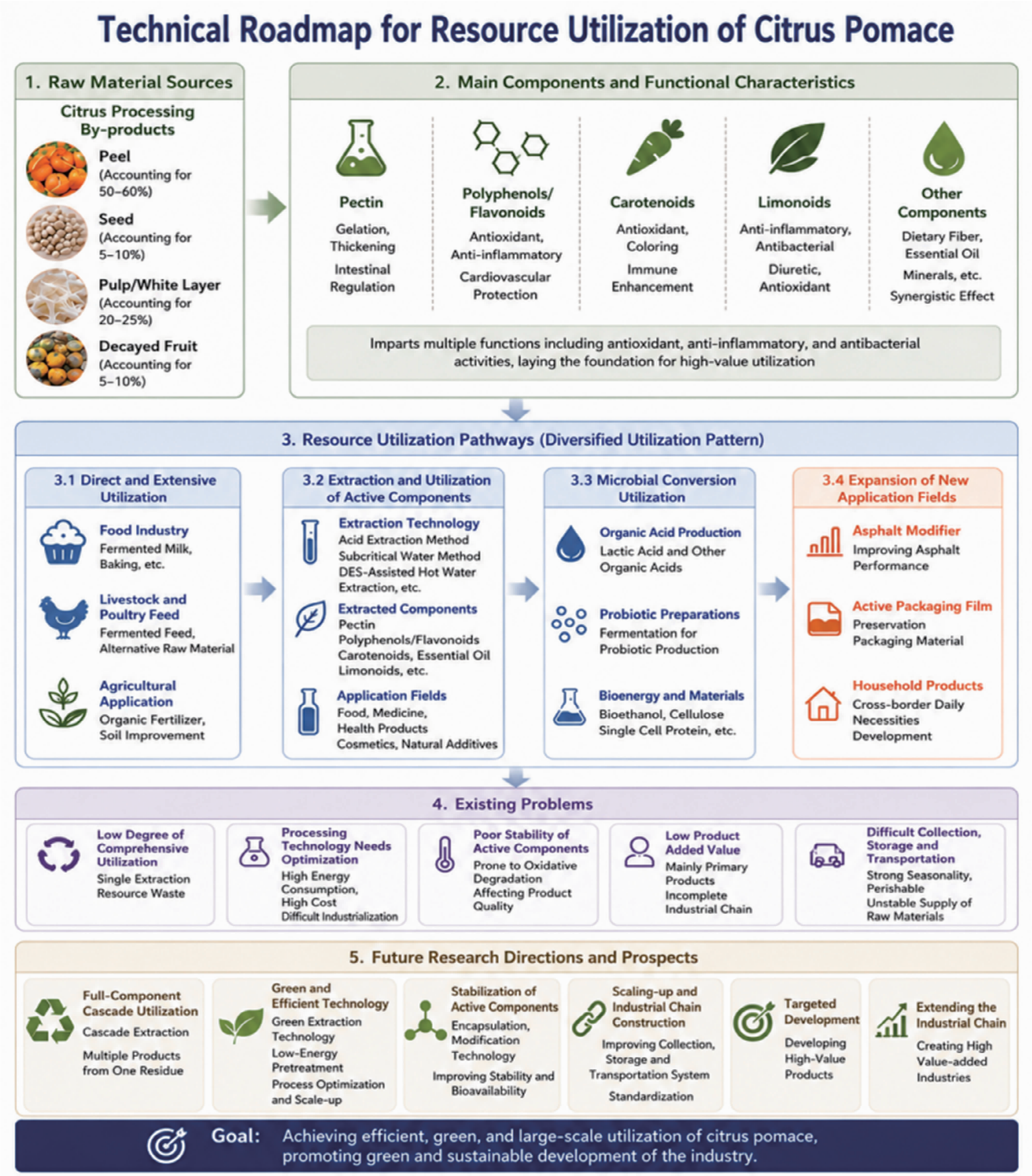

Fig. 1 Overall framework for the resource utilization of citrus pomace

Core active components and their functions

Pectin Citrus pectin is a natural anionic polysaccharide with great development value among citrus processing by-products. It is mainly extracted from citrus peels, commonly with a degree of esterification of 67.20% -69.57%, and is predominantly high-methoxyl pectin[9]. At the molecular structural level, pectin has homogalacturonan (HG) and rhamnogalacturonan I (RG-I) as its core structural domains. Its monosaccharide composition is mainly galacturonic acid, and also includes neutral sugars such as rhamnose and arabinose. In addition, the structural domain contents and branching degrees of pectin vary among different citrus varieties[9].

