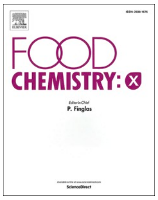
Food Chemistry: X 24 (2024) 101845

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x



The high-value and sustainable utilization of grape pomace: A review

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ARTICLE INFO

Keywords:
Grape pomace
Green extraction
Bioactive substance
Biorefinery
Circular economy
Upcycled product

ABSTRACT

A large portion of global grape production has been utilized for wine production, accompanied by tremendous pressure to dispose grape pomace. To achieve circular economy, the high-value recycling of grape pomace must be considered. The social level barriers to circular economy promotion are also important constraints, like the acceptability of upcycled products. The main components of grape pomace and their utilization are summarized, and critical reviews of green extraction methods analyzed the key points of grape pomace recycling process to achieve the goal of sustainability in the production process, culminating in discussions of the factors affecting the acceptability of upcycled products. Grape pomace bioactive substances have higher added value. To realize its green extraction, various emerging technologies need to be made a comprehensive choice. Nevertheless, the acceptability of upcycled products is influenced by personal, context and product factors, optimizing them is essential to remove the constraints of circular economy development.

1. Introduction

The grain system is an essential aspect ensuring human survival amidst challenges like population growth and climate change. Approximately one-third of the food provided by the grain system is lost or wasted during production and supply processes before human consumption, impacting food security, prices, and the environment significantly (Tubiello et al., 2022). Data from several sources have identified that the food system alone contributes to over 30 % of global greenhouse gas emissions (Cerutti et al., 2023; Clark et al., 2020; Zhu et al., 2023). Implementing food waste management programs and actions is an effective strategy to control this impact.

Grapes are widely cultivated fruit crops worldwide, commonly used for direct consumption, wine, juice, raisins and other products. Wine, due to its higher content of phenolic compounds, offers health benefits. This explains the famous 'French paradox' (Shaito et al., 2020), where despite habitual intake of high saturated fat and sugar, France maintains a low coronary heart disease mortality rate. Accompanying this explanation is the increasing consumption of wine over the years, with approximately 75 % of grapes used for wine production (Zhu et al., 2015). The world wine production was maintained between 240 and 300 million hectoliters (mhl) in the past decades (data taken from https://oiv.int/index.php/what-we-do/statistics). Particularly in the world's major wine-producing regions, according to OIV data in 2022, global wine production was approximately 260mhl, with Europe accounting for the highest proportion at around 66.27 %, and Asia the lowest at about 2.99 % (Fig. 1). Grape pomace, as the primary by-product of winemaking, accounts for approximately 30 % of the total material weight (Machado & Domínguez-Perles, 2017), its yield is corresponding to the trend of increasing wine production.

The large-scale production of wine increases the pressure of grape pomace disposal. Handling or incinerating grape pomace in ways that emit heat is one of the primary activities contributing to global warming (Nirmal et al., 2023). Considering the current international emphasis on environmental protection and numerous environmental laws (Muhlack et al., 2018) in various countries, recycling and reusing grape pomace are crucial.

In terms of technology, producing additional high value-added products (e.g., energy, compost, feed, etc.) or incorporating the handling process into production processes is a potential strategy to increase product value and reduce costs. Economically, the circular economy system aids in managing and evaluating grape pomace to reduce environmental pollution, promote sustainable economic growth, and design new product value system. Recent research driven by sustainable development indicates that grape pomace is an important source of value-added bioactive molecules. Panić et al. (2019) developed a set of extraction procedures for anthocyanins in grape pomace and validated these methods at a pilot scale in their research. Denny

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https://doi.org/10.1016/j.fochx.2024.101845
Received 15 August 2024; Received in revised form 14 September 2024; Accepted 16 September 2024

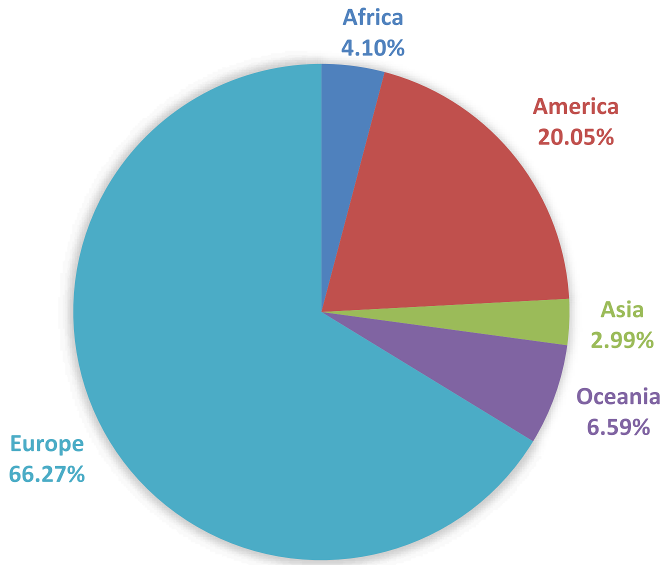

Fig. 1. Proportion of world wine production by continent in 2022 (data taken from https://oiv.int/what-we-do/data-discovery-report?oiv).

et al. (2014) investigated the feasibility of using grape pomace as a source of anti-inflammatory compounds and confirmed its potential. Additionally, the application of bioactive substances derived from grape seeds in grape pomace has been extensively studied (Prado et al., 2012; Štambuk et al., 2016). They has been through I) characterizing chemical properties to identify valuable compounds, II) designing green extraction methods, and ultimately III) determining both laboratory and pilot-scale process flows. This ensures value-added bioactive molecules enter the food value chain as products. To establish a complete recovery process, the treatment of post-extraction residues should also be considered in the process.

Experts believe that while the technological aspects of establishing a sustainable circular economy are rapidly evolving, societal barriers have a greater impact on its promotion (Kirchherr et al., 2018). Acceptability of upcycled products is a significant limitation for industrial development caused by personal, context or product factors, which required efficient strategies to attract attention and confidence of customers.

The diverse nutritional or bioactive ingredients in grape pomace offer rich possibilities, and many research articles on the high-value utilization of grape pomace have emerged. This review will summarize the valuable components in grape pomace first, whether they are value-added bioactive molecules or nutrients, and introduces their applications. This paper then provides a summary and critical review of the green extraction technology research progress of bioactive substances in grape pomace reuse and recycling programs for post-extraction residues. The paper also outlines key points in the wine production chain for developing a circular economy to recover and reuse winemaking by-products and discusses factors influencing consumer acceptability of waste-derived products with potential solutions. The wine industry can use this review to promote research and development of specific by-products, while relevant departments can use it to evaluate high-value waste recovery and establish markets, promoting sustainability and circular economy development.

2. Grape pomace high value ingredients

Information about the composition of grape pomace is important because the nature and properties of the residue are the most important factors in selecting the most appropriate recycling and treatment technology. Its richness in bioenergy and bioactive substances has led to its use in producing value-added components. These components include natural pigments, phenolic compounds, dietary fiber, and poly-unsaturated fatty acids etc. (Ilyas et al., 2021). Grape pomace serves as a significant source of polyphenols, flavonoids, proanthocyanidins, and phenolic acids, while the utilization of related bioactive components has been widely reported. Beyond the utilization of organic ingredients, minerals are non-negligible in grape pomace, like potassium, iron, and zinc, indicating that it can be used as material in health supplements and cosmetics (Sousa et al., 2014).

2.1. *Dietary fiber*

Dietary fiber is defined as 'edible or similar parts of carbohydrates in plants that can resist human small intestine digesting and absorbing and are fully or partially fermented in the large intestine' (Howlett et al., 2010). Grape pomace contains a significant amount of dietary fiber, with grape skins being a prime source (Bender et al., 2020). It's one of the components greatly influenced by grape variety, with red grape skins comprising 51–56 % by weight, while white grape skins contain 17–28 % (Deng et al., 2011). The connection between dietary fiber consumption and health has been a long-standing research topic. Dietary fiber, mainly composed of insoluble fiber, can enhance digestive efficiency and promote digestion due to its physical properties (Bender et al., 2017). Some fiber compounds can also combine with phenolic substances to produce antioxidant dietary fiber, thus possessing stronger free radical scavenging capabilities (Mildner-Szkudlarz et al., 2013). Researchers point out that its consuming also has positive effects on reducing the incidence of cardiovascular diseases, and diabetes (Macagnan et al., 2016).

It is worth noting that pectin, a water-soluble dietary fiber, is widely found in plant cell walls, with concentrations exceeding 20 % in the polysaccharides of grape skins (Spinei & Oroian, 2021). Consequently, grape pomace has been identified as a rich source of pectin. Pectin is primarily composed of esterified D-galacturonic acid (GalA) residues linked by α-(1,4) chains, with the degree of esterification being a key characteristic (Lara-Espinoza et al., 2021). The extraction processes of pectin from grape pomace, along with their effects on pectin's structural and functional properties, have been extensively studied (Megías-Pérez et al., 2023; Mobasserfar et al., 2024; Spinei & Oroian, 2022; Vakilian et al., 2023). Pectin has numerous applications in the food and pharmaceutical industries, commonly serving as a gelling agent, emulsifier, and stabilizer (Ezzati et al., 2020; Minjares-Fuentes et al., 2014). Due to its excellent film-forming ability, pectin is also used to produce edible films and coatings that extend the shelf life of food products (Mobasserfar et al., 2024; Spinei & Oroian, 2021). Additionally, pectin's antioxidant, prebiotic, immunomodulatory, anti-inflammatory, antibacterial, and hypoglycemic properties have made it a research focus, highlighting its vast biological potential (Spinei & Oroian, 2021).

2.2. *Bioactive substances*

Phenolic compounds are secondary metabolites from various physiological plant mechanisms. They are not fully extracted and used during the wine production process, leaving some residue in grape pomace. Flavonoids are the primary phenolic compounds found in grapes, including flavonols, flavanols, and anthocyanins, while non-flavonoid compounds including some phenolic acids, stilbenes, and volatile phenols. Flavonols are flavonoids typically found in seeds, represented by catechins, quercetin, and myricetin, are associated with co-pigment precipitation (Hilbert et al., 2015). Flavanols are highly abundant flavonoid compounds in grape berries, with their content closely related to grape varieties, and are often present in the form of tannin polymers. Anthocyanins are red pigments primarily found in red grapes, playing a significant role as natural colorants in the food industry (Beres et al., 2017).

Grape pomace contains numerous small molecular metabolites, which have been widely explored due to the increasing interest in bioactive substances. Some substances have been confirmed to exhibit excellent biological activities, e.g. anti-cancer, anti-inflammatory, and anti-hypertensive effects. The functional characterization studies of the relevant bioactives are listed in Table 1.

