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High-Value Utilization and Future Development of Grape Pomace

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Abstract. As a major country in grape production and processing, China generated 600,000 to 800,000 tons of pomace from the wine industry alone in 2025. Long-term disposal of such pomace through landfilling and other methods leads to resource waste and imposes substantial pressure on environmental governance in producing areas. This paper collects and summarizes the activity characteristics of three core functional components in grape pomace, namely polyphenols, anthocyanins and resveratrol. It compares and analyzes the technical features and industrial adaptability of eight extraction processes including traditional maceration, ultrasound-assisted extraction and enzymatic extraction, as well as the current commercialization status and existing industrial bottlenecks of high-value products in functional food, natural pigment and other fields. This work can provide feasible technical routes and references for future development for domestic grape processing industrial parks to carry out high-value utilization of by-products.

Keywords: grape pomace, bioactive components, high-value utilization, extraction technology

1. Introduction

With the rapid development of China's grape planting industry and wine processing sector, grape output and processing volume have risen year by year, accompanied by massive generation of by-products such as grape pomace [1]. Grape pomace is the major industrial residue produced after wine brewing, juice pressing and jam making. Its output is considerable. Direct discarding or landfilling of grape pomace not only wastes resources, but also causes environmental pollution, promotes the growth of harmful microorganisms and creates heavy pressure on the ecological environment, which may harm local residents' health [2]. Therefore, realizing the high-value utilization of grape pomace can serve as an important direction for the comprehensive utilization of food processing by-products.

Grape pomace is rich in multiple bioactive components including grape polyphenols, anthocyanins, resveratrol, dietary fiber, pectin and protein [3]. These substances exhibit favourable properties such as antioxidant and antibacterial activities [4] and anti-ageing effects [5], and possess great potential and value for development. At present, researchers at home and abroad have verified that extracts obtained from grape pomace can be widely applied in food preservation, functional food development, natural pigment preparation, feed modification, cosmetic raw material processing

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and other industries. Examples include dietary fiber (insoluble and soluble fractions), anthocyanins (malvidin-3-glucoside) and so on [6]. Nevertheless, domestic grape processing enterprises still maintain a low utilization rate of by-products other than grape pulp. Existing problems include crude extraction processes, severe loss of activity of extracted components, and insufficient exploitation of abundant high-quality resources.

Efficient separation and extraction of natural bioactive components form the fundamental supporting process for the development of functional raw materials. Current extraction methods have evolved from traditional maceration to novel green processes such as ultrasound-assisted extraction, supercritical fluid extraction and enzymatic extraction. Supporting techniques including filtration, chromatography and membrane separation can effectively improve the extraction yield and biological activity of target products, enabling efficient separation and purification of active ingredients from various plants and agricultural by-products. These active ingredients have already been adopted in fields such as food fortification, skin care products and dietary supplements, yet they have not been widely implemented in grape industrial parks. Hence, the high-value utilization of grape pomace holds promising practical market value [7]. Further research should be carried out to make extraction processes more intelligent to increase extraction yield and continuously improve the industrial chain development system for grape pomace.

2. Overview of grape pomace resources and its functional components

2.1. Overview of grape pomace resources

According to the latest official statistical data released by the International Organisation of Vine and Wine (OIV) in November 2025, the total global area under grape cultivation reached approximately 7 million hectares in 2025, and global wine production rebounded to 232 million hectolitres. Although this figure represented a 3% year-on-year increase from the historical low recorded in 2024, it remained below the average level of the past five years for the third consecutive year [8]. China, Italy, France, Spain and the United States are the world's five major grape-producing countries, together accounting for more than 60% of global grape output. As a new member that joined the OIV in November 2024, China has continuously strengthened its voice in the global grape industry [9]. China's grape cultivation areas are mainly located in Xinjiang, Shandong, Hebei, Ningxia and other regions. Among them, Xinjiang has long ranked first nationwide in both planting area and yield [10].