Pectin possesses excellent functional properties, with its core functionality being its gelling ability. It can form a stable three-dimensional network structure in an acid/sugar system, while also exhibiting good thickening and dispersion stabilization effects[10]. Moreover, when complexed with peptides, pectin can be used to prepare stable emulsions for encapsulating active components such as β-carotene, allowing them to pass through the gastrointestinal barrier and be released gradually, thereby improving the bioavailability of the active substances. The diverse functions of pectin give it broad application prospects in fields such as food and medicine[11].

Table 1 Summary of main active components in citrus pomace and their functions

Active component	Main existing part	Core functional properties
Pectin	In the cell walls of citrus peel and pomace	Thickening, gelling, stabilizing, emulsifying; application in food, medicine, packaging and other fields
Polyphenols and flavonoids	In citrus peel, fibers, and pomace	Antioxidant, anti-inflammatory, antibacterial, lipid metabolism regulation, and cardiovascular protection effects,
Carotenoids	In citrus peel, pulp, and pomace	Antioxidant, immunomodulatory, vision protection, and natural coloring effects
Limonoids	In citrus seeds, peel, and pomace	Anti-inflammatory, antibacterial, antioxidant, metabolic regulation and effects
Dietary fiber	In all parts of citrus pomace	Intestinal health-improving, blood glucose-regulating, and cholesterol-lowering effects

Polyphenols and flavonoids Citrus polyphenols and flavonoids are core active components abundant in citrus fruits, with accumulation levels significantly higher in the peel than in the pulp. They represent an important value carrier for the resource utilization of citrus processing by-products[12]. Among them, the main components of polyphenols are phenolic acids such as caffeic acid, chlorogenic acid, and gallic acid[13], while the dominant flavonoids are hesperidin, naringin, and rutin. The specific contents of these two classes of substances are influenced by different citrus varieties, growing regions, and harvesting time. For example, the hesperidin content in the peels of citrus fruits from Hunan can reach 2.5% -7.2% of the dry weight[12], and the total polyphenol and flavonoid contents in the peel of Tarocco blood orange are significantly higher than those in other varieties[14].

These components have diverse and well-defined functional properties. In terms of antioxidant activity, polyphenols exhibit potent effects through mechanisms such as scavenging free radicals and chelating metal ions, and their content shows a highly significant positive correlation with in vitro antioxidant indicators such as DPPH· and FRAP[14]. In terms of anti-inflammatory and anti-proliferative activities, flavonoids exert their physiological effects by inhibiting the expression of inflammatory cytokines and arresting the cell cycle of cancer cells[15]. In addition, the synergistic effect of these two types of components can regulate blood lipid metabolism and protect cardiovascular health[16], and they show inhibitory effects against pathogenic fungi such as *Penicillium* species[17]. They also have important application value in fields such as food preservation, the development of natural antioxidants, and pharmaceutical research[12-13].

Carotenoids Carotenoids are a class of natural pigments composed of isoprene units containing conjugated double bonds, widely present in plant tissues such as citrus peels. Based on whether the molecule contains oxygen, they can be classified into carotenes and xanthophylls. The main components in citrus peels include lutein, zeaxanthin, β-carotene, and lycopene[18].

Carotenoids have multiple important functions. First, they have strong antioxidant activity. They can effectively scavenge DPPH and ABTS free radicals, inhibit erythrocyte autohemolysis, and suppress lipid peroxidation in liver tissue and mitochondria, thereby protecting biological membranes[18]. Second, they act as natural colorants. When added to the feed for laying ducks, they can significantly increase the a* value, b* value, and Roche color scale of the egg yolk, and can accumulate in tissues such as the liver and egg yolk[18]. Third, they regulate metabolism. They can increase the activities of superoxide dismutase and catalase in the liver of laying ducks while reducing the malondialdehyde content[18]. In addition, some components, such as β-carotene, can be converted into vitamin A and have potential health benefits, including enhancing immunity and preventing cardiovascular diseases[19]. They thus have broad application prospects in the fields of food additives and feed health products.