Cancer is one of the leading causes of human death. A promising chemo-preventive strategy can be defined as the use of synthetic or natural substances alone or synergistically to either block, reverse, or postpone the carcinogenesis process (Surh, 2003). Phenolic compounds and flavonoids, such as quercetin, can have an anticancer effect on breast cancer cells by inducing inflammation, apoptosis, impaired mitochondrial function and other mechanisms which lead cell death (Xi et al., 2022). According to the results of previous studies on the identification of bioactive substances in grape pomace, grape pomace is an important source of polyphenols and flavonoids. Phenolic compounds are considered potential components in food and beverages that can lower the cancer risk. Significant chemo-preventive potential against colon cancer (HT-29) cells was found in flavorings derived from grape pomace, which reduced cell viability by 50 % and exhibited anti-proliferative activity (Del Pino-García et al., 2017). Jara-Palacios et al. (2015) utilized purified white grape pomace extract and observed anti-proliferative effects on Caco-2 colon cancer cells, achieving a 52.1 % decrease in cell proliferation at a dose of 100 μg/mL after 48 h. Additionally, Peixoto et al. (2018) conducted a classification study on grape pomace, concluding that grape seed extracts derived from grape pomace presented higher anti-tumor activity. Grape seeds are important components of grape pomace, and the proanthocyanidins in grape seeds have been shown to possess strong anticancer properties. Studies have shown that grape seed proanthocyanidins significantly inhibited the growth of HepG2 hepatocellular carcinoma cells and induced apoptosis and phosphorylation of mitogen-activated protein kinase (MAPK)-related proteins, which are critically important for cancer growth and metastasis, in both in vitro (Wang et al., 2020) and in vivo (Wang et al., 2019) assays, demonstrating the potential for targeted treatment of hepatocellular carcinoma. These studies clearly indicate that phenolic compounds from grape pomace are of great recycling value due to their anticancer properties.

Coronary heart disease and stroke are among the leading causes of human mortality and disability caused by atherosclerosis. Various plant phenolic compounds can protect the cardiovascular system through different mechanisms. Rivera et al. (2019) studied mice with dietary-induced atherosclerosis given grape pomace, concluding it reduced premature death, and improved atherosclerotic symptoms. This proves grape pomace's benefits against cardiovascular diseases. Carullo et al. (2020) focused on the vasorelaxant activity of Arvino grape pomace. They determined grape pomace seed and skin extracts can relax blood vessels, with better performance from seed extracts. Dietary intake of a high-fat diet can cause postprandial oxidative stress, leading to endothelial dysfunction and atherosclerosis (Choleva et al., 2023). To counter this hazard, Choleva et al. (2023) recommended consuming grape pomace extracts. They studied metabolic and oxidative stress responses in healthy women on high-fat diets with grape pomace extract supplementation. The finding showed grape pomace extracts regulated superoxide dismutase activity, lipid peroxidation and uric acid levels, indirectly preventing atherosclerosis. In addition, trimethylamine-*N*-oxide (TMAO), produced by gut microbiota, is known to promote atherosclerosis (Annunziata et al., 2021). A grape pomace-derived polyphenol, Taurisolo®, reduced TMAO, oxidized low density lipoprotein, and reactive oxygen species, presenting a preventative strategy (Annunziata et al., 2021). The potential beneficial roles exhibited by phenolic compounds derived from grapes pomace in counteracting atherosclerosis merit attention, underscoring the significance of these compounds in creating innovative and effective functional food products in the future.

Diabetes is a complex metabolic syndrome, and its complications include retinal, renal, limb, cardiac, neurological, and vascular dysfunctions, which can lead to death. Researchers' interest in bioactive compounds with anti-diabetic activity is increasing. Insulin, recognized as a peptide hormone, is secreted by pancreatic β-cells under excessive blood sugar levels, playing an instrumental role in regulating blood sugar levels. Numerous studies have corroborated that polyphenols can regulate the insulin pathway, enhancing insulin receptor sensitivity in peripheral tissues (Domínguez Avila et al., 2017). Cho et al. (2014) studied the role of a mix of grape pomace with Omaja fruit extract on metabolic changes in type II diabetic mice, confirming its capacity to regulate blood glucose by preserving insulin expression in β-cells and liver insulin sensitivity. An additional regulatory pathway is an intense inhibitory function exhibited by polyphenolic constituents on α-amylase and α-glucosidase, key enzymes operative in glucose absorption within the gut and maintaining equilibrium in blood sugar levels (Vayalil, 2012). Hogan et al. (2010) compared red apple and red grape pomace extracts; the latter contained higher phenolic and flavonoid levels with significantly inhibited gut α-glucosidase. An intake of 400 mg/kg body weight decreased postprandial hyperglycemia in diabetic mice by 35 %. Grape pomace extract was also compared with traditional synthetic drugs. Huamán-Castilla et al. (2021) showed the extract's α-amylase and α-glucosidase inhibitory abilities at 56 % and 98 % compared to 56 % and 73 % for acarbose at same level, indicating its potential usage as a substitute for conventional drugs. The evidence presented in this section suggested that bioactive compounds derived from grapes pomace can prevent or treat hyperglycemia and diabetes. The grape pomace can be promising source of the utilization of these compounds.

The plant phenolic metabolites demonstrate noteworthy inhibitory and cytotoxic impact upon specific inflammatory cell, either via adjusting of cytokines and their cognate receptors, or through alteration of their secretory processes. The potential of diet-derived polyphenols in inducing antioxidant activity to eliminate reactive oxygen species (ROS), converting pro-inflammatory cytokines to promote anti-inflammatory attributes is frequently observed (Yahfoufi et al., 2018). The previously mentioned study by Rivera et al. (2019) examined grape pomace in mice diets showed atherosclerosis mitigation, with observing of a phenomenon of regulating the levels of TNF-α and IL-10, which are key factors in several inflammatory diseases. Denny et al. (2014) similarly confirmed that treatment with partial extracts of grape pomace reduced TNF-α levels in mice while also observing a decrease in another pro-inflammatory factor IL-1β. Both experiments verified that grape pomace could exert anti-inflammatory effects by regulating pro-inflammatory factors. Fariña et al. (2023) compared the NF-κB-induced anti-inflammatory and antioxidant capacity of six red grape pomace varieties, concluding that all pomace varieties showed inhibited TNF-α-induced NF-κB activation and IL-8 production (Fariña et al., 2023).The anti-inflammatory activities of grape-derived active molecules make grape pomace has the potential to be recycled for these diseases. In addition to the health-related benefits mentioned above, polyphenols also have other important effects, such as excellent anti-bacterial (Xu et al., 2016), blood pressure control (Gerardi et al., 2020), obesity control (You et al., 2017), neuro-protective (Rojas-García et al., 2023) and improvement of gut microbiota (Han et al., 2020).

Red grape pomace always be extracted more phenolic compounds by wine due to the maceration period, when grape pomace contacts with grape juice during winemaking. Nevertheless, red grape pomace still has a higher phenolic content than white (Beres et al., 2017). Numerous studies have characterized phenolic compounds in various grape pomace varieties. In summary, researchers have identified 73 compounds present in grape pomace, including 13 phenolic acids, 22 flavonols (in various forms), 3 flavanols and proanthocyanidins, 3 stilbenes, and 16 anthocyanins in red grape pomace; 11 phenolic acids, 19 flavonols (in various forms), 14 flavanols and proanthocyanidins in white grape pomace (Costa-Pérez et al., 2023; Jara-Palacios et al., 2015; Mildner-Szkudlarz et al., 2013; Oliveira et al., 2013; Onache et al., 2022; Peixoto et al., 2018; Teixeira et al., 2014).

Table 1
Functional study of bioactive substances in grape pomace.

Therapeutic target	Research target	Solution	Therapeutic effect	Reference
Cancer				
Colon Cancer	HT-29 Cells	Powdered red wine pomace	HT-29 survival was inhibited by 50 % (IC50 value) after 845 to 1085 μg/mL treatment 200 μg/mL attenuates oxidative DNA damage in normal cells Exhibited antiproliferative activity	(Del Pino-García et al., 2017)
Colon Cancer	Caco-2 Cells	purified white grape pomace extract	Exhibits geno-protective effects 100 μg/mL inhibited the proliferation of cells by 52.1 % at 48 h,	(Jara-Palacios et al., 2015)
Breast Cancer Cervical Cancer	MCF-7 Cells HeLa Cells	Grape seed extracts Grape pomace extracts	The seeds inhibited the growth of MCF-7 (GI50 = 352 μg/mL) and HeLa (GI50 = 253 μg/mL) cell lines Grape pomace extracts were effective against MCF-7 line (GI50 = 332 μg/mL)	(Peixoto et al., 2018)
Hepatocellular carcinoma	HepG2 Cells	Grape seed proanthocyanidins	Inhibited the viability of HepG2 cells Induced apoptosis and G2/M phase cell cycle arrest Regulated cell cycle-related proteins, cyclin B1, cyclin-dependent kinase 1, and p21 Increased reactive oxygen species production and caspase-3 activity Increased the expression of p-ERK, p-JNK, p-p38 MAPK and NAG-1	(Wang et al., 2020)
Hepatocellular carcinoma	HepG3 Cells Mice with HepG2-derived xenografts	Grape seed proanthocyanidins	Induces autophagy and increases apoptosis in HepG2 cells Decreased expression of surviving involved in apoptosis in HepG2 cells The doses of 100 mg/kg and 200 mg/kg significantly inhibited the growth of HepG2 cells in nude mice while inducing the phosphorylation of mitogen-activated protein kinase (MAPK) pathway-associated proteins, p-JNK, p-ERK, and p-p38 MAPK, but did not cause significant toxicity and autophagy, and decreased the expression of surviving	(Wang et al., 2019)
Cardiovascular disease				
Lethal ischemic heart disease	SR-B1 KO/ApoER61$^{h/h}$ mice	Red wine grape pomace	Reduced premature death Increased plasma antioxidant activity Decreased atheromatous aortic and brachiocephalic plaque sizes Attenuated myocardial infarction and dysfunction	(Rivera et al., 2019)
Cardiovascular diseases	Rat thoracic aorta rings contracted with phenylephrine or KCl	Red wine grape pomace	Relaxed blood vessels	(Carullo et al., 2020)
Metabolic and oxidative stress responses	Normal and overweight healthy women	High-fat meal with grape pomace extract	Reduced UA, TBARS levels, and SOD activity in normal-weight women Increased UA and reduced PC levels in overweight/obese women	(Choleva et al., 2023)
Atherosclerosis	Human serum	A novel nutraceutical formulation based on grape pomace polyphenols (Taurisolo®)	Reduced TMAO, oxidized low density lipoprotein, and reactive oxygen species	(Annunziata et al., 2021)
Diabetes				
Type 2 diabetic	*db/db* mice	Grape pomace and Omija fruit extracts	Lowered the levels of blood and plasma glucose, HbA1c, insulin and HOMA-IR Decrease in hepatic gluconeogenic enzymes activities and adiposity Improved preservation of the pancreatic β-cells Lowered plasma leptin and resistin levels Higher the plasma adiponectin level Increased hepatic glucokinase activity and gene expression Improved hepatic steatosis by elevating fatty acid oxidation	(Cho et al., 2014)
Type 2 diabetic	C57BLKS/6NCr mice	Red wine grape pomace extracts White wine grape pomace extracts	Inhibited gut α-glucosidase significantly 400 mg/kg body weight decreased postprandial hyperglycemia by 35 %	(Hogan et al., 2010)
Type 2 diabetic	α-amylase α-glucosidase	Red wine grape pomace extracts	The α-amylase and α-glucosidase inhibitory abilities of extracts at 56 % and 98 % higher than acarbose at same level	(Huamán-Castilla et al., 2021)
Inflammations				
Lethal ischemic heart disease	SR-B1 KO/ApoER61h/h mice	Red wine grape pomace	Adjusted TNF-α and IL-10 levels	(Rivera et al., 2019)
Inflammations	Male Balb/c albino mice SPF	Red wine grape pomace	Reduced paw edema and neutrophil migration Reduced levels of TNF-α and IL1-β in the peritoneal fluid	(Denny et al., 2014)
Inflammations	HT-29-NF-κB-hrGFP Cells	Six types of red wine grape pomace	All pomace varieties showed inhibited TNF-α-induced NF-κB activation and IL-8 production	(Fariña et al., 2023)