Winemaking is the primary destination for processed grapes. A large quantity of solid by-products collectively referred to as grape pomace is generated after pressing and separation during fermentation. Grape pomace mainly consists of skins, seeds and a small amount of stems, accounting for roughly 20%–25% of the weight of fresh grapes [11]. Based on this proportion, the annual global output of grape pomace exceeds 8 million tonnes [12]. In China, the wine industry alone discharges 600,000 to 800,000 tonnes of grape pomace every year [13]. Such a huge volume of by-products, if not utilised properly, will not only waste resources but also create environmental pressure due to microbial proliferation. Therefore, understanding the main chemical constituents in grape pomace lays the foundation for its high-value utilisation.

2.2. Major bioactive functional components

Grape pomace is not a single substance but a complex mixture composed of diverse bioactive compounds. After pressing, certain polyphenolic compounds remain in the grape skins and seeds,

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making pomace a concentrated carrier of functional components including polyphenols, pigments and resveratrol [14].

2.2.1. Polyphenols

Polyphenols are the most abundant and extensively studied secondary metabolites in grape pomace. According to their chemical structures, they can be divided into several subclasses, including phenolic acids, flavonols, flavanols and stilbenes [15]. In terms of biological functions, the properties of grape pomace polyphenols are mainly reflected in antioxidant and antibacterial activities [16]. For antioxidant capacity, proanthocyanidins and gallic acid contain multiple phenolic hydroxyl groups in their molecular structures. They can terminate free radical chain reactions by donating hydrogen atoms and chelate transition metal ions such as iron and copper to suppress oxidative damage mediated by the Fenton reaction [17]. Numerous in vitro experiments have verified that the scavenging capacity of grape pomace polyphenol extracts against DPPH free radicals and ABTS cationic radicals is comparable to that of synthetic antioxidant BHT, and some indicators are even better [18]. As for antibacterial effects, grape pomace polyphenols mainly act by disrupting the integrity of microbial cell membranes, inhibiting biofilm formation and interfering with quorum sensing systems [19]. Studies have shown that catechin and epicatechin exert inhibitory effects of varying degrees on common foodborne pathogens such as *Staphylococcus aureus*, *Escherichia coli* and *Salmonella* [20]. These properties give grape pomace polyphenols potential applications as natural preservatives in food preservation. They can slow down the oxidative rancidity of lipids and proteins and restrict microbial growth and reproduction, thereby extending the shelf life of food products [21].

2.2.2. Anthocyanins

Anthocyanins are another group of characteristic phenolic compounds in grape pomace, which are mainly distributed in the skin tissues of red grapes and serve as natural colourants [22]. The anthocyanins identified in grape pomace are dominated by malvidin-3-glucoside, cyanidin-3-glucoside and peonidin-3-glucoside. Glycoside derivatives of malvidin generally account for more than 40% of total anthocyanin content [23]. Anthocyanins function both as antioxidants and natural pigments. As natural colourants, anthocyanins from grape pomace have the advantages of bright colour, renewability and non-toxicity. They have already replaced synthetic colourants in some beverages, ice cream and confectionery products [24]. Nevertheless, anthocyanins are highly sensitive to pH value, temperature, light and oxygen. In practical applications, copigmentation technology is often required to stabilise the compounds and retain colour performance [25]. As antioxidants, the activity of anthocyanins is closely related to the ortho-dihydroxyl structure on their B-ring. Electron delocalisation enables anthocyanins to effectively scavenge superoxide anions and peroxyl radicals under physiological pH conditions [26]. Animal experiments and human intervention studies further demonstrate that moderate intake of anthocyanin-containing food can significantly raise the total plasma antioxidant capacity and produce positive regulatory effects on vascular endothelial function [27].