Limonoids Limonoids are a class of triterpenoid plant secondary metabolites. They are mainly present in the fruits, seeds, endocarp, and segment membranes of *Citrus* species, and are abundant in citrus processing wastes[20]. Limonoids exhibit multiple significant biological activities. First, they have anti-inflammatory, analgesic, antiviral, and antibacterial effects[20]. Second, they can regulate cholesterol levels in the body and prevent atherosclerosis[20]. Third, they possess anti-tumor activity and show inhibitory effects on cancers such as oral cancer[21]. In addition, limonoids can improve sleep quality and exert a diuretic effect, and some components have DPPH free radical-scavenging antioxidant capacity[20].

As natural active substances, they have great development prospects in the fields of functional food ingredients and pharmaceutical raw materials.

In summary, citrus pomace has a rich nutritional composition. It has notable contents of active substances such as pectin, polyphenols, flavonoids, carotenoids, and limonoids. It possesses multiple biological activities, including antioxidant, anti-inflammatory, and antibacterial effects, thus providing a good material basis for subsequent resource development. In recent years, research on the comprehensive utilization of citrus pomace has gradually deepened. Based on differences in processing depth and product added value, various utilization models have been developed, including direct crude utilization, active component extraction, microbial conversion, and novel application expansion. This chapter will elaborate on relevant research progress.

Current Research Status of Citrus Pomace Utilization

At present, the utilization of citrus pomace has formed a diversified pattern of "basic utilization + high-value development". According to the processing depth and product added value, it can be divided into three major categories: direct crude utilization, active component extraction and utilization, and microbial conversion and utilization. These pathways complement each other and cover multiple fields, including food, feed, agriculture, medicine, and chemical engineering[22].

Direct crude utilization

Direct utilization is the most basic application model for citrus pomace. Its processes are simple and cost-effective, making it suitable for large-scale promotion. It mainly focuses on three scenarios: food ingredients, livestock and poultry feed, and agricultural production.

In the food industry, Duan *et al.* used citrus pomace as a raw material and added erythritol for fermentation to develop a low-sugar functional yogurt[23]. The product had a rich texture with a citrus aroma and met the standards of GB 19302-2010. During 21 d of storage at 4 ℃, the yogurt showed better water-holding capacity, hardness, and antioxidant activity than ordinary yogurt, achieving high-value utilization of citrus by-products[23]. In addition, after green modification, citrus pomace can be used in foods such as biscuits, improving product quality, functionality, and taste[24]. When citrus by-products are added to emulsified sausages, they can increase the dietary fiber content of the product, improve its water- and oil-holding capacity, reduce the residual nitrite content, and extend the shelf life[25].

In feed production, fresh citrus pomace has poor palatability due to its high water content and the presence of anti-nutritional factors, making it difficult to use directly. Liu *et al.* [26] used solid-state fermentation with *Bacillus amyloliquefaciens* to treat citrus pomace. After fermentation, the pectin and fiber contents of the pomace were reduced, the crude protein proportion increased, and the bitterness was eliminated. When added to broiler chicken feed at a level of 5% – 10%, it improved nutrient digestibility and enhanced the antioxidant capacity and immunity of the broilers. Yao *et al.* [27] showed that fermented citrus peel residue has improved nutritional value. In addition to broiler chickens, when added to the feed of fattening cattle and pigs at an appropriate ratio, it can provide energy, reduce breeding risks, or improve digestibility, making it a high-quality feed supplement. The combined use of apple pomace and citrus pomace can further enhance the nutritional value of the feed and reduce breeding costs[28]. Citrus pomace by-products also show good application effects in herbivore production and can replace part of conventional feed ingredients[29]. Citrus pomace has rich nutritional value, and systematic progress has been made in research on its application in livestock and poultry diets, providing support for its large-scale promotion.

In agricultural applications, citrus pomace can be used as a raw material for organic fertilizer. After composting and fermentation, it is transformed into an organic fertilizer rich in humus. When applied to farmland and orchards, it has the effects of improving soil structure, increasing soil fertility, enhancing water and nutrient retention, and promoting crop growth. In addition, citrus peel can be used to prepare adsorbent materials for application in wastewater treatment, achieving multiple utilization of resources[30].

Active component extraction and utilization

The extraction of active components is the core pathway for the high-value utilization of citrus pomace. By using physical, chemical, or biological methods to separate and purify components such as pectin, polyphenols, flavonoids, seed oil, and carotenoids, the economic value of the pomace can be increased several tens of times. This is a key area of current research.

