Emerging technologies in grape juice production: advances, challenges, and sustainability perspectives

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ABSTRACT

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| The growing demand for functional foods and more sustainable processes has driven the search for innovative technologies in the juice industry. Among the products with high added value, grape juice stands out for its nutritional properties and its socioeconomic role in producing regions. This study aimed to review the main emerging technologies applied to grape juice production and was conducted through a narrative literature review, surveying scientific studies published in the last two decades. Technologies such as enzymatic extraction, ultrasound, pulsed electric fields (PEF), membrane filtration, high hydrostatic pressure (HPP), and pulp wash are discussed. The study highlighted the operational advantages, impacts on bioactive compound preservation, and barriers to industrial implementation. The review suggests that emerging technologies should be further explored and applied in combination to obtain juices with improved nutritional and sensory quality. Furthermore, despite the initial investment required, these methods often contribute to waste reduction and by-product valorization, thereby aligning with the principles of the circular economy. According to the assessment, integrating these technologies could improve the quality of juice while promoting waste minimization and byproduct value, which is consistent with the ideas of the circular economy. These technologies present promising avenues to modernize and maintain the beverage industry, despite the initial investment required. To reach their full potential, more market acceptability research and regulatory clarification are needed.  |

*Keywords: Emerging technologies, extraction methods; juice industry; agro-industrial waste; food technologies; sustainable processes.*

1. INTRODUCTION

Grapes are considered an excellent source of vitamins and minerals, known as one of the best natural agents for preventing aging. Their antioxidant capacity, attributed to bioactive compounds such as flavonoids, reduces free radicals, protecting against oxidative stress and chronic diseases. In addition to fresh consumption, grapes play a fundamental role in the wine industry and juice production, standing out as a key raw material in the global market (Shayanfar and Bodbodak, 2014).

Grape juice is widely consumed due to its sensory attributes and recognized health benefits, attributed to compounds like polyphenols and anthocyanins. However, product quality is closely linked to the processing methods used. The chemical composition of grape juice varies by species and extraction method, directly impacting its nutritional and sensory value (Dutra et al., 2021).

Viticulture is an essential agribusiness activity in many regions. Grapevines are cultivated worldwide, resulting in various species such as *Vitis vinifera* (European), *Vitis labrusca* (American), and *Vitis rotundifolia* (Muscadine). Among these, *V. vinifera* is the most cultivated and widely used for wine production. Grape juice, appreciated for its balance of sweetness and acidity, can also serve as a natural sweetener and base for other beverages and foods, with the United States, Brazil, and Spain being the main producing countries (El Kersh, 2023).

In the Americas, juices and nectars are derived from *V. labrusca*, such as Bordô, Concord, and Isabel varieties, while in Brazil, hybrids of this species predominate. In countries like Chile and Argentina, *V. vinifera* is the primary raw material for juices, whereas in Europe, *V. rotundifolia* stands out for juice production. Brazilian viticulture is marked by geographic diversity, spanning from the South to regions near the Equator, with varying climatic conditions favoring the cultivation of different grape types. In Brazil, the Serra Gaúcha, particularly the Vale dos Vinhedos, is the main producing region, renowned for high-quality wines and designation of origin (Cella et al., 2021). In 2024, the state of Rio Grande do Sul recorded a grape production of 485,564.477 tons. The Bordô and Isabel varieties stood out as the most cultivated, reaching 124 million and 121 million kilograms, respectively. These grapes form the basis for table wine and juice production in the region, resulting in 66,850,173 liters of whole juice and 16,034,794 liters of concentrated grape juice. In addition to these purposes, the raw material was also used for wine production, musts, and other derivatives like vinegar, as well as for the fresh grape market (SEAPDR, 2024).

Regarding production methods, grape juice is typically obtained through traditional processes. However, various emerging technologies have been explored to optimize production and final product quality. Among these, ultrasound (US), pulsed electric fields (PEF), and high hydrostatic pressure (HPP) stand out. Ultrasound uses high-frequency sound waves to generate acoustic cavitation, a phenomenon that causes the formation and collapse of microbubbles in the liquid. This process facilitates the rupture of fruit cells, increasing the release of bioactive compounds and improving juice extraction efficiency (Alvarenga et al., 2021). Pulsed electric fields (PEF) involve applying high-intensity electric pulses that permeabilize cell membranes, facilitating the extraction of desirable components (Bobinaitė et al., 2015). High hydrostatic pressure (HPP) subjects the juice to extremely high pressures for short periods, inactivating spoilage microorganisms and enzymes. Unlike traditional thermal methods, HPP preserves heat-sensitive compounds such as vitamins and antioxidants, resulting in a product with high nutritional and sensory quality (Evrendilek, 2018).

In this context, exploring techniques that maintain quality and address sustainability aspects has been valued by consumers and the industry. Thus, the pulp wash technique emerges as another innovative alternative focused on raw material utilization in juice production. Originally widespread in the citrus juice industry, especially for concentrated orange juice, this technique involves washing the pomace with water to recover residual soluble solids. Due to its productive efficiency and lower need for additives and sophisticated equipment, its use is envisioned for other raw materials, such as grapes, contributing to the circular economy and reducing losses in fruit processing (Rezzadori et al., 2012; Dutra et al., 2025a).

Therefore, this study aimed to present a narrative review of emerging technologies in grape juice production, identifying advancements that contribute to product quality improvement, loss reduction, and increased sector competitiveness. For this review, relevant academic and scientific references on the topic were used, enabling a comprehensive analysis of traditional juice extraction methods and technological innovations aimed at enhancing process efficiency, maximizing raw material utilization, and ensuring sustainable production.