2.2.3. Resveratrol

Resveratrol is a stilbene compound with a relatively low content in grape pomace but outstanding functional value. It mainly accumulates in grape skins and is a phytoalexin synthesised by grapes in

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response to external stress [28]. Part of the resveratrol transfers into wine during processing, while the rest remains in pomace. This makes grape pomace an important raw material for resveratrol extraction [29]. Different from polyphenols and anthocyanins, functional research on resveratrol has expanded from in vitro antioxidant tests to the regulation of cellular signalling pathways. The most representative finding is its activating effect on silent information regulator 1 (SIRT1) [30]. SIRT1 is an NAD^+-dependent deacetylase that participates in the regulation of cellular senescence, energy metabolism and stress response. Resveratrol elevates SIRT1 activity through allosteric modulation, which further changes the deacetylation level of downstream substrates such as PGC-1α and FoxO transcription factors, and thus exerts effects on delaying cellular senescence and improving mitochondrial function [31].

2.3. Value and significance

Overall, polyphenols, anthocyanins and resveratrol in grape pomace have distinct functional focuses. Both polyphenols and anthocyanins possess antioxidant activity, but polyphenols stand out for their antibacterial properties, anthocyanins are responsible for colouration, and resveratrol occupies a unique position in anti-ageing and skin-brightening research by virtue of its specific signalling regulation mechanism [32]. Gradient separation of these three components can be achieved during pomace extraction. They can exert synergistic antioxidant effects without complete isolation from one another.

3. High-value extraction technologies for grape pomace

3.1. Conventional extraction

3.1.1. Hot water extraction

Hot water extraction adopts water as the polar solvent. By raising temperature, it breaks the cell wall structure of grape pomace and promotes the diffusion of soluble functional components into the aqueous phase, so as to dissolve and separate target substances. This method features simple operation procedures, low equipment requirements, no addition of extra organic solvents and high safety, which is suitable for basic and large-scale rough processing scenarios. It was widely applied in early-stage extraction of polar components such as polysaccharides and water-soluble anthocyanins from grape pomace [33], and serves as the most common basic extraction process for small domestic grape processing enterprises. Its drawbacks include low extraction efficiency and long processing time. High temperature during extraction tends to degrade heat-sensitive active substances, the obtained extract has low concentration, subsequent purification procedures are complicated, and the overall energy consumption is relatively high [34].

3.1.2. Organic solvent extraction

Organic solvent extraction follows the principle of like dissolves like. Organic solvents with matching polarity such as ethanol and methanol are selected to selectively dissolve lipophilic functional components including polyphenols, flavonoids and anthocyanins in grape pomace, achieving targeted dissolution of target compounds. This process is mature and compatible with general-purpose equipment. The type and concentration of solvent can be flexibly adjusted according to target components, and most active substances show higher solubility in organic solvents than in water extraction. It is the dominant basic method for extracting total phenols from

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grape pomace in laboratories, and has also been adopted for preliminary anthocyanin extraction in many small and medium-sized grape deep-processing enterprises. Its disadvantages lie in long extraction duration. Active substances are prone to oxidative degradation under prolonged solvent contact, and solvent recovery consumes large amounts of energy. Improper handling may lead to residual toxic solvents, which fails to meet the specifications of green food processing [35].

3.2. Green assisted extraction

3.2.1. Ultrasound-assisted extraction

Ultrasound-assisted extraction utilises cavitation effect, mechanical vibration and thermal effect generated by ultrasonic waves to rapidly rupture the cell wall structure of grape pomace, accelerate the diffusion rate of intracellular functional components into the solvent and greatly shorten the mass transfer time. It has the advantages of high extraction efficiency, short duration and controllable extraction temperature, which can maximally preserve the biological activity of heat-sensitive active substances such as polyphenols and anthocyanins. Operational parameters can be adjusted flexibly. At present, it has become the most widely used auxiliary technique in studies on extracting polyphenols and anthocyanins from grape pomace. An optimisation study published in *Antioxidants* in 2025 reported that under the conditions of 35 °C, 22.5 min of ultrasonic treatment and 70% ethanol system, the extraction yield of total anthocyanins from grape pomace reached 105.32 mg C3G/g DW and total polyphenol content reached 465.81 mg GAE/g, significantly higher than that of conventional maceration [36]. Its limitations are poor uniformity of sound field distribution over a large area and high equipment cost for large-scale industrial scaling. Continuous high-intensity ultrasound (>500 W) may damage the structure of some highly unstable delphinidin-type anthocyanins, and controlling process parameters on large production lines is difficult.