Extraction and application of pectin Pectin extraction uses agricultural and forestry by-products such as citrus peel and pomace as raw materials. Mainstream processes and new green technologies have developed synergistically, forming a diversified extraction system. The mainstream technology in traditional industry is acid extraction[30]. Recent studies have shown that under the conditions of 72 ℃, pH 1.75, and an extraction time of 4.5 h, the average yield of citrus pectin can reach 25.70%, with an esterification degree of 71.97% and a gel strength of 253.00 g/cm^2[31]. As a green extraction technology, subcritical water extraction uses only water as the medium to efficiently dissolve pectin under subcritical conditions. The optimal extraction yield of pectin from apple pomace reached 17.55%, and the extraction yield of pectin from citrus peel ranged from 19.21% to 21.95%. This method has the advantages of no reagent addition, environmental friendliness, and high extraction efficiency[32]. Deep eutectic solvent (DES)-assisted hot water extraction is a new green process. Using choline chloride-lactic acid and choline chloride-glycerol systems to pretreat the raw material can significantly improve the extraction yield. Among these, the pectin extraction yield using choline chloride-lactic acid assistance reached 16.31%, and that using choline chloride-glycerol assistance reached 11.34%, both much higher than the traditional hot water extraction method. This process also reduces the protein and total phenolic contents in the pectin, thereby improving product purity[33]. A variety of extraction technologies are adapted to different production needs, driving pectin extraction toward high efficiency, green chemistry, and high purity.

Extraction and application of flavonoids Flavonoids are important bioactive substances in citrus peels, and their efficient extraction is key to the high-value utilization of citrus processing by-products. At present, ethanol heating reflux extraction is a commonly used process for flavonoid extraction. This method is simple to operate and uses mild conditions. After optimization using the information entropy weighting method and response surface methodology, the optimal extraction conditions were a temperature of 70 ℃, an extraction time of 1.5 h, a liquid-to-solid ratio of 35 : 1, and an ethanol concentration of 70%. Under these conditions, multiple components such as hesperidin, nobiletin, and tangeretin could be efficiently extracted simultaneously, with a total flavonoid yield of (13.94 ± 0.12) mg/g[34].

To further improve extraction efficiency, ionic liquid-ultrasound-assisted extraction has been applied as a green new technology for flavonoid separation. This method uses ionic liquids such as tributylhexylphosphonium bromide as solvents, and utilizes the cavitation effect of ultrasound to disrupt cell walls. Under the conditions of an ionic liquid concentration of 54%, a solid-to-liquid ratio of 1 : 10, a temperature of 50 ℃, and an extraction time of 10 min, the flavonoid extraction yield reached 69.13 mg/g, significantly higher than that of traditional organic solvent methods. Moreover, efficient recovery of flavonoids can be achieved by back-extraction with n-butanol, with a recovery rate of 80.11%[35].

In recent years, natural deep eutectic solvents (NaDES) combined with microwave-assisted extraction technology have attracted considerable attention. Using NaDES systems such as choline chloride-urea and betaine-urea to extract polyphenols from citrus waste residues, the extracts exhibit excellent antioxidant activity and cell regeneration-promoting functions[36-37].

The two technologies are respectively suited to the needs of laboratory research and large-scale production, providing reliable technical support for the efficient extraction of flavonoids from citrus peels.

Extraction and application of carotenoids Extraction methods for carotenoids include organic solvent extraction, enzyme-catalyzed reaction, microwave-assisted extraction, ultrasound-assisted extraction, and supercritical fluid extraction[18]. Ultrasound-assisted extraction is one of the more efficient methods. The optimal conditions are petroleum ether-acetone (2 : 1) as the extraction solvent and freeze-dried peel as the sample material. Parameters such as ultrasonic power, ultrasonic time, solid-to-liquid ratio, extraction frequency, extraction temperature, and particle size significantly affect the extraction yield. Under optimized conditions, the carotenoid extraction yield can reach a relatively high level[18]. Recovery of carotenoids from citrus processing wastewater can be achieved using a mixed solvent of d-limonene/ethanol/acetic acid, with a yield of 1.97 mg/g dry solid, and efficient recovery can be realized through a continuous adsorption/desorption system[38]. The extracted carotenoids can be used as natural colorants and antioxidants in fields such as food, feed, and cosmetics.