(*continued on next page*)

Table 1 (*continued*)

Therapeutic target	Research target	Solution	Therapeutic effect	Reference
Others				
Antimicrobial activity	Two species of pathogenic Gram-positive bacteria and Gram-negative bacteria	Grape pomace extracts	Observed against *Listeria monocytogenes* ATCC 7644 and *Staphylococcus aureus* ATCC 29213, but not against *Escherichia coli* O157:H7 ATCC 3510 and *Salmonella typhimurium* ATCC 14028	(Xu et al., 2016)
High blood Diabetes	Adult male Wistar Kyoto rats Spontaneously hypertensive rats	Grape pomace product	Reduced wall aortic thickness, cross sectional area and wall/lm ratio Decreased ROS Increased eNOS activation	(Gerardi et al., 2020)
Obesity	*db/db* mice	Cyanidin-3-glucoside	Increased energy expenditure Limited weight gain Maintained glucose homeostasis Reversed hepatic steatosis Improved cold tolerance Enhanced BAT activity Can induce brown-like adipocytes (beige) formation in subcutaneous white adipose tissue (sWAT) Can regulate the transcription of uncoupling protein 1 (UCP1) both in BAT and sWAT through increasing mitochondrial number and function	(You et al., 2017)
Improvement of gut microbiota	Male C57BL/6Cnc mice	Red wine grape pomace extracts	Increased energy metabolism and prevents obesity Enhanced the *Firmicutes*-to-*Bacteroidetes* ratio Increased the abundance of the *Bifidobacteria*, *Akkermansia*, and *Clostridia genera*	(Han et al., 2020)

UA: uric acid, TBARS: thiobarbituric acid substance, SOD: superoxide dismutase, PC: protein carbonyls, TMAO: Trimethylamine-N-oxide, HOMA-IR: homeostasis model assessment of insulin resistance, ROS: radical oxygen species, Enos: endothelial nitric oxide synthase, BAT: brown adipose tissue, sWAT: subcutaneous white adipose tissue.

2.3. Others

Soluble sugars, tartaric acid, mineral elements, and oils in grape pomace present significant potential for recycling. The sugar content of grape pomace varies greatly depending on grape variety and subsequent winemaking methods. Red grape pomace, typically co-fermented with grape juice and influenced by yeast, contains lower concentrations of soluble sugars (1.3–1.7 %) in grape pomace skin (Deng et al., 2011). In contrast, white grape varieties are usually pressed prior to fermentation, resulting in higher sugar content in white grape pomace skin (56–78 %) (Deng et al., 2011). The presence of sugars in grape pomace makes it a promising raw material for applications in cosmetics and plastic processing (Jin et al., 2019).

Tartaric acid, widely used in the food and pharmaceutical industries, is in high demand. Although tartaric acid is found in various plants, grape waste is a significant potential source for its production. Winery by-products, such as grape pomace and lees, are particularly valuable for tartaric acid extraction (Muhlack et al., 2018). In grape waste, tartaric acid often appears as soluble potassium hydrogen tartrate or calcium tartrate crystals, mixed with dead yeast, particulate solids, and other organic materials. The recovery of tartaric acid from winery waste, including pomace and lees, is well established (Devesa-Rey et al., 2011; Nurgel & Canbas, 1998).

Additionally, Grape pomace also contains various trace mineral elements derived from grape plants, such as potassium, which is beneficial for preventing osteoporosis and cardiovascular diseases (Çetin et al., 2011), zinc, which benefits the immune system, and iron, essential for blood cell production (Sousa et al., 2014). The trace elements in grape pomace have the potential to meet daily intake requirements (Institute of Medicine (US) Panel on Micronutrients, 2001).

Moreover, the primary component of grape seeds in grape pomace is oil, rich in unsaturated fatty acids, offering high nutritional value and efficacy (Kim et al., 2020; Unusan, 2020). Grape seed oil also contains vitamin E, phytosterols, and other bioactive compounds with antioxidant and anticancer properties (Wen et al., 2016).

2.4. Grape pomace value components: A critical discussion

As already mentioned, although there are studies that identify the most important valuable components of grape pomace, the data obtained are usually hardly comparable. There are numerous reasons for this. First, grape pomace comes from different countries and regions, and in addition to varietal differences, even the same grape variety varies significantly in composition in different environments. In addition, there are differences in the fermentation methods, the pomace production as well as the extraction and testing methods. This combination of factors contributes to the variation in the type and content of the pomace. It requires determining potential value-added product components based on actual raw material conditions.

It is important to recognize that, in addition to health-promoting compounds, grape pomace may also contain harmful substances, such as mycotoxins, including ochratoxin A, which is classified as a carcinogen. The presence of ochratoxin A in grape crops is primarily influenced by climate conditions, grape variety, crop damage, and other factors, and is produced by the fungus *Aspergillus carbonarius* (Dachery et al., 2019; Visconti et al., 2008). During grape processing, most of the ochratoxin A remains in the grape pomace and is difficult to remove through heat treatment (Khan et al., 2018). Although studies have shown that the levels of ochratoxin A in analyzed samples of grape pomace are far below the limits set by the European Union (Dachery et al., 2019; Ribeiro & Alves, 2008), potential health risks from harmful substances should still be considered if grape pomace is used as an ingredient in certain foods.

3. Value-added utilization of grape pomace

Based on the main components in grape pomace summarized above, traditional heat treatment (incineration, etc.) not only results in the waste of valuable substances, but also causes serious environmental problems, thus high-value utilization of these components has been a hot spot in recent years (Capanoglu et al., 2022).

3.1. Feed

Grape pomace can function as healthful animal feed. Presently, approximately 3 % of grape pomace output is allocated to animal feeding (Brenes et al., 2016). In addition to providing essential nutrients such as fiber and protein to animals, grape pomace has been shown to improve the quality of animal meat through its bioactive compounds (Arend et al., 2022). One of the most common strategies for enhancing the levels of healthy fatty acids in animal products (such as meat and dairy) is the use of feed rich in linoleic and linolenic acids (Guerra-Rivas et al., 2017). Grape seeds, in particular, contain a high proportion of linoleic acid, which serves as a substrate for the production of bioactive fatty acids. Furthermore, the high polyphenol content in grape pomace exhibits antioxidant activity, which can enhance the oxidative stability of meat by limiting or delaying lipid oxidation (Sharma et al., 2007). Research on grape pomace's substitution potential for feed and its implications has been conducted (Supplementary 1). For example, sheep fed grape pomace showed improved meat oxidation stability (Flores & Nornberg, 2019), while a similar observation was made for piglet vital organs (Chedea et al., 2019). Feeding dairy cows with grape pomace enhances milk lactose and β-lactoglobulin contents with no negative impact on other nutrition factors (Chedea et al., 2017). Similarly, poultry subjected to grape pomace leads to higher meat quality (Aditya et al., 2018), increased meat yield (Kumanda et al., 2019), and cost reductions for feed (Ebrahimzadeh et al., 2018). Nonetheless, variety, wine-making procedures, and pomace compositions impact bioactive component composition and overall functionality. Consequently, further standardization and enhancement of grape pomace usage as feed need separate study for optimal performance across grape pomace applications.

However, this option should be carefully considered in practice. Since not every animal is suitable for grape pomace as a feed alternative, preference and nutritional conflicts can arise. From a health perspective, grape pomace used as a feed alternative may contain compounds that can cause health problems or even illness, like mycotoxin, depending on the tolerance of the species. At the same time, liver and intestinal toxicity and DNA damage caused by excessive or prolonged intake of polyphenols need to be considered (Lambert et al., 2007). In addition, the costs of heating, repairs, transportation, etc. may limit the use of this option and make it unfeasible (Salemdeeb et al., 2017). In summary, the advantages compared to other alternatives are mainly due to the partial substitution of traditional feed as well as the beneficial environmental and health effects. However, the fact that this option is only available in some countries or regions, such as the European Union, currently raises questions about its legality (Salemdeeb et al., 2017).

3.2. Soil amendments

Fertilizer is a consequence of aerobic decomposition of organic matter. Studies have shown that extensive application of contemporary farming methods, including chemical fertilizers and pesticides, reduces soil fertility and quality, posing environmental pollution hazards, potentially causing accumulation of toxic heavy metals in crops, thereby affecting food nutrition and edibility (Basalingappa et al., 2018). Biological fertilizers offer environmentally friendly, cost-effective options with superior nutrient content. Grape pomace, a rich source of organic matter, has gained attraction among agricultural field for its application in composting. Mixed addition of grape pomace to soil amendments significantly alters the leaching kinetics of soil nutrients, with high polyphenol content controlling nutrient release (Korz et al., 2023). Moreover, grape pomace efficiently removes soil pesticides and insecticides. According to Ohashi et al. (2023), grape pomace can be used as a hydrogen donor for anaerobic microorganisms to dechlorinate vinyl chloride (VCM) and vinyl chloride (VC) to ethylene, thereby detoxifying and eliminating vinyl chloride from soil solutions. Marín-Benito et al. (2013) discovered that grape pomace effectively diminishes leaching of the non-mobile insecticide 'Diazinon' due to its cellulose and lignin adsorption capacity. It's noteworthy that compost production with grape pomace not only adds agricultural value but also returns stable organic matter and nutrients to the soil, potentially contributing to climate change mitigation by binding soil elements.

However, in practice, this solution must focus on factors such as the classification of the organic content, the energy supply and the amount of water added. Under unsuitable conditions, odor emissions can impact the environment while producing poor quality compost.

3.3. Energy sustainability

The current energy dilemma results from increasing demands for heat and electricity in industrial processes. This requires sustainable energy alternatives like biofuels, mainly derived from biomass resources. These include biogas, bioethanol, biodiesel, and others (Iyyappan et al., 2022). Processing waste and raw materials into biofuels helps mitigate cost and pollution. Grape pomace is a promising biofuel resource due to its high organic matter content, ideal for anaerobic digestion to produce biogas. Studies indicate a biogas yield of up to 8.7 kJ/100 g by that (Failla & Restuccia, 2014). It should be noted that when biogas is obtained from landfills, recalcitrant lignin and lignocellulose can inhibit the bioavailability of cellulose without appropriate pretreatment, thereby reducing biogas production (Kibler et al., 2018). Another important environmental problem is the formation of leachate, which mainly comes from the infiltration of rainwater and can be mixed with residual water from grape pomace. This fluid flow represents a complex matrix in which the concentration of substances depends on the weather, the waste composition, the age of the site and the depth of the landfill (Bhatt et al., 2017). This requires specialists to install appropriate facilities for treatment, which may result in higher costs.

Additionally, research on generating bioethanol from grape pomace as a carbohydrate source has shown promising results. It outperforms traditional straw and bagasse, potentially yielding up to 400 l/ton (Corbin et al., 2015). In addition, grape seed oil refining products can produce biodiesel with high oxidative stability (Fernández et al., 2010). It was reported that grape pomace-derived biodiesel has direct compatibility with internal combustion engines (Keiluweit et al., 2010). Therefore, grape pomace-derived biofuels offer potential as sustainable substitutes for transportation fuels, and gasoline.

3.4. Bioactive ingredient

Based on the health benefits and unique characteristics of grape pomace functional components, numerous products derived from grape pomace extracts are presently being intensively developed. Extensive literature supports their use in the food, cosmetic, and pharmaceutical sectors. Typically used as an additive or multifunctional ingredient in these industries with considerable potential.