3.2.2. Microwave-assisted extraction

Microwave-assisted extraction works through microwave electromagnetic fields, which drive polar molecules inside grape pomace cells to vibrate rapidly at high frequency. Instant internal heating generates high pressure and bursts cell walls, so intracellular active substances are quickly released into the solvent. This method achieves extremely fast extraction with low solvent consumption, uniform heating and better extraction selectivity than conventional processes. Its overall energy consumption is markedly lower than traditional hot maceration. It is currently mostly used for targeted extraction of anthocyanins and proanthocyanidins from grape pomace. A study published in the *International Journal of Food Engineering* in 2020 showed that the total phenolic content and ABTS, DPPH antioxidant activities of extracts obtained by microwave-assisted extraction (1000 W, 10 min) and ultrasound-assisted extraction increased with prolonged treatment time, and microwave treatment at 1000 W for 10 min was identified as the optimal extraction condition [37]. Its drawbacks are local overheating caused by concentrated thermal effect, which easily destroys heat-sensitive functional components. The allowable material throughput is limited, extraction performance is unstable for high-viscosity and large-particle materials, and the technique is poorly adapted to continuous industrial production.

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3.2.3. Enzymatic extraction

Enzymatic extraction uses cellulase and pectinase to specifically degrade cellulose and pectin components in the cell walls of grape pomace. It breaks the dense cell wall barrier and reduces the mass transfer resistance for intracellular active substances to diffuse outward, enabling component release under mild conditions. Its advantages are mild extraction conditions (generally 40–50 °C, pH 4–5) without intense physical or chemical effects throughout the process. The natural structure and functional activity of active substances can be well retained, the extract has high purity, and subsequent purification is less demanding. This technology is widely adopted for high-activity extraction of polysaccharides, anthocyanins and flavonoids from grape pomace. A study on recovering phenolic antioxidants from Syrah grape pomace via enzymatic extraction demonstrated that optimised enzymatic extraction can significantly improve the recovery rate and antioxidant activity of phenolic compounds, making it a mild and efficient extraction strategy [38]. Its disadvantages include high cost of enzyme preparations and strict requirements for reaction condition control. The extraction cycle is relatively long, and the enzymatic reaction is susceptible to interference from material composition and pH fluctuation. The inactivation step for residual enzymes in the final system will bring extra production costs.

3.2.4. Supercritical CO_2 extraction

Supercritical CO_2 extraction adjusts CO_2 to conditions above its critical temperature and critical pressure to form a supercritical fluid. Relying on its excellent permeability and lipophilic dissolving capacity, it selectively dissolves weakly polar substances in grape pomace such as seed oil and volatile essential oil. Rapid separation of solutes from the extractant is achieved through pressure reduction and temperature rise. This method leaves no organic solvent residues throughout the process, and its extraction temperature is close to ambient temperature. It can well preserve heat-sensitive and easily oxidised active components including oils and terpenes. Extracts do not require solvent removal and can meet food-grade safety standards. It is a mainstream high-end process for extracting grape pomace seed oil and natural volatile essential oil from grape skins. Supercritical CO_2 extraction can selectively dissolve weakly polar fractions under near-ambient conditions. It has been adopted to recover seed oil and volatile essential oil from grape pomace, and the obtained products meet food safety requirements without desolventisation, bringing a notable increase in product added value [39]. Its disadvantages include extremely high upfront investment for the high-pressure system and difficult operation and maintenance. It only delivers satisfactory extraction performance for weakly polar substances and can hardly be used alone to extract polar functional components such as polyphenols and polysaccharides. Its maximum processing capacity is limited, making it unsuitable for large-scale industrial production.