For a more intuitive comparison of the technical characteristics of the different extraction processes described above, the core principles, applicable components, advantages, and disadvantages of various processes are summarized in Table 2.

Table 2 Comparison of different extraction processes for active components from citrus pomace

Extraction process	Core principle	Core advantages	Main disadvantages
Acid extraction method	Dilute acid hydrolyzes the cell wall, promoting the conversion of protopectin to soluble pectin.	Mature process, low cost, easy to scale up	Large reagent consumption, prone to component degradation, relatively poor environmental friendliness
Subcritical water extraction method	Subcritical water serves as the medium to efficiently dissolve pectin.	No organic reagents, environmental friendliness, high extraction efficiency	High equipment requirements, high energy consumption
Deep eutectic solvent (DES)-assisted hot water extraction method	Deep eutectic solvent (DES) pretreats the raw material, assisting hot water in efficiently dissolving pectin.	Green and low toxicity, high extraction efficiency, high product purity	High solvent cost, difficult subsequent separation
Ethanol heating reflux method	Ethanol is used as the solvent, and heating under reflux promotes the release of flavonoids.	Simple operation, mild conditions, low equipment requirements	Long extraction time, large solvent consumption, high volatility
Ionic liquid-ultrasound-assisted extraction method	Ionic liquid serves as the solvent, combined with ultrasonic cavitation to disrupt the cell wall and enhance mass transfer.	High extraction efficiency, short extraction time, recoverable solvent	High cost of ionic liquids, difficulty in large-scale application
Ultrasound-assisted extraction method	Ultrasonic cavitation disrupts the cell wall, promoting the release of carotenoids.	High extraction efficiency, short extraction time, minimal damage to components	High equipment energy consumption, needs for improvement of stability in large-scale production

As can be seen from Table 2, the extraction processes for different active components from citrus pomace each have their own characteristics. In practical applications, the appropriate method should be selected according to the target component and production conditions. The extraction of active components is an important means for the high-value utilization of pomace. On this basis, microbial conversion further promotes the resource utilization of citrus pomace to a deeper level.

Microbial conversion and utilization

Microbial conversion and utilization represent an important innovative direction for the deep development of citrus pomace. Through microbial metabolism, the macromolecular substances in pomace are broken down into small-molecule nutrients, or high value-added products are synthesized, thereby achieving the resource utilization of agricultural and forestry wastes. This mainly covers fields such as organic acid production, probiotic preparation, bioenergy and biomaterial synthesis, and others.

Citrus pomace can be utilized as a resource through lactic acid bacteria fermentation. Low-sugar fermented milk prepared using citrus pomace as a raw material exhibited good water-holding capacity, texture properties, and antioxidant activity during storage, and the physicochemical and microbiological indicators of the product all met national standards. The development and storage quality study of low-sugar citrus pomace fermented milk provides technical support for the development and application of citrus pomace in functional fermented foods.

Citrus pomace is rich in cellulose and hemicellulose and can be utilized at high value through various bioconversion pathways. In the field of bioenergy, the use of citrus peels through anaerobic fermentation enables the co-production of hydrolytic enzymes (cellulase activity up to 4481 U/mg) and fermentable sugars, with a bioethanol productivity of 363 g/(L · h), providing a new solution for low-cost biofuel production[39]. In the field of biomaterials, after recovering sugars from citrus processing wastewater, bacterial cellulose can be produced by fermentation using *Komagataeibacter sucrofermentans*, with a yield of 4.98 g/L. Further acid hydrolysis of the bacterial cellulose can produce bacterial cellulose nanocrystals with a crystallinity of 85.2%[38]. Due to its excellent biocompatibility and mechanical properties, this material is widely used in high value-added fields such as medical dressings and food packaging. In addition, citrus pomace can also be used for the fermentation production of single-cell protein, replacing part of fishmeal and soybean meal, thereby effectively alleviating the shortage of protein raw materials for feed.

Expansion into novel application fields

In the biomedical field, extracts from citrus waste residues can be used for the green synthesis of bionanomaterials. A recent study used pectin extracted from citrus peel residue to construct a three-dimensional network hydrogel. This hydrogel was loaded with silver nanoparticles prepared by reducing active components extracted from Ponciri Trifoliatus Fructus. The resulting nanocomposite exhibited a 99.8% killing rate against drug-resistant methicillin-resistant *Staphylococcus aureus* (MRSA). In a diabetic mouse wound infection model, the wound healing rate reached 92% after 11 d of treatment, which is 2.7 times higher than that of traditional dressings[40]. Extracts from citrus waste residues can also be prepared using the green NaDES extraction technology, and have shown antioxidant, wound healing-promoting, and DNA damage protective effects in keratinocyte cell models, indicating their application prospects in the cosmetics field[36,41].