3.4.1. Bioactive ingredient in foods

In the food sector, grape pomace extracts are frequently utilized as natural food additives (Antonić et al., 2020). Traditional synthetic agents (example: propyl gallate, butylated hydroxytoluene, etc.) have been extensively employed as antioxidants, additives, and preservatives in recent decades, concerns have arisen regarding their potential toxicity at high doses, with studies implying proliferation and carcinogenesis risks (Williams et al., 1990) Consequently, some nations have imposed limitations on these additives. Hence, natural food additives have become attractive alternatives. Grape pomace is rich in dietary fiber, phenolic compounds, and bioactive substances, such as antioxidants, all of which contribute to its health-promoting properties. Studies have shown that incorporating grape pomace into food products can enhance antioxidant capacity (Maestre et al., 2010), improved fatty acid profile (Choi, Choi, Han, Kim, Lee, Kim, et al., 2010), increase dietary fiber content and improve gut health (Bender et al., 2017), while also aiding in the prevention of cardiovascular diseases, cancer, and obesity. Additionally, grape pomace exhibits antimicrobial effects against food spoilage microorganisms (Lorenzo et al., 2014) and foodborne pathogens (Xu et al., 2014), while supporting the growth of probiotics (Aliakbarian et al., 2015).

Given its beneficial biological properties, the use of grape pomace in functional foods is gaining traction as a natural and sustainable way to improve food quality and health outcomes. Beres et al. (2017) assessed the functional characteristics of grape pomace extracts, like natural antioxidants, preservatives, and color stabilizers, in meat products. Evidence indicates that edible films and coatings from chitosan preserving food, with incorporation of grape pomace extracts potentially prolonging the shelf life (Ferreira et al., 2014). This is due to the capacity of grape pomace extracts to protect food against oxidative damage and lipid peroxidation. Studies have utilized grape seed extracts in lamb patties (Andrés et al., 2017), red grape pomace extracts in pork burgers (Garrido et al., 2011), and red and white grape pomace extracts in chicken meatballs (Selani et al., 2011), demonstrating to the effectiveness of grape pomace extracts in preventing lipid oxidation and extending food product shelf life. The addition of grape pomace extracts to dairy products is common, enhancing the phenolic content, antioxidant activity, and providing other advantages. Table 2 presents some research related to the application of grape pomace extracts in the food industry. Whether through the addition of grape pomace or grape seed extract, or the direct use of grape pomace powder and grape seed oil, grape pomace can provide additional nutritional and functional properties to various foods, such as meat products, fish products, dairy, and pasta. The most common benefit is the increased phenolic content, which enhances antioxidant activity, contributing to color preservation, lipid oxidation prevention, and antimicrobial effects. Additionally, the dietary fiber in grape pomace improves the sensory quality and texture of food, while offering potential gut health benefits. Interestingly, adding grape pomace to fermented foods may accelerate the fermentation process, likely due to the residual yeast and nutrients present in the pomace.

3.4.2. Bioactive ingredient in cosmetic and pharmaceutical

The cosmetic and pharmaceutical industries frequently utilize grape pomace extracts, abundant in bioactive compounds (Tapia-Quirós et al., 2022). Concerns regarding synthetic substances in cosmetics, causing allergic reactions, health risks, and skin irritation, require the incorporation of natural bioactive constituents, primarily for their antioxidant and anti-aging properties (Ferreira & Santos, 2022). Grape pomace extract, especially gallic acid, has capacity to inhibit collagenase and elastase, enzymes that degrade extra-cellular matrix proteins like collagen and elastin, make them suitable replacements (Wittenauer et al., 2015). Common commercially available cosmetics incorporating grape pomace extracts include sunscreens, facial serums, skincare products, day creams, night creams, anti-aging moisturizers, eye creams, etc. The pharmaceutical sector primarily utilizes grape pomace extracts as dietary supplements and complementary medicines. With the significance of grape polyphenols in human health, the market for related pharmaceutical products has grown. Country Life ®'s dietary supplement 'Grape Complete' has a wide range of markets which is high in polyphenols from 100 mg grape skin extract, 25 mg grape seed extract, and 25 mg pine bark extract per capsule. Life Extension®'s resveratrol product containing synergistic nutrients is described to support healthy inflammatory response, promote healthy mitochondrial function, and insulin sensitivity. In Table 3, Seagate, Solgar, and Lamberts, among other supplement manufacturers, also offer similar products. There is also products used to prevent diseases, like Taurisolo® mentioned earlier (Annunziata et al., 2021).

In conclusion, grape pomace extraction and utilization have attracted attention due to their superior bioactivity and antioxidant effects. In

Table 2
Functions of grape pomace extract in food.

Product	Material	Usage Level	Results	References
Fermented skim milk	Grape pomace extract	100 mg/L polyphenols	Maximum acidification rate Reduced fermentation time	(Aliakbarian et al., 2015)
Fermented skim milk	Grape pomace extract	80 mg/L polyphenols	Maximum acidification rate Improved cell viability Reduced fermentation time	(Souza de Azevedo et al., 2018)
Lamb patties	Grape pomace extract	0.1 % *w*/w	Reddish color Increased antioxidant activity Decreased microbial counts	(Andrés et al., 2017)
Pork burger	Grape pomace extract	0.06 % w/w	Increased color stability Reduced lipid oxidation	(Garrido et al., 2011)
Chicken meatballs	Grape pomace extract	60 mg/kg total phenolic	Slowing of lipid oxidation Promote color change of cooked products	(Selani et al., 2011)
Spaghetti	Grape pomace powder extract	/	Increased phenolic content Increased flavonoid content Increased antioxidant activity Reduced cooking losses	(Marinelli et al., 2015)
Model food	Grape seed extract white grape marc extract	3.5–15.0 g/L total phenolic in osmotic solution	Increased phenolic content	(Rózek et al., 2010)
Biscuit	Grape marc extract	0.45 mL extract/g flour	Increased phenolic content Enhanced antioxidant activity Higher sensory scores in color, fruitiness and acidity Lower brittleness	(Pasqualone et al., 2014)
Orange and apple juices	Grape pomace extracts	2–10 % w/w	Improved antifungal activity (variety-dependent)	(Sagdic et al., 2011)
Beef burger	Grape pomace powder	0.5, 1, 1.5 & 2 % w/w	Can improve fiber content and be used as a natural alternative to butylated hydroxytoluene	(De Alencar et al., 2022)
Beef sausage	Grape pomace powder	0, 2 & 4 % w/w	Increased phenolic content, taste and odor scores and reduced lipid oxidation	(Riazi et al., 2016)
Salmon burgers	Grape pomace powder	1 & 2 % w/w	Slowed down lipid oxidation without affecting flavor	(Cilli et al., 2020)
Yogurt	Grape pomace powder	1 % free or microencapsulated w/w	Enhanced phenolic and antioxidant activity, tightened structure, increased gel strength	(Saberi et al., 2023)
Reduced-fat frankfurter	Grape seed oil	10 % w/w	Reduced calories, cholesterol & trans fats	(Choi, Choi, Han, Kim, Lee, Jeong, et al., 2010)

Table 3
Some commercially available grape pomace products.

Source	Product	Functions	Key Ingredients
Seagate®	Grape Seed Extract	Nutritional support for body to against oxidative damage caused by free radical compounds, and support for heart and circulatory systems	60 % Freeze-dried red grape seed extract (*Vitis vinifera*) 40 % Freeze-dried red grape skin extract (*Vitis vinifera*) Vegetable capsule
Best Naturals®	Grape Seed Extract	Powerful antioxidant and free radical scavenger Cardiovascular and Immune Health Supports Supports healthy brain and nerve tissue Protect & strengthen collagen Keep healthy skin, connective tissue and vascular walls	Grape seed extract with 95 % polyphenols
Solgar®	Grape Seed Extract	Provide antioxidant	Grape seed extract with 90 % polyphenols
Country Life®	Grape Complete	Provide antioxidant	100 mg grape skin extract, 25 mg grape seed extract, and 25 mg pine bark extract per capsule
Life Extension®	Resveratrol Optimized	Promotes 'youthful gene expression' similar to calorie-restricted diets Promotes healthy insulin sensitivity and mitochondrial function Supports a healthy inflammatory response	Blend of red grape extract and wild cranberry fruit. Augmented with trans-pterostilbene, quercetin, and synergistic fisetin.
Taurisolo®	Fluxovas	Regulate the correct function of the cardiovascular system and contributes to the normal function of microcirculation	Pomace (*Vitis vinifera L.*), fruit and seeds extract

line with the United Nations' Sustainable Development Goals, utilizing eco-friendly extraction technologies is significant. A pyramid (Supplementary 3) sourced and adapted from Berbel and Posadillo (2018) summarizes the ways in which grape pomace can be utilized and ranked according to its product yield and value.

3.5. Limitations and prospects for value-added utilization of grape pomace

Developing value-added use of waste such as grape pomace is very complex as it requires a high level of involvement by everyone, including consumers and policy makers (Laufenberg et al., 2003a, 2003b). Most of the value-added technologies developed in recent years have not yet been implemented at scale. From an economic point of view, the procurement and transport of grape pomace from the origin to the processing plant is extremely expensive, and the associated preservation methods, which involve the decomposition and breakdown of residues in the process, increase the overall costs. Therefore, establishing value-added industries in each region that produce large quantities of grape pomace is an effective means of cost saving. Another reality is that the impact of processing costs, final product prices and consumer purchasing propensity can play a crucial role.

Although much has been achieved so far in the extraction, purification and use of valuable compounds from grape pomace, there are still technical limitations in converting these residues into valuable products, including problems in finding efficient extraction techniques and recycling the extracted residues, minimizing the impact on the environment and consumer acceptance of the products. For better value-added utilization of grape pomace, developing cleaner production processes, reducing waste and recovering valuable by-products can be short-term goals, while innovative products such as functional foods are developed in the long term.

4. Green extraction of bioactive ingredients

The importance of recovering antioxidants, pigments, polymers, and oils from agricultural and industrial waste in the food industry is increasing. Traditional solvent extraction techniques for value-added products from plant are based on the selection of solvents and the use of heat and/or agitation. Soxhlet extraction is a traditional standard technique. When the solvent is heated to boiling, the vapor rises, condenses into droplets, and enters the extractor containing the solid powder, where the solvent refluxes through siphoning, enriching the soluble substances in the solid (Luque de Castro & Garcia Ayuso, 1998). Although this method has the advantages of low equipment cost, simple operation, and high yield (López-Bascón & Luque de Castro, 2020), its drawbacks are also evident: long extraction times, large solvent consumption, and the need for evaporation or concentration after extraction to obtain purer compounds, which may lead to extra environmental issues (Fontana et al., 2013; Patra et al., 2022), not meeting the requirements of green extraction and sustainable development.

Emerging extraction technologies have been studied to extract valuable components from wine industry waste (Table 4). The emergence of these extraction technologies aims to overcome the limitations of traditional methods in recovering industrial waste (Gil-Martín et al., 2022; Ilyas et al., 2021). These technologies are based on the basic goal of 'green' extraction. 'Green' extraction technologies require less time, energy, and solvent, meeting the requirements of sustainable development. Additionally, compounds produced using 'green' solvents are purer and free from harmful substances, making them favored by consumers for their safety (Drevelegka & Goula, 2020) .