3.2.5. High-pressure pulsed electric field extraction

High-pressure pulsed electric field (PEF) extraction applies instantaneous high-voltage pulsed electric fields to grape pomace samples placed between two electrodes at normal temperature and atmospheric pressure. Electroporation generates numerous irreversible micropores on cell membranes, disrupting the structural barrier of cells and accelerating the release of intracellular functional components. This technique produces almost no obvious thermal effect during extraction, so thermal damage to active substances is minimal. It features extremely fast treatment speed and low energy consumption, and can be integrated into continuous production lines. It has gradually

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been applied in studies on mild extraction of polyphenols and anthocyanins from grape pomace in recent years. Research on PEF-assisted extraction shows that when the cell disintegration index is set as the response variable, optimising PEF pretreatment within the field strength range of 0.5–5 kV/cm can significantly raise the extraction yield of bioactive components from red grape pomace [40]. Its drawbacks are the high cost of core equipment components and poor compatibility with high-conductivity materials. Electrodes tend to corrode during treatment, and the stability under long-term operation remains to be verified. This technology is mostly at the pilot scale at present, with few large-scale industrial implementations.

3.2.6. Subcritical water extraction

Subcritical water extraction heats water in a closed system to a temperature between 100 °C and the critical temperature of 374 °C. Pressure is controlled to keep water in the liquid state, which alters water's polarity, viscosity and dissolving properties to realise selective dissolution of grape pomace functional components with different polarities. It uses pure water as the extraction medium with no organic solvent addition. It achieves fast extraction and high mass transfer efficiency, and stepwise extraction of multiple components can be realised by adjusting temperature. It is environmentally friendly with no residual solvent after treatment. A large number of studies have explored its use for extracting polysaccharides, phenolic acids and oligosaccharides from grape pomace. Related research indicates that extraction at 120 °C and 1.3 bar yields the highest soluble fraction recovery (61 g per 100 g pomace), with a phenolic content of 4.1 g GAE per 100 g extract. The extract also exhibits inhibitory activity against *Listeria monocytogenes* [41]. Its disadvantages are the risk of degradation of some heat-sensitive active substances under high-temperature and high-pressure conditions. The equipment must withstand high pressure, leading to higher upfront cost than conventional extractors. Precise control of process parameters is challenging, and the supporting technical system for industrial application is still immature.

3.2.7. Deep eutectic solvent-assisted extraction

Deep eutectic solvent (DES)-assisted extraction adopts novel green solvents synthesised from hydrogen bond donors (e.g. choline, citric acid) and hydrogen bond acceptors (e.g. polyols) at specific molar ratios. Strong hydrogen-bonding interactions bind the solvent with cellulose and lignin in grape pomace cell walls to break the dense cell wall structure. Meanwhile, DES shows strong selective dissolving capacity toward polar active substances such as polyphenols and anthocyanins. DES is completely non-toxic and biodegradable, with extremely low vapour pressure and negligible volatilisation loss. The solvent can be recovered and recycled. Its dissolving capacity for polar active components far exceeds that of conventional ethanol, and oxidative loss during extraction is very low. A study using natural deep eutectic solvents to assist anthocyanin extraction from grape pomace reports that at a batch scale of half a litre, NADES combined with auxiliary technologies such as ultrasound or microwave can efficiently extract anthocyanins from grape pomace, serving as a green alternative to traditional organic solvents [42]. This technology has completed pilot tests for extracting plant bioactive compounds and is a hot research direction for high-value grape pomace utilisation in recent years. Its limitation is the high viscosity of deep eutectic solvents. Separating target products from the solvent after extraction is harder than using ordinary solvents, requiring additional elution and recovery steps. Some solvent formulations are still more costly than food-grade ethanol.