In the field of biodegradable packaging materials, citrus by-products can be used to develop edible packaging films and biological activated carbon[42]. Bacterial cellulose nanocrystals prepared from citrus processing wastewater through biorefining provide a new source of high-performance biomaterials[38].

In the fields of building materials and daily necessities, citrus peel extracts can be used in recycled asphalt and asphalt mixtures to improve asphalt performance[43]. Home product designs based on citrus peel materials have achieved cross-boundary applications of pomace in the daily necessities sector[44]. Active packaging films developed from citrus peel powder have good preservation effects and can be applied in the field of food packaging[45].

Core Problems in the Utilization of Citrus Pomace

Although significant progress has been made in the utilization technologies of citrus pomace, many bottlenecks still remain in moving from laboratory research to industrial application, restricting its efficient and large-scale development. These are mainly reflected in the following five aspects.

Low comprehensive utilization efficiency and prominent resource waste

At present, the utilization of pomace mostly adopts a "single-component extraction" model, such as extracting only pectin or polyphenols. The residual pomace after extraction, though still rich in dietary fiber, phytosterols, and other components, is mostly discarded, failing to achieve a "multiple products from one pomace" cascade utilization of all components. Meanwhile, the components of peel, seed, and core have significant differences, but existing processes mostly use mixed processing, failing to achieve targeted development, further exacerbating resource waste[4]. A specialized utilization system for rotten citrus fruits has not yet been established, and a large number of rotten fruits are still treated by traditional landfilling[6].

Improvements needed in processing techniques and challenges in industrialization

Current extraction processes for active components from citrus pomace still have many shortcomings. Traditional solvent extraction methods suffer from high solvent consumption and low extraction yields. Although new techniques such as ultrasound-assisted and microwave-assisted extraction have higher extraction efficiency, their production capacity is limited, making large-scale industrial production difficult. Supercritical CO_2 extraction yields products with high purity and good quality, but the equipment investment and operating costs are high, limiting its popularization and application in industrial production. Although green extraction technologies such as subcritical water extraction have shown potential, they still need improvement in terms of process optimization and equipment scaling up[32]. In addition, the high energy consumption and poor treatment effects of pretreatment processes such as debittering and drying of pomace increase the difficulty of industrial utilization of pomace. Comparative studies of different extraction processes are not systematic enough, and there is a lack of standards for selecting the optimal process for different types of pomace.

Poor stability of active components, affecting product quality

Active components in citrus pomace, such as polyphenols, flavonoids, and carotenoids, are sensitive to environmental factors including light, heat, oxygen, and pH. They are prone to oxidative degradation during extraction, processing, and storage, leading to loss of activity and affecting product quality and functionality. Studies on the stability of citrus peel polyphenols in an ultrasonic field have shown that their stability is influenced by multiple factors, and targeted stabilization technologies are urgently needed. Currently, research on stabilization technologies for these components is insufficient, and there is a lack of low-cost, high-efficiency encapsulation and modification methods, which restricts the development and promotion of high value-added functional products.

Low product added value and imperfect industrial chain

At present, the products developed from pomace are still mainly primary products, such as ordinary pomace powder, crude pectin extracts, and pomace feed. There are few deeply processed, high value-added end products, and the technological content and market competitiveness are insufficient[4]. The industrial transformation of new application fields is insufficient. Products such as active packaging films and asphalt modifiers have not yet achieved large-scale production. Meanwhile, the collection, pretreatment, processing, and sales of citrus pomace are not closely linked, and there is a lack of specialized processing enterprises and a well-established market system, so a closed-loop industrial chain has not yet been formed.