4.1. Supercritical fluid extraction

Supercritical fluid extraction (SFE) is a technique that uses the unique properties of solvents at supercritical conditions. Supercritical

Table 4
Novel green extraction technology and its application to the extraction of bioactive substances from grape source.

Material	Target substance	Treatment	Yield / Improvement	Reference
SFE				
Grape pomace	Resveratrol	SC-CO_2. V = 0.8 g/min 5 % v/v of ethanol *T* = 35 °C, PR = 400 bar, t = 3 h	250 %	(Casas et al., 2010)
Grape seed	Total phenolic compounds proanthocyanidins	1st SC-CO_2, V = 10.0 kg/h, *T* = 45 °C, PR = 280 bar, *t* = 3 h 2nd SC-CO_2, V = 6.0 kg/h 15 % w/w 57 % (*v*/v) ethanol T = 45 °C, *PR* = 80 bar, *t* = 200 min	4940 mg GAE/100 g DW > 1800 mg catechin/100 g DW	(Da Porto & Natolino, 2017)
Grape pomace	Anthocyanins phenolic	SC-CO_2, V = 20 g/min 20 % v/v of ethanol V = 5 g/min *T* = 55 °C, *PR* = 100 bar, t = 3 h	116.1 mg MCE/g DE 135.7 mg GAE/g DE	(Otero-Pareja et al., 2015)
Grape pomace	Total polyphenols total flavonoids	SC-water, V = 1–2 mL/min *T* = 140 °C, PR = 11.6 MPa, *t* = 130 min	31.69 mg/g DW 15.28 mg/g DW	(Aliakbarian et al., 2012)
Grape marc	Total polyphenols	SC-CO_2, V = 15.93 g/min 0.056 mL ethanol/g CO_2 V = 0.90 mL/min *T* = 40 °C, *PR* = 500 bar, *t* = 30 min	28.12 mg GAE/100 g DW	(Fiori et al., 2009)
NADES				
Grape skin	Total anthocyanin contents	UAE-NADES citric acid:D-(+)-maltose = 4:1 T = rt., *t* = 9.23 min, C = 76.20 % w/w, *R* = 0.83 mL/100 mg	63.36 mg of Cyan-3,5-D-E /g of grape skin more than 200 %	(Jeong et al., 2015)
Grape skin	Anthocyanins	UAE-NADES choline chloride: oxalic acid = 1:1 *T* = 65 °C, *t* = 50 min, C = 75 %, UF = 35 kHz, R = 1 mL/100 mg	500 % more than water 200 % more than aqueous methanol	(Cvjetko Bubalo et al., 2016)
Grape pomace	Anthocyanins	UMAE-NADES choline chloride: citric acid = 2:1 *T* = 65 °C, *t* = 10 min, C = 70 %, P_{MW} = 300 W, P_{US} = 50 W, UF = 37 kHz, R = 1 mL/30 mg	1.77 mg/g DW	(Panić et al., 2019)
Grape pomace	Total phenolic contents total anthocyanin contents	UAE-NADES choline chloride: malic acid = 1:1 T = 65 °C, *t* = 50 min, C = 70 %, R = 1 mL/100 mg	91 mg/g DW 24 mg/g DW	(Radošević et al., 2016)
MAE				
Grape pomace	Polyphenol anthocyanins	MAE 50 % ethanol and acid water T_p = 100 °C, pH 1.0, t_p = 120 s, MF = 2.45GHz, R = 1 mL/0.75 g T_a = 80 °C, pH 1.0, t_a = 60s, MF = 2.45GHz, R = 1 mL/0.75 g	48 % 85 %	(Álvarez et al., 2017)
Vine shoot waste	Polyphenol	MAE ethanol: water = 60:40 *T* = 100 °C, t = 20 min, *R* = 20 mL/100 mg	32.1 mg GAE/g DW	(Moreira et al., 2018)
Grape seed	Total phenolic contents	MAE-EAE-salting-out extraction D = 540 U/g T_{EAE} = 30 °C, t_{EAE} = 30 min 25 % (*w*/w) ethanol/20 % (w/w) ammonium sulfate T_{MAE} = 45 °C, pH 4.5, t_{MAE} = 90s, *P* = 180 W, *R* = 7.5 g/1 g. incubate T = rt., *t* = 60 min	125.52 mg/g DW	(Jia et al., 2021)
Wine lees	Anthocyanins	MAE hydro-alcoholic mixture with 50 % EtOH (% vol.) *T* = 25 °C, *t* = 90s, *P* = 300 W, R = 1 mL/100 mg	6.20 mg Mal-E/g DW	(Romero-Díez et al., 2019)
Grape pomace	Total polyphenol content	MAE-hydroalcoholic solvent 42 % aqueous ethanol t = 5 min, *P* = 408 W, *R* = 24 mL/1 g	36.44 mg GAE/g DW	(Drevelegka & Goula, 2020)
UAE				
Grape pomace	Anthocyanins polyphenol	UAE-hydroalcoholic solvent hydroalcoholic solvent (44 % of ethanol) *T* = 50 °C, t = 3 min, *P* = 500 W, UF = 20KHz, *R* = 40 mL/100 mg	187.57 mg of anthocyanins/g WW 290.62 mg catechin-E/g WW	(Poveda et al., 2018)
Grape pomace	Total polyphenol content total monomeric anthocyanins	UAE-hydroalcoholic solvent ethanol/water = 1:1 T = 30 °C, t = 50 min, *P* = 100 W, UF = 39KHz, R = 20 mL/1 g	21.6 mg GAE/g DW in fresh pomace 51.4 mg GAE/g DW in freeze-dried pomace 4.0 Cyan-E/g DW in fresh pomace 5.25 mg Cyan-E/g DW in freeze-dried pomace	(González et al., 2020)
Grape pomace	Total polyphenol content	UAE-hydroalcoholic solvent 53 % aqueous ethanol *T* = 56 °C, t = 20 min, *P* = 130 W, A = 34 %, R = 8 mL/1 g	34.37 mg GAE/g DW	(Drevelegka & Goula, 2020)
PEF				
Grape seed	Total polyphenol content	30 g EtOH/100 g suspension of grape seeds T = 50 °C, t = 60 min, E = 20 kV/cm, t_p = 7-8 ms, R = 5 mL/1 g	9 g GAE / 100 g DW	(Boussetta et al., 2012)
Grape pomace	Total anthocyanin contents	50 % aqueous ethanol *T* = 20 °C, *t* = 420 min, E = 1.2 kV/cm, t_p = 7-8 ms, R = 5 mL/1 g	18.90 %	(Brianceau et al., 2015)
EAE				
Grape pomace	Phenolic acids non-anthocyanidin	pectinolytic: cellulolytic enzyme (2:1) EC = 4500 mg/kg (based on dry matter) T = 40 °C, pH 4.0, t = 2 h after aqueous pre-extraction	91.9 % 92.4 % 63.6 %	(Maier et al., 2008)

(*continued on next page*)

Table 4 (*continued*)

Material	Target substance	Treatment	Yield / Improvement	Reference
	flavonoids anthocyanins			
Grape seed	Gallic acid flavan-3-ols	pectinases EC = 20.00 mg/g *T* = 48 °C, pH 3.5, t = 2 h43 min	70.2 % 21.1 %	(Štambuk et al., 2016)
Grape pomace	Total polyphenol content	4 % w/w cellulase EC = 2 mL/1 g T = 50 °C, pH 5.0, t = 130 min, P = 130 W,	45.35 mg GAE/g DW	(Drevelegka & Goula, 2020)

SFE: supercritical fluid extraction, NADES: natural deep eutectic solvents, MAE: microwave-assisted extraction, UAE: ultrasound-assisted extraction, PEF: Pulsed electric field, EAE: enzyme-assisted extraction, SC: supercritical, V: flow rate, T: temperature, PR: pressure, t: time, R: ratio of liquid or solid (solvent):solid(material), C: concentration of solvent, rt.: room temperature, UF: ultrasonic frequency, P: power, MF: microwave frequency, A: amplitude, E: electric field strength, EC: enzyme content, HHP: high hydrostatic pressure, GAE: gallic acid equivalent, Cyan-3,5-D-E: cyanidin-3,5-diglucoside equivalents, MCE: malvin chloride-equivalents, Mal-E: malvidin-equivalents, Cyan-E: cyanidin-equivalents, DW: dry weight, WW: wet weight, DE: dry extract.

fluids exhibit properties similar to both liquids and gases when temperature and pressure exceed the critical point (Kai Bin et al., 2020): density similar to liquids, while viscosity and diffusion coefficient values are close to gases, which property enables supercritical fluids to have strong solvating capabilities and excellent controllability and extraction efficiency. Simultaneously, the high diffusion rate allows supercritical fluids to penetrate the porous matrix of solid particles, increasing the effective surface area for extraction, suitable for volatile recovery of liquid/solid components (Kai Bin et al., 2020). The solvent used in SFE is easier to remove, requires fewer organic solvents, and has lower storage risks, making the extract purer and cost-effective (Ilyas et al., 2021). SFE can be conducted at relatively lower temperatures compared to traditional extractions, ensuring the storage of thermally unstable compounds and the quality and functionality of recovered compounds (Khaw et al., 2017). Most solvents used in SFE do not cause any harm to the environment. Supercritical carbon dioxide (SC-CO_2) is the popular supercritical fluid in the food industry. The advantages of carbon dioxide are low cost, high purity, non-toxicity, ease of availability, and reusability (Khaw et al., 2017).

In past studies, much research has involved SFE technology, demonstrating the potential for recovering and reusing bioactive substances from winemaking by-products. Casas et al. (2010) successfully recovered resveratrol from grape pomace using SC-CO_2 and analyzed the effects of co-solvents, pressure, and temperature on extraction capacity, achieving a maximum extraction yield of 19.2 mg/100 g dry weight (DW), representing a 250 % increase in extraction efficiency. Two-step SC-CO_2 extraction designed for polar compounds from grape sources involved first removing non-polar components from grape seeds using SC-CO_2 and then *co*-recovering polyphenols from defatted grape seeds through SC-CO_2 with a co-solvent (ethanol aqueous mixture), it achieves total phenol and proanthocyanidin component (including monomers and oligomers) recovery efficiencies of 4940 mg GAE/100 g dry matter (DM) and 1800 mg catechin/100 g DM, respectively (Da Porto & Natolino, 2017). Similar studies confirmed that SC-CO_2 can be used to separate and purify anthocyanins, phenolic compounds, and antioxidants from grape seeds (Otero-Pareja et al., 2015).

Although SFE technology offers various advantages and conveniences, some reports have pointed out limitations that restrict its use. For example, the lack of universal methods, high operational requirements (Zougagh et al., 2004), and high equipment operating costs and scale limitations. Another limitation is the difficulty in extracting polar compounds using SFE, which typically requires the addition of co-solvents as modifiers (Al-Hamimi et al., 2016). Despite the demonstrated potential for widespread use, the industrial application of this technology is still in its infancy.

4.2. Natural deep eutectic solvent extraction

A novel solvent extraction method involves the use of deep eutectic solvents (DES). DES, a new type of solvents, has potential applications in different industrial fields, and its popularity has grown rapidly in recent years. DES is a chemical mixed by two or three components to form intra-molecular hydrogen bonds which are hydrogen bond acceptors (HBAs) like tetraalkyl ammonium, quaternary ammonium or phosphine salts, as well as hydrogen bond donors (HBDs) such as sugars, alcohols, amino acids, organic acids, etc. and sometimes with the most of 50 % (*v*/v) water (García-Roldán et al., 2023). The physicochemical properties of DES can be customized by their numerous structural variations (Choi et al., 2011). Metabolites produced by cell metabolism and biodegradable substances can also combine to form DES, known as natural deep eutectic solvents (NADES), exhibiting properties like DES. NADES have attracted attention as green solvents in food fields, comprising the extraction of plant bioactive compounds.