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3.2.8. Supersonic impinging stream extraction

Supersonic impinging stream extraction accelerates the suspension of grape pomace material and extraction solvent separately to supersonic velocity, then lets them collide head-on at high speed inside the reaction chamber. Instantly generated strong shear force, cavitation and turbulence directly disrupt grape pomace cells, completing mass transfer and dissolution of functional components within an extremely short time. The whole extraction process finishes within several seconds with nearly zero mass transfer resistance. It operates at ambient temperature without extra heat input, so active substances barely undergo thermal degradation. The equipment can be directly connected to continuous industrial production lines, with hourly processing capacity reaching the tonne level. Existing studies on ultrasound-assisted extraction have confirmed that cavitation and mechanical vibration can rapidly destroy cell walls, shorten mass transfer time, and regulate the extraction efficiency of polyphenols and anthocyanins flexibly by adjusting power (250–450 W) and treatment duration [43]. Its disadvantages include strict requirements for wear resistance of the reaction chamber and a high threshold for parameter tuning. At present, a dedicated process database for agricultural and forestry by-products such as grape pomace remains incomplete.

4. Development of high-value-added products from grape pomace

China consistently ranks among the world's top producers of wine and fresh grapes. More than 1.2 million tonnes of grape pomace are generated annually as processing by-products [44]. For a long time, most pomace has been disposed of by landfilling or simply processed into feed, with a resource utilisation rate below 30% [45]. In recent years, as technologies for the high-value utilisation of agricultural and forestry wastes have matured, the utilisation of valuable components in grape pomace has formed a complete functional system. Its economic value and environmental benefits have been fully unlocked in products ranging from functional food ingredients and natural pigments to degradable packaging materials.

4.1. Functional food ingredients

Bioactive substances enriched in grape pomace, including polyphenols, anthocyanins and resveratrol, exhibit strong free-radical scavenging capacity [46], making them a major research hotspot in the field of natural antioxidants. Related products have achieved commercial application. One study adopted the response surface methodology to optimise extraction pH and duration, significantly improving the recovery rate and antioxidant capacity of grape pomace polyphenols [47]. Other research used *Aspergillus niger* and *Aspergillus oryzae* for solid-state fermentation of grape pomace, which simultaneously enhanced the antioxidant and prebiotic activities of extracts [48]. These findings provide feasible process references for converting bioactive components from grape pomace into functional food raw materials. In addition, highly purified bioactive components extracted from grape pomace can be added as natural nutritional fortifiers into sports drinks [49] and breakfast cereals [50], upgrading product functions without synthetic additives.

4.2. Natural pigments

Anthocyanins from grape pomace are natural red pigment raw materials permitted for unrestricted use under China's *National Food Safety Standard for the Use of Food Additives*. Compared with synthetic pigments such as carmine, anthocyanins offer colouring capacity together with antioxidant

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properties and are free from the safety risks associated with some synthetic colourants [51]. Researchers have developed economical and environmentally friendly separation processes for anthocyanins from grape pomace, enabling efficient production of natural anthocyanin preparations suitable for food colouration [52]. Furthermore, after optimisation via full-factorial design, grape pomace pigments achieve satisfactory dyeing effects on modified cotton fabrics and other materials, demonstrating cross-field application potential [53].

4.3. Dietary fibre

After polyphenols and other components are removed from grape pomace, insoluble dietary fibre accounts for over 60% of the remaining solid fraction [54], while some bound bioactive compounds are retained. High-quality grape skin dietary fibre products can be obtained by direct grinding and modification. Incorporating grape pomace powder into wheat flour at an appropriate proportion produces functional bread rich in polyphenols and antioxidant activity, realising nutritional upgrading of staple food [56]. Pectin and other dietary fibre fractions from grape pomace can also be converted into oligosaccharides through enzymatic hydrolysis. Studies have confirmed their prebiotic potential to stimulate the growth of beneficial intestinal bacteria [55], making them popular raw materials for functional staple foods such as whole-grain bread and meal replacement powders in recent years.