Difficulties in collection, storage, and transportation of pomace, and unstable raw material supply

Citrus processing is highly seasonal. Fresh pomace has a high water content and is prone to rot and spoilage. If not treated in time, it will lose its utilization value. Citrus processing enterprises in China are relatively scattered in distribution, and there is a lack of a unified and efficient system for the collection, storage, and transportation of citrus pomace. The high cost of pomace collection and the great difficulty of storage and transportation lead to an unstable supply of pomace to processing enterprises, making continuous, large-scale production difficult to achieve[1]. In addition, the component contents of pomace vary greatly among different varieties and origins, and a unified raw material quality standard has not yet been established, affecting the stability of product quality. The collection, preservation, and transportation technologies for rotten fruit are immature, restricting the efficiency of their resource utilization. It is noteworthy that fungal infection of citrus fruits during planting, harvesting, transportation, and storage leads to a large number of rotten fruits, and there is currently a lack of a whole-industrial-chain mold prevention and control strategy and a specialized utilization system[5].

Future Research Directions and Prospects for Citrus Pomace Utilization

In light of the current industrial pain points and technological development trends, the future utilization of citrus pomace should focus on the four core principles of "full-component utilization, green processing, high added value, and large-scale application". Through technological innovation, system improvement, and industrial integration, the comprehensive utilization of citrus pomace should be promoted to a new level.

Development of full-component cascade utilization technologies to improve resource efficiency

The core direction is to establish a "multiple products from one pomace" processing model, so as to achieve targeted development and cascade extraction based on the compositional characteristics of different parts of the pomace[4]. For example, pectin can first be extracted from the peel, followed by the extraction of polyphenols and flavonoids from the extraction residue. Oils and proteins can be extracted separately from the seeds, and finally, all remaining residues can be modified to produce dietary fiber or used for microbial fermentation. This approach truly achieves "complete utilization", maximizing resource efficiency and minimizing waste discharge. A specialized technical system for the utilization of rotten citrus fruits should be established to enable the efficient extraction of components such as synephrine and naringin from rotten fruit. Dietary fiber is the main component of the residue after the extraction of pectin and flavonoids from pomace. Studies have shown that using a high-speed homogenization combined with a multi-enzyme hydrolysis technology to modify the dietary fiber of Ponkan peel can increase the content of soluble dietary fiber by 3.37 times. The modified fiber has a honeycomb-like porous structure, and its water-holding capacity, oil-holding capacity, glucose adsorption capacity, and α-glucosidase inhibitory activity are significantly enhanced. In a diabetic mouse model, it can reduce fasting blood glucose, triglyceride, and total cholesterol levels, and regulate the gut microbiota[46]. This strategy provides a new pathway for the high-value conversion of residues in the full-component utilization of pomace.

Meanwhile, some studies have proposed a circular economy strategy of "taken from citrus, used for citrus", that is, using extracts from citrus by-products to develop preservation products, which in turn support the anti-corrosion and preservation efforts of the citrus industry chain, thus forming a closed loop[5].

Innovation in green and efficient processing technologies to reduce industrialization costs

The focus should be on developing green technologies such as ultrasound-microwave synergistic extraction, enzyme-assisted extraction, and deep eutectic solvent extraction to replace traditional organic solvents, thereby reducing environmental pollution and production costs. The pretreatment processes for pomace, such as debittering and drying, should be improved. Low-energy-consumption, high-efficiency drying technologies and efficient, safe debittering technologies should be developed to reduce processing costs. Meanwhile, the domestic production and scaling-up of extraction equipment should be promoted to enable the large-scale industrial application of new technologies and processes, thereby addressing the difficulty of industrialization. Comparative studies of different extraction processes should be strengthened, and process selection standards based on pomace type should be established.

Strengthening research on stabilization technologies for active components and developing high value-added products

The degradation mechanisms of components such as polyphenols, flavonoids, and carotenoids should be thoroughly analyzed. Low-cost stabilization technologies, including microencapsulation, liposome encapsulation, and molecular modification, should be developed to improve the stability and bioavailability of active components during processing and storage. Using stabilized high-purity active components as raw materials, diversified, high value-added end products should be developed, such as high-end functional health foods, natural food additives, pharmaceutical intermediates, and cosmetic ingredients. This will increase the technological content and market competitiveness of products and extend the industrial chain of citrus pomace utilization[47]. The application of pomace in new materials, daily necessities, and other fields should be expanded, and more high value-added cross-boundary products should be developed.

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synergistic linkage of teaching, research, and industry, a systematic innovation ability cultivation system can be constructed to enhance students' comprehensive competencies. This approach provides theoretical ideas and implementation frameworks for cultivating innovative pharmaceutical talents who meet the needs of the highquality development of the pharmaceutical industry, thereby contributing to the Healthy China strategy and the highquality development of the pharmaceutical field.

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