Recent literatures provide numerous examples of bioactive compound extraction mediated by NADES, particularly polyphenols. In one study, researchers used a NADES prepared from citric acid (HBA) and maltose (HBD) in a 4:1 M ratio to extract anthocyanins from grape skins, achieving an extraction efficiency of 63.36 mg of cyanidin-3,5-diglucoside equivalents/g of grape skin, which is twice or more the efficiency of traditional acidic methanol and ethanol extraction, proving to be an efficient green extraction method (Jeong et al., 2015). Most NADES extraction methods use choline chloride (ChCl) as the HBA. In another study by Cvjetko Bubalo et al. (2016), it was noted that NADES configured with choline chloride (HBA) and oxalic acid (HBD) in a 1:1 M ratio exhibited excellent extraction capabilities for grape skin anthocyanins, with efficiencies five times higher than water and twice than methanol-water mixtures, showing a similar trend for (+)-catechin, which has similar polarity to anthocyanins. NADES as a solvent can be used in conjunction with other auxiliary extraction methods, promising to produce higher yields. Panić et al. (2019) further optimized the simultaneous ultrasound and microwave-assisted NADES to extract anthocyanins from grape pomace on pilot scale, achieving anthocyanin extraction of 1.77 mg/g DW, comparable to laboratory-scale results. In terms of solute and solvent recovery, Panić et al. (2019) also studied the purification of anthocyanins using macroporous resin and NADES recovery, achieving anthocyanin and solvent recovery rates of 99.46 % and 96.8 %, respectively, by adding additional water to disrupt the intermolecular bonding between extracted substances and NADES molecules.

Extraction methods, whether applied to foodstuffs or in line with the green extraction concept, must be guaranteed to be non-hazardous. Teams have conducted studies on the potential toxicity of NADES to the human body. Radošević et al. (2016) evaluated the extraction of anthocyanins and total phenolic compounds from grape skins using five different ChCl-based binary NADES. They ultimately selected a NADES configured with choline chloride (HBA) and malic acid (HBD) in a 1:1 M ratio, which exhibited optimal performance in extracting phenolic compounds and anthocyanins and antioxidant activity. They assessed the cytotoxicity of five NADES using human cell lines (MCF-7 and HeLa) based on cell viability and demonstrated low toxicity results, making

NADES a good candidate for green extraction of bioactive substances from grape sources. In their another study, they found that NADES originally formulated with oxalic acid as the HBD exhibited excellent performance in extracting phenolic substances but were excluded due to their inhibitory effect on cell viability, indicating potential moderate cytotoxicity (Radošević et al., 2015). This suggests that even with the use of natural products as constituent ingredients, some NADES still pose a risk of cytotoxicity to humans. Based on the toxicity study results of oxalic acid as an HBD in NADES by Radošević et al. (2015), the study by Cvjetko Bubalo et al. (2016) mentioned earlier selected the same components but did not perform cytotoxicity analysis. Identification of cytotoxicity is an indispensable step in determining whether solvents/methods comply with green extraction.

Published research data primarily involve laboratory and pilot-scale studies, and there are currently no commercial processes based on NADES. NADES exhibit advantages demonstrating significant potential for industrial applications. Issues related to mass transfer difficulties caused by the high viscosity and high energy consumption for agitation and pumping can be controlled by adding water (Panić et al., 2019). The detailed relationship between cell membrane aggregation and NADES toxicity is still unclear, but the properties of the constituent components help predict potential toxicity. According to current research results on the cytotoxicity of NADES to cell lines, NADES toxicity is generally lower than that of DES. Careful selection of components and toxicity assessment before synthesis are essential steps to obtain green extraction solvents and methods.

4.3. Microwave-assisted extraction

Microwaves primarily find application within food processing operations, categorically belong to non-ionizing radiation which operating across a frequency spanning between 300 MHz to 300 GHz (Picot-Allain et al., 2021). Within green extraction methodology, Microwave-assisted extraction (MAE) proves an extensively used method for the recycle of food constituents. Its main advantage is to greatly shorten the extraction time, reduce the amount of solvent and improve the extraction rate (Garrido et al., 2019). Within the context of wine production waste disposal, this methodology has been implemented, yielding encouraging outcomes. Álvarez et al. (2017) took advantage of the MAE technology to amplify the extraction efficacy of phenolics derived from grapes as much as 48 % and incremental yields of total anthocyanins by an impressive 85 %. MAE can also work in conjunction with other auxiliary extraction methods to enhance extraction efficiency. Study of Jia et al. (2021) indicated that using a solution of salt precipitation with 540 U/g pectinase and 180 W microwave treatment can achieve a total phenol extraction of 125.32 mg/g DW from grape seeds and exhibit better antioxidant activity. The MAE is frequently used as an initial treatment before conventional extraction procedures to augment output and diminish extraction duration (Romero-Díez et al., 2019). The efficiency, refinement, and rapidity involved in isolating valuable substances are favorable attributes identified within MAE, offering minimal requirements for implementation and operation. Nevertheless, continued or uneven exposure to high-power microwave radiation may result in the deterioration of phenolic substances with low recovery rates (Suktham et al., 2021), and the non-selectivity of the extracted substances may lead to a complex composition of the extract, representing the fundamental limitation of MAE.

4.4. Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE), a novel extraction methodology, presents significant implications for application within the food field. This approach can significantly shorter extraction duration and simultaneously enhancing extract yield and quality (Singla & Sit, 2021). Ultrasound waves, operating at intervals exceeding the auditory range for human capacity (ranging from 20 Hz to 20 kHz), are capable of radiating and transmitting as mechanical vibrations within a spectrum spanning approximately 20 kHz to 100 MHz in diverse media (Kumar et al., 2021; Singla & Sit, 2021). UAE disrupts the cell walls of plant materials, thereby promote the release of bioactive compounds (Kumar et al., 2021). Based on this mechanism of action, UAE has effectively extracted various food components from different stroma, such as flavor compounds, pigments, antioxidants, and other organic compounds. The advantages of UAE include allowing solvents to penetrate porous materials more effectively, thereby reducing processing time, increasing product yield, and reducing solvent and energy consumption (Kumar et al., 2021). Poveda et al. (2018) noted that compared to the aqueous extract obtained by accelerated solvent extraction, extracts from winemaking by-products using ultrasound-assisted aqueous-alcohol solution (44 % ethanol) exhibited stronger antioxidant and antibacterial properties, with extraction efficiencies of anthocyanins and polyphenols reaching 187.57 mg of anthocyanins / g of wet weight (WW) plant and 290.62 mg equivalents of catechin / g of WW plant, far exceeding traditional extraction methods. In a study by González et al. (2020), a method utilizing UAE combined with aqueous-alcohol solution extraction was optimized to recover active ingredients from grape pomace, resulting in a 50 % and 180 % increase in the extraction of active substances from fresh and dry grape pomace, respectively, enhancing the total antioxidant extraction rate and antioxidant activity. Research using UAE for the extraction of phenolic substances from grape pomace has shortened extraction times and yielded satisfactory recovery rates, the maximum yield of phenolic substances using ultrasound-assisted 50 % v/v ethanol extraction at 40 °C for 10 min can reach 34.37 mg GAE/g DW (Drevelegka & Goula, 2020). In contrast, heating and mechanical agitation required 17 h (Goula et al., 2016) and 20 h (Da Porto & Natolino, 2018), to extract the same level or much lower levels of phenolic content, and comparing the levels of 28 mg GAE/g DW and 28.12 mg GAE/100 g DW obtained by high-pressure discharge (Boussetta et al., 2011) and supercritical extraction (Fiori et al., 2009), respectively, the UAE was extremely advantageous in extraction rapid and rate.

Nonetheless, evidence presented by Kumar et al. (2021) showed the potential for polyphenol degradation through the production of hydroxyl radicals and cavitation bubble formation during UAE, which are potential drawbacks of this technology and must be used with caution. Similar to MAE, UAE is a non-selective extraction that can lead to complex extract compositions, and it has been claimed that aging equipment can lead to a decrease in ultrasonic intensity, which can affect extraction results (Roohinejad et al., 2017). Nevertheless, UAE possesses advantages that make it the most promising green extraction method for industrial production.

4.5. Pulsed electric field extraction

Pulsed electric field (PEF) treatment is a non-thermal processing technique. Samples are subjected to short voltage pulses with relatively minimal energy and moderate potency, releasing beneficial compounds from cells (Bobinaitė et al., 2015). This methodology functions as a substitute for conventional heat-based processing techniques. Similar to UAE, PEF disrupts cell walls with high-voltage pulses, facilitating the extraction of relevant components more easily and quickly. The substances during PEF processes are not subjected to high temperatures, thus decreasing the degradation of heat-sensitive compounds (Barba et al., 2015). Comparatively to other conventional extraction methods, this technology needs a shorter processing duration, lower energy cost, less waste, higher selectivity and can run continuously, rendering it a viable technology in the food sector (Martínez et al., 2020). Moreover, the non-thermal processing of PEF maintains the sensory and nutritional attributes of compounds, e.g., preservation of heat-sensitive flavor compounds, vitamins, and sensory characteristics. PEF technology has been used to recover valuable compounds from winemaking by-products. A study by Boussetta et al. (2012) demonstrated that grape seeds, when co-extracted with water-alcohol solvents using PEF, retained the structure of polyphenols, achieving a maximum yield of 9 g GAE /100 g DW. Another research indicates that the total phenolic content of fermented grape pomace treated with PEF increased by approximately 12.9 % compared to untreated grape pomace, and within certain temperature and electric field intensity ranges, the extraction rates of anthocyanins and flavan-3-ols increased with increasing temperature and electric field intensity (Brianceau et al., 2015). PEF emerges as an eco-friendly food processing technology with substantial benefits, thereby showing significant implementation potential in the industry. Although significant initial expending and requirements for media remain challenges (Martínez et al., 2020), PEF can be recognized as a valuable technology in food processing.

4.6. Enzyme-assisted extraction

Enzyme-assisted extraction (EAE) is a green extraction technology, unlike traditional solvent extraction, does not involve the use of toxic organic solvents. The employment of enzymes facilitates the extraction of polyphenols aimed at improving the release of bioactive constituents from the substrate. The extraction procedure involves destruction of cell walls, consequently liberating components into the extraction fluid. Cell disintegration is catalyzed by diverse enzymes such as tannases, pectinases, hemicellulases, and cellulases (Puri et al., 2012). EAE has demonstrated efficacy in extracting polyphenolic compounds from numerous plant substrates including apple and grape skin, as well as press residuals (Tomaz et al., 2016). A crucial benefit of EAE is its eco-friendly, selectivity, and secure in extracting bioactive compounds. Maier et al. (2008) provide a process for the extraction of grape pomace pigments using an enzyme mixture of pectinolytic and cellulolytic enzymes in a 2:1 ratio after aqueous pretreatment of grape skin residues, resulting in increases of 63.6 %, 92.4 %, and 91.9 % in the extraction yields of anthocyanins, non-anthocyanin flavonoids, and phenolic acids, respectively. Similar results were obtained by Štambuk et al. (2016), they utilized commercially available winemaking pectinase Lallzyme EX-V for phenolic recovery from grape seeds, demonstrating advantages of cost, simplicity, speed, and precision, exhibiting excellent performance in the extraction of various simple phenolic compounds (monomers and dimers), particularly gallic acid and catechin, with increases of 70.2 % and 21.1 %, respectively. EAE approach is in demand due to it uses biologically sourced material which is environmentally friendly. Extraction of natural products using organic solvents may lead significant drawbacks such as environmental hazards, potential toxicity, high energy inputs, and low product quality (Puri et al., 2012). These issues can be overcome with enzyme-assisted extraction methods, as they leverage the inherent catalytic capabilities of enzymes in aqueous solutions under mild processing conditions. However, the high cost of the enzyme and the high demands on the substrate environment (Puri et al., 2012) are the main constraints limiting the diffusion of this technology to industrialization.