4.4. Grape seed oil and essential oil

Grape pomace contains a considerable amount of seed oil. Grape seed oil obtained by cold pressing and other processes is dominated by unsaturated fatty acids. Cheng Bijun and colleagues systematically analysed the fatty acid composition of Amur grape seed oil and found that unsaturated fatty acids such as linoleic acid predominate, delivering outstanding nutritional value [57]. For personal care applications, one study evaluated the bioactivity of red grape pomace extracts against skin pathogenic bacteria and skin cells and verified their potential for developing skin-care products [58]. Moreover, bioactive extracts can be obtained from grape pomace using green extraction techniques such as subcritical water extraction, providing natural raw materials for high-end skin care formulations [59].

4.5. Biological feed, organic fertiliser and biochar

Residues remaining after multi-step extraction of grape pomace still contain abundant crude protein, lignocellulose and mineral elements. Biological feed produced by solid-state fermentation with probiotics can effectively improve intestinal digestion in livestock and poultry and reduce the feed conversion ratio in breeding. Research confirms that biochar pyrolysed from grape pomace, when applied to vineyard soil, can effectively control soil-borne pests such as root-knot nematodes and support a closed loop of grape cultivation, processing and waste return to farmland [60]. Grape pomace biochar also shows favourable adsorption performance for anionic and cationic dyes in water, presenting value for environmental pollution remediation [61] and fundamentally easing the environmental burden caused by conventional landfilling.

4.6. Degradable packaging materials

The plant-based degradable packaging sector has expanded rapidly in recent years. Natural fibres and pectin isolated from grape pomace can be modified simply and blended with matrices such as

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gelatin and glycerol to fabricate fully natural edible films. The latest research shows that biocomposite films prepared with pectin and plant protein matrices incorporated with grape pomace polyphenols combine good mechanical performance and antioxidant activity. They can be used for sustainable fresh-food preservation packaging [62]. Relevant reviews note that modified natural fibres and pectin derived from grape pomace can be used to develop active and intelligent packaging materials, representing one of the most promising industrial frontiers for high-value grape pomace utilisation at present [63].

5. Existing problems

5.1. Low industrial adaptability of novel green extraction technologies, production costs far exceeding utilization benefits

Many novel green processes reported in the literature, such as enzyme-assisted extraction and ultrasound-assisted extraction, generally deliver satisfactory extraction efficiency and good activity retention in small-scale laboratory tests [64]. Nevertheless, when scaled up to ton-level continuous industrial production lines, they commonly show adaptation drawbacks including uneven equipment load, poor stability during continuous operation, fast wear of core components and excessively high overall operating costs [65, 66]. Taking deep eutectic solvent extraction and other emerging green processes as examples, existing studies mostly focus on laboratory verification of extraction efficiency and antioxidant activity. Systematic techno-economic assessments of their costs after scaling up to industrial scale remain scarce [67]. Most small and medium-sized winemaking enterprises cannot afford equipment renovation costs of several million yuan, as well as long-term expenses for reagents and maintenance. Significant economic thresholds and technical barriers still hinder large-scale commercial application of these novel green processes [68].

5.2. Poor stability of core components, difficulties in maintaining bioactivity throughout the whole process

Core bioactive substances in grape pomace, including polyphenols, anthocyanins and resveratrol, are typical heat-sensitive, light-sensitive and oxidation-prone compounds. During the whole workflow of extraction, concentration, sterilisation, transportation and storage, they are vulnerable to multiple factors such as temperature fluctuation, oxygen exposure, direct light irradiation and contact with metal ions, which cause degradation or structural isomerisation and lead to a remarkable decline in biological activity [69, 70]. Bioactive components without stabilisation treatment lose most activity under conventional storage and high-temperature sterilisation, while encapsulation techniques such as microemulsions and liposomes can effectively slow down degradation [71]. Such characteristics greatly shorten the shelf life of downstream functional end-products and raise the technical requirements and production costs for bioactivity preservation along the whole production chain.