4.7. Green Extraction of Bioactive Ingredients: A Critical Discussion

Researchers have conducted scientific studies on issues such as how to extract beneficial substances from grape pomace and optimize extraction processes. However, there is still a certain distance from large-scale application in food, medicine and other industries; enhancement of the comprehensive utilization rate of grape pomace resources; alleviation of environmental protection pressure; and promotion of the value-added and sustainable development of the grape and wine industry and formation of a certain market scale. Traditional solvent extraction has a history of over a century in separating bioactive substances and remains the common industrial extraction method. Traditional solvent extraction is facing challenges in terms of high economic and environmental costs. There is a requirement to develop new extraction processes using green solvents. Green extraction processes aim to reduce energy consumption, use low-pollution solvents, and obtain renewable natural products, thereby ensuring environmentally friendly, safe, and high-quality extraction processes. An increasing number of novel extraction techniques are emerging, such as natural deep eutectic solvents (NADES) extraction and supercritical fluid extraction, which meet the requirements of green extraction processes and are favored by scholars and industries. The advantages and disadvantages of each new extraction method are listed in Table 5. NADES has advantages on simple synthesis , low cost and can be used as a green solvent for extracting bioactive substances. Supercritical fluids are good alternatives to traditional organic solvents and are suitable for various extraction methods. Based on the use of green solvents, solvent penetration into cells can enhance to improve extraction efficiency by increasing the solubility of target compounds or by disrupting biomass cells, such as through the combined action of ultrasound. Microwave-

Table 5
The advantages and disadvantages of green extraction processes.

Method	Advantages	Disadvantages	Reference
Supercritical fluid extraction	Controllable; high throughput; selective; non-thermal technology; high stability; easy removal; solvent recoverable	Lack of universal methods; high operational requirements; high equipment operating costs; scale limitations; highly influenced by solvent polarity	(Al-Hamimi et al., 2016; Ilyas et al., 2021; Kai Bin et al., 2020; Khaw et al., 2017; Zougagh et al., 2004)
Natural deep eutectic solvent extraction	Wide range of polarity; high extraction capacity; high stability; biodegradability; sustainability; low cost; simple preparation; high environmental benefits	Density, viscosity, and low vapor pressure affect large-scale applications; difficulty of purification	(Cvjetko Bubalo et al., 2016; Palos-Hernández et al., 2022)
Microwave-assisted extraction	High extraction rate; short extraction time; low solvent usage; low energy consumption; low equipment cost	Non-selectivity; uneven microwave treatment leading to low extraction efficiency or thermal degradation of components; microwave penetration affecting large-scale applications	(Garrido et al., 2019; Suktham et al., 2021)
Ultrasound-assisted extraction	High extraction rate; high quality; short extraction time; low solvent usage; low energy consumption; high versatility	Non-selectivity: aging of equipment affects ultrasound intensity and extraction efficiency; heat generation by ultrasound degrades heat-sensitive components	(Kumar et al., 2021; Roohinejad et al., 2017; Singla & Sit, 2021)
Pulsed electric field extraction	Short extraction time; low energy costs; low waste; high selectivity; continuous operation capability; low heat production	High equipment cost; medium conductivity dependence	(Barba et al., 2015; Martínez et al., 2020)
Enzyme-assisted extraction	High environmental friendliness; high selectivity; high product safety; high yield	High cost; high substrate and environmental requirements	(Puri et al., 2012)

assisted extraction greatly encourages the recovery of bioactive compounds at the laboratory scale due to its ease of operation, relatively low equipment setup, and operating costs. Ultrasound-assisted extraction has no restrictions on solvent selection, substrate type, and moisture content, allowing its application to expand to the extraction of any type of natural compound. Therefore, from an industrial perspective, the expansion of ultrasound-assisted extraction processes is more attractive. From an environmental perspective, ultrasound-assisted extraction also represents one of the best non-thermal technologies. In addition to the application of individual extraction techniques, the combined use of multiple extraction techniques is a feasible method to further improve extraction efficiency. The research field of developing green combination technologies for extracting natural compounds is expanding. Replacing traditional solvents with emerging green alternatives aligns with green sustainable development strategies. However, some green extraction technologies have drawbacks such as high capital investment, high operating costs, complex configuration, training, and maintenance costs, which constrain their large-scale application. More comparative studies are required to evaluate the efficacy of green extraction methods. Extraction optimization is necessary to design the optimal parameters for using them. Overall trends indicate that the momentum is increasing for using them to process agricultural by-products to recover valuable natural compounds, offering promising strategies for waste management and pollution mitigation.

5. Biorefining of post-extraction residues

By employing green extraction methods, grape pomace yields valuable bioactive compounds, all in line with sustainable development principles. Nonetheless, residues still exist after extraction. Proper management of these residues is crucial to prevent environmental risks posed by uncontrolled degradation of organic matter, including greenhouse gas emissions. As circular economy principle, these residuals ideally should convert into raw materials for ‘zero waste’ production. Biomass residue recovery and utilization via biorefining is not novel. Biorefining refers to producing valuable products from biomass and waste using diverse processes, thus expanding substrate utilization (Leong et al., 2021). Currently, biorefining stands as a prominent strategy to recycle waste and attracts more attention and application.

The predominant constituents of residues from high-value extractions comprise lignocellulosic fibers (cellulose, hemicellulose, and lignin), possessing biotechnological value (Chandel et al., 2018) and application value (Boarino & Klok, 2023). The complexity, inhomogeneity, and high binding capacity of lignin obstacle its direct extraction and application. Therefore, refining of lignocellulosic biomass is crucial for obtaining useful materials. For instance, cellulosic and hemicellulosic polymers can be released via enzymatic hydrolysis, followed by enzymolysis to obtain fermentable sugars (Singh et al., 2022). Some of the studies on recycling of residues are summarized in Supplementary 2. Fermenting residues follows two main paths: abundant sources yield high-value products like bioethanol, biopolymers, and organic acids. The study by Jin et al. (2018) gives a case for this path. Initially, ethane was employed for accelerated solvent extraction of grape pomace powder to extract oils. Subsequently, the remaining portion was extracted with an aqueous alcohol solution to obtain polyphenols, with lignin subsequently eliminated using NaOH. The solid fraction, after enzymatic hydrolysis, yielded a high concentration of hydrolyzed sugars reaching 167 mg/g DW, double the sugar content obtained directly from grape pomace. Lastly, anaerobic fermentation of these hydrolyzed sugars resulted in an ethanol mixture. The authors noted that 1 kg of dry grape pomace can yields approximately 71.9 g oil extracts, 322.8 g of polyphenol extracts, and 20.7 g of ethanol mixtures, thereby valuing grape pomace. Martinez et al., 2015) also established a biorefining process for grape pomace, employing both supercritical fluid extraction and conventional methods to obtain phenolic substances (roughly 180 mg GAE/g DE). The residue was subjected to anaerobic acidogenic wet batch processes producing a volatile fatty acid mix containing butyric acid and acetic acid. These mixtures were utilized for polyhydroxyalkanoate production, then processed into biopolymers. Additionally, several studies have suggested transforming residues into organic acids by diverse microorganisms, such as succinic acid (produced by *Actinobacillus succinogenes* and *Aeromonas succinogenes*) and fumaric acid (produced by *Actinobacillus succinogenes* and fungus *Rhyzopus oryzae*) (Mokwatlo & Nicol, 2017; Naude & Nicol, 2018; Thomas, 2008). Another direction is anaerobic digestion or solid-state fermentation of residues with unclear or final solid components. Almeida et al. (2021) examined the grape pomace methane production capability pre- and post-polyphenol extraction, demonstrating methane yields of 176 L/kg and 120 L/kg, respectively, and demonstrated the extraction process not affecting methane potential. Martinez et al. (2015), mentioned before, used the post extraction and acid production solid residues to generate methane. Another promising strategy for recovering non-specific residues is the use of vermicomposting technology. This eco-friendly technology offers advantages such as rapidity, energy efficiency, low cost, and ease of control, producing valuable vermicompost by feeding on and digesting organic solid waste. Besides biotransformation methods, physical and chemical methods can also be used to treat residues, such as hydrothermal treatment for cellulose hydrolysis to obtain sugars and decomposition products (Cantero et al., 2013), or recovery of oil; produce of high-value nanomaterials through hydrothermal treatment under nitrogen initiators (Monte-Filho et al., 2019). It is noteworthy that non-biological conversion methods require additional energy consumption and environmental impacts.

Overall, due to the accumulation of valuable organic compounds following phenolic extraction and to avoid potential environmental hazards of residues, their consideration as raw materials for biorefining to achieve circular economy is necessary.

6. Sustainability and circular economy of grape pomace disposal

In recent years, human exploitation of natural resources has surpassed the environmental limits, and the demand for resources is surmised to increase sharply in the coming decades. The United Nations, through its 17 Sustainable Development Goals, explicitly states the need to reduce food waste by 50 % by 2030 (Ardra & Barua, 2022). Sustainable Development Goal 12 aims to achieve sustainable consumption and production (SCP) patterns. The current traditional ‘linear economic cultural model’ is considered severely inadequate in addressing supply and demand issues, which may lead to various risks involving social, environmental, and other aspects of life (Osorio et al., 2021). To overcome this ‘linear economic cultural paradigm,’ a more sustainable ‘circular economy model’ has attracted increasing attention from academia, industry, and policymakers, primarily reflected in the growing research related to the circular economy, increased scientific literature, and international institutions' focus on the issue (Campos et al., 2020; Yang et al., 2023). The fundamental idea behind this economic model can be summarized as reduce, reuse, and recycle, actions crucial for waste management and achieving sustainability.

Grape pomace is the main by-product of the winemaking industry, managing of waste is an important measure to promote the development of a circular economy in the wine industry. Several studies have confirmed improvement schemes for the circular economy model of grape pomace. For example, a ‘zero-waste process’ that converts grape pomace into solid biofuel and yeast raw materials has been established, transforming it into high-value resources (Lisičar Vukušić et al., 2023). Another strategy is to add grape pomace as an additive in the fermentation to improve the aromatic composition as well as to introduce more polyphenols, which has already proved its positive effect in the winemaking process of Pinot Noir wines (Wimalasiri et al., 2022). Canalejo et al. (2024) explored the potential of grape pomace components as wine aroma clarifiers and verified their excellent performance. Guerrero et al. (2013) observed that grape pomace clarification may have dosedependent adsorption capacity for wine components, and its strong selectivity can be used in the formulation of commercial products. Fig. 2 summarizes key points in wine production and integrates them with high-value utilization schemes for wine by-products, demonstrating a circular economy roadmap for grape pomace generation and the involvement of some value-added products in the wine production chain.

Based on the previous discussion, grape pomace has the potential to further promote development of industrial economic sustainability. As consumers' interest in novel products such as nutritionally modified foods and functional products grows, the application of grape pomace in the wine industry is gradually trending towards becoming a parallel industry chain with wine production, thereby developing the circular economy. Unfortunately, the market for products derived from grape pomace recycling is still in its infancy, which may be related to the acceptability of the product.

7. Upcycled foods acceptability

The promising solutions discussed in this review for addressing food waste can be termed as 'upcycled food,' defined by the Upcycled Food Association as 'using ingredients that would otherwise not be consumed by humans, purchased and produced using a verifiable supply chain, and having a positive impact on the environment.' Considering its popularity, it is also referred to as 'value-added surplus products' or 'waste-to-value foods' (Moshtaghian et al., 2021).

Factors influencing consumers' acceptance of 'upcycled food' can be classified into personal, context, and product factors (Aschemann-Witzel & Stangherlin, 2021) which is explained in Fig. 3. Personal factors may show in the acceptance of emerging technologies and consumers' awareness of environmental issues, with some studies finding that certain consumer groups with a profound understanding of environmental issues exhibit a positive attitude towards 'upcycled food' (Grasso & Asioli, 2020). Consumer age, gender, and level of education are also major factors (Aschemann-Witzel & Stangherlin, 2021). Another personal factor is consumers' cognition and identification of products (van Bussel et al., 2022), such as brand perception, trust level, design, and marketing of 'upcycled food,' which significantly impact consumers' evaluation of such products (Aschemann-Witzel & Peschel, 2019; Peschel & Aschemann-Witzel, 2020). Previous research has shown that consumers are interested in purchasing 'upcycled food' only when they perceive and recognize its higher nutritional, health, or environmental

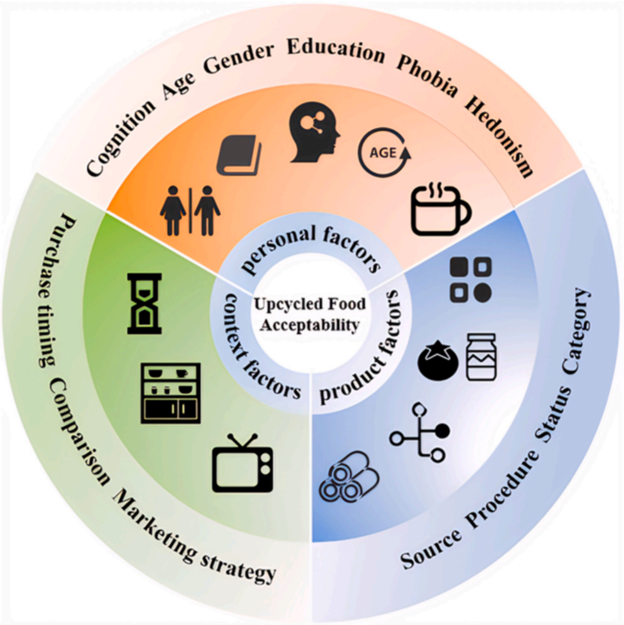

Fig. 3. Factors affecting upcycled food acceptability.

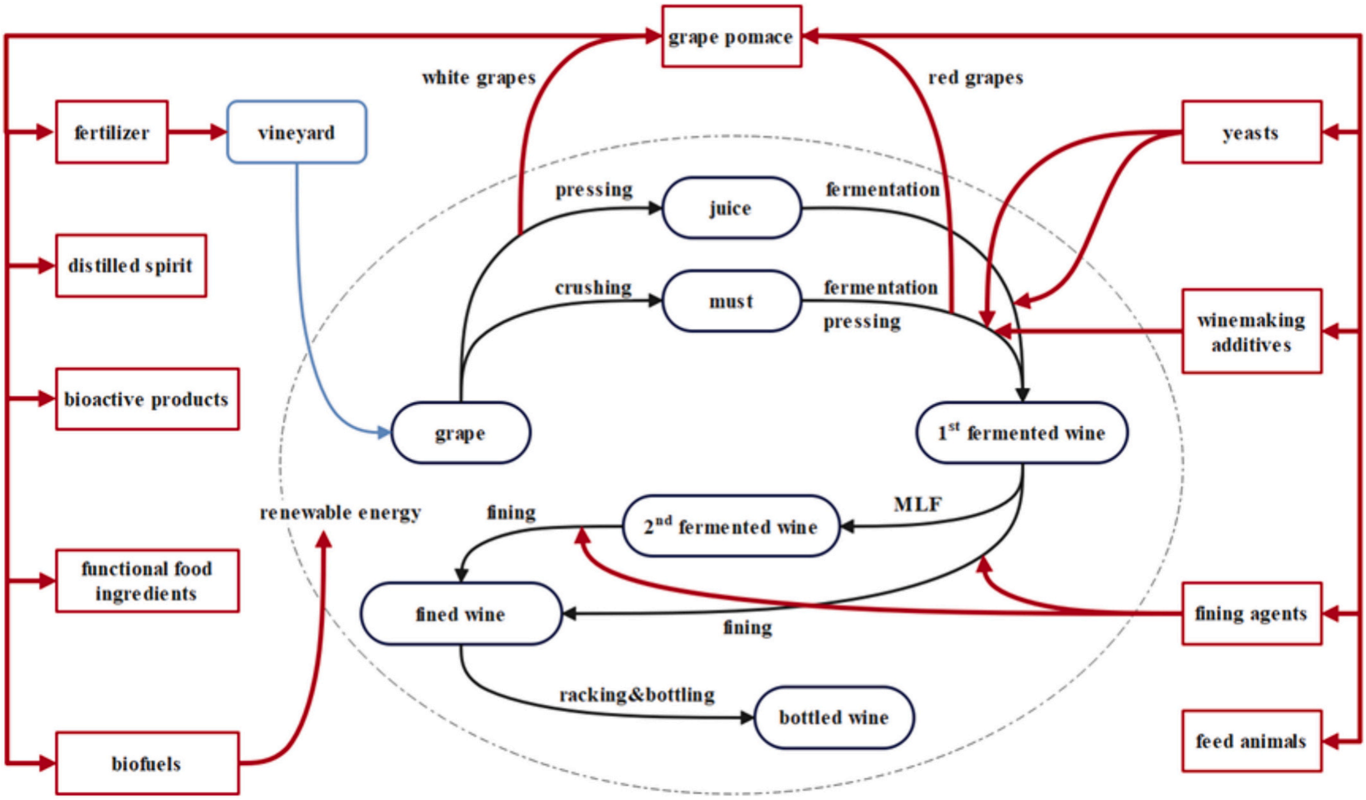

Fig. 2. Simplified diagram of the circular economy of the wine production process combined with the high value utilization of grape pomace.

benefits (Yilmaz & Kahveci, 2022), emphasizing the importance of consumer product cognition in choices. Furthermore, the existence of food neophobia or technophobia among some consumers is considered a significant barrier to accepting 'upcycled food' (Cattaneo et al., 2019). There is evidence to suggest that hedonism also influences consumer choices, as consumers who have experienced positive outcomes after trying such products are more likely to be interested in them (Ellis et al., 2019).

Context-related factors mainly involve the circumstances of obtaining product information and making choices. The extent to which consumers accept 'upcycled food' is related to the environment. For example, the choice of 'upcycled food' is not ideal when selecting alongside traditional and organic products (Aschemann-Witzel & Peschel, 2019). Currently, information about 'upcycled food' is still lacking, requiring appropriate marketing strategies to promote consumer consumption behavior towards circular economy products (Grasso et al., 2023), such as encouraging the combination of sustainable product consumption with concepts of healthy eating in the market.

Product-related factors are the characteristics of the product, such as its source and production process. Food neophobia or technophobia tends to decrease with the increased healthiness of product sourcing, which is an important factor for consumers to consider 'upcycled food' (Cattaneo et al., 2019). Consumer suspicion, aversion, or even new phobias about the origin and potential safety issues of products significantly affect consumer acceptance (Savchenko et al., 2019). Research also indicates that the distinction between product states, such as fresh or processed products, may affect consumers' acceptance, with more negative reactions towards fresh food (Savchenko et al., 2019). Additionally, product categories of vice and virtue may also influence consumers' acceptance levels, with lower acceptance of virtue products compared to vice products (Peschel & Aschemann-Witzel, 2020).

Future research should expand green and sustainable production methods, apply more consumer psychology theories, enhance the promotion of sustainable product advantages, and conduct research from the consumer perspective to develop the circular economy in diverse cultural backgrounds.

8. Conclusion

In the current situation of strained natural resource supply-demand relations, the food system stands as a crucial component supporting human survival, but a significant amount of food is wasted during production and supply. Sustainable food production is a key objective for optimizing the global food system. The wine industry generates a considerable amount of grape pomace globally, with the linear production model being assessed as the main culprit for resource wastage and environmental impact. Therefore, new circular production systems and a re-evaluation of their value are necessary considerations. The bioactive components of grape pomace have been proven to be high in content and activity, with various components individually or in combination capable of preventing or treating various human diseases, making it a high-value product with recycling potential.

The application of grape pomace extracts has been widely researched. Achieving these goals requires green, efficient, and sustainable extraction methods, which are crucial aspects. Traditional extraction methods are not considered sustainable due to their high consumption of solvents and thermal energy. Novel extraction methods such as supercritical fluid extraction and natural deep eutectic solvent extraction are emerging solvent extraction technologies, with their excellent environmental properties, low toxicity, simplicity of production, low cost, and high recyclability driving their continuous application in active ingredient extraction. Numerous auxiliary solvent extraction schemes have also been proven to optimize processes in terms of time, efficiency, and energy consumption, such as microwave, ultrasound, enzymes, etc. This has been the focus of sustainable extraction method research in recent years. However, these new methods still have limitations in terms of widespread adoption, thus requiring further research to optimize these methods and extraction rates at pilot and industrial scales.

Other components found in grape pomace or the post-extraction residues have also been proven to be usable as energy, compost, feed, etc., or raw materials return to the grape wine production process path to achieve a circular economy model. It shows that utilizing industrial by-products as raw materials for product development can reduce costs, achieve high-value utilization, and promote the development of sustainable circular economies. Therefore, producers can explore more applications for by-product recycling to enhance value, reduce production costs, and expand the market's material sources for products.

The emergence of numerous value-added surplus products has attracted consumer attention to this emerging industry, with consumer acceptance being one of the tests for the comprehensive promotion of value-added surplus products. Consumer acceptance of value-added surplus products depends on personal, context, and product-related factors, with personal factors possibly influenced by the other two factors. Many surveys indicate that raising consumer awareness of environmental issues, food waste issues, and education are effective strategies for increasing the acceptability of value-added surplus products. More adaptation of sustainable production methods, consumer behaviors, and environmental psychology theories to different cultures is the future direction for promoting the development of the circular economy.

CRediT authorship contribution statement

Changsen Wang: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Investigation, Formal analysis, Data curation. **Yilin You:** Visualization, Supervision, Resources, Methodology, Data curation. **Weidong Huang:** Validation, Software, Resources, Formal analysis, Conceptualization. **Jicheng Zhan:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This project was supported from Ningxia Hui Autonomous Region Department of Agriculture and Rural Development Key Programs.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101845.

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