5.3. Lagging development of integrated co-extraction technology for all components and low resource utilisation rate

At present, high-value utilisation of grape pomace in China mainly targets single bioactive components. Research on synergistic extraction and co-production technologies for multiple components including polyphenols, anthocyanins, polysaccharides and dietary fibre in pomace is insufficient. Most enterprises only extract polyphenols or resveratrol, while other valuable

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components in pomace are directly discarded as waste, resulting in severe raw material loss. Extraction processes for single components such as anthocyanins from grape pomace have been relatively well established [72]. However, most of these processes are designed only for one target component. A large amount of potential active fractions such as polysaccharides and dietary fibre remain unexploited in extraction residues. Full-value utilisation of grape pomace cannot be achieved, and the overall economic benefit is much lower than that of multi-component co-production systems.

5.4. Imperfect raw material collection, storage and transportation system and unstable supply

Grape cultivation and winemaking industries are unevenly distributed across China. Grape pomace is produced with obvious seasonality, creating a prominent supply-demand gap between peak and off-peak production periods. Meanwhile, pomace has high moisture content and is prone to spoilage. Conventional collection, storage and transportation modes generally suffer from high costs and heavy material loss. Most small and medium-sized wineries still adopt crude disposal methods such as on-site landfilling or incineration. Although studies have shown that mixing grape pomace with forage for silage can well preserve its nutrients and extend the usable period [73], such technologies mostly stay at the research stage. A large-scale and standardised collection, storage and transportation network has not yet been built. Unstable raw material supply further restricts the scaled development of downstream high-value utilisation industries.

5.5. Lack of product standards and difficulties in industrialisation

Uniform product quality standards and functional evaluation systems for high-value grape pomace utilisation have not yet been established in China. Extracts produced by different enterprises lack unified specifications for component content, activity indicators and safety, making it hard for downstream food and health product manufacturers to control raw material quality and resulting in inconsistent quality of end products. In addition, most technologies remain at the laboratory bench scale, lacking supporting processes and equipment suitable for industrial manufacturing. Disconnection between technology and industrial demand directly prevents many high-value technologies from translation and application, and the level of industrialisation cannot be further improved [74].

6. Future development directions

The future grape pomace high-value utilisation industry will focus on reducing the costs of green extraction technologies, developing multi-component co-extraction processes, constructing full-chain bioactivity stabilisation control systems and building regional standardised raw material collection and storage networks. Unified standards for various indicators of extracts will be established at an accelerated pace to promote the transformation of mature laboratory technologies into ten-thousand-ton industrial production lines. Ultimately, industrial upgrading will be realised, shifting grape pomace management from traditional waste disposal to full-component and full-value utilisation. The economic added value and resource utilisation efficiency of the whole wine industrial chain will be further enhanced [75, 76]. Combined with current industrial practice and cutting-edge research, future application scenarios of grape pomace can be prioritised in functional foods [77, 78], natural antioxidants [79, 80], eco-friendly biomass fuels [81] and other fields. Industry-university-research collaborative innovation can break through the two core bottlenecks of

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poor industrial adaptability and unstable bioactivity, supporting the resource utilisation of agricultural wastes and the achievement of carbon peaking and carbon neutrality goals [82, 83].

7. Conclusions

China produces over one million tonnes of grape pomace every year. With abundant raw materials and high contents of natural bioactive compounds, grape pomace is an agricultural processing by-product with great development potential [84, 85]. In recent years, relevant extraction processes at home and abroad have gradually shifted from conventional organic solvent maceration to greener approaches such as ultrasound-assisted and enzymatic extraction. The obtained active products including polyphenols and polysaccharides show promising application prospects in functional foods, cosmetic raw materials and other fields [86, 87]. The industry is still restricted by practical bottlenecks such as high scaling costs of green processes, poor storage stability of active ingredients and insufficient multi-component co-production technologies, and large-scale commercialisation has not yet been realised. Subsequent industrial development will centre on synergistic extraction of all components, research of low-energy green co-production technologies and development of high-value end products, gradually bridging the final gap between laboratory findings and industrial mass production [88, 89].

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