2. overview of EXTRACTION METHODS

2.1 Traditional Grape Juice Production

Grape juice is defined as a non-fermented beverage obtained from simple, must treated with sulfur dioxide, or concentrated must, derived from healthy and ripe fruit. Whole juice consist of 100% fruit and at least 14% soluble solids, or 14° Brix. Concentrated grape juice, on the other hand, is obtained through partial dehydration of grape must or whole juice, removing water and reducing volume until reaching a concentration of at least 50° Brix (Brasil, 2018). In fruit processing, simple must is obtained by crushing or pressing healthy, fresh, and ripe grapes, with or without solid parts, through decantation, filtration, or centrifugation (Waterhouse et al., 2016). The solid part, called pomace, is rich in soluble solids and other substances responsible for color, flavor, and aroma.

The traditional grape juice production method comprises a set of well-established steps, widely used by both large industries and small producers. The process includes manual or mechanized grape harvesting, followed by selection, crushing, pressing, clarification, pasteurization, and bottling. The primary raw material used is fresh and ripe grapes, especially from the *Vitis labrusca* species, predominant in countries like Brazil. After crushing, the resulting must undergo direct pressing or a maceration period to intensify phenolic compound extraction. The generated residue (pomace) consists of skins and seeds and still retains a significant fraction of sugars and bioactive compounds . However, this pomace is often discarded or destined for low-value uses, highlighting the potential waste of resources (Balestro et al., 2011; Dutra et al., 2021).

It is worth noting that although grape pomace is a biodegradable agro-industrial by-product, its reuse is still limited, primarily employed as organic fertilizer and animal feed. However, due to its rich phenolic composition, improper disposal can pose environmental problems and represent a waste of high-value ingredients. The accumulation of this residue underscores the need to develop new extraction methods that allow better utilization of these compounds, reducing environmental impacts and expanding their application in the food and beverage industries (Wang et al., 2024).

Subsequently, clarification is performed by decantation or filtration before the product undergoes thermal pasteurization, which aims to eliminate spoilage microorganisms. However, this step may degrade heat-sensitive compounds such as anthocyanins, flavonoids, and vitamin C, compromising the juice's sensory and nutritional attributes. Generally, juice pasteurization occurs at temperatures between 70°C and 80°C, but even brief thermal exposure can significantly reduce antioxidant activity due to the loss of key compounds (Chang et al., 2017; Ospina-Maldonado et al., 2024).

In the industrial context, a common practice is juice concentration by evaporation, using multiple-effect evaporators with temperature and pressure control to minimize volatile compound losses. Concentration in juices is a standard industry practice, as it reduces volume, lowering transportation, storage, and packaging costs. Additionally, concentrated juices are more stable and resistant to microbial and chemical deterioration than the original juice due to lower water activity (Aguiar et al., 2012).

Juice can be concentrated by evaporation or freeze concentration. Historically, evaporation has been the most used process for grape juice. Although many types of evaporators are available, all essentially have the same components, including a heat transfer surface, a feed distribution device, a liquid-vapor separator, and a condenser. Despite logistical efficiency, the concentration process also impacts on the product's chemical composition (Morison and Hartel, 2018). Thus, heat exposure time should be minimized to preserve sensory quality, especially regarding flavor, aroma, and sugar components (Pinto et al., 2022).

The use of conventional techniques, though well-established, still faces criticism for their limited by-product utilization and their inability to effectively preserve functional compounds. According to Patras et al. (2010), thermal processing methods such as pasteurization can significantly reduce the content of phenolic compounds and the antioxidant capacity of fruit juices. Similarly, Baldwin et al. (2011) highlight that heat treatments can negatively affect the sensory attributes and nutritional quality of juices, including color and bioactive compound retention. These limitations underscore the need to explore alternative or complementary technologies to maintain juice functionality while enhancing sustainability.

Given this scenario, there is growing interest in alternative techniques that favor juice extraction with lower thermal impact to preserve nutritional and sensory quality. Thus, different methods have been applied to optimize yield, preserve bioactive compounds, and ensure greater sustainability in processing. Table 1 provides a brief comparison of the methods currently employed in juice extraction, highlighting their advantages and limitations.

**Table 1. Comparison of grape juice extraction methods**

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| **Method** | **Juice type\*** | **Main advantages** | **Limitations** | **References** |
| Enzymatic Extraction | Whole | High yield; preserves color; improves antioxidant potential | Costly enzymes; sensitive to pH and temperature | Xavier Machado et al. (2021); Zubaidi et al. (2025); Stanek-Wandzel et al. (2025). |
| Membrane filtration | Clarified | Clear juice; extends shelf life; no additives | Membrane clogging; high investment | Stoffel and Moreira (2013); Ghosh et al., (2015); Bhattacharjee et al. (2017); Conidi et al. (2020). |
| Ultrasound (US) | Whole | Enhances bioactives extraction; shortens processing time | Depends on frequency/intensity settings | Morata et al. (2021); Comarella et al. (2022); Souto et al. (2024). |
| Pulsed electric fields (PEF) | Whole | Retains nutrients; inactivates microbes; energy-efficient | High equipment cost; requires calibration | Bobinaitė et al. (2015); Koubaa et al. (2015) Li and Padilla-Zakour (2024); Wang et al. (2024). |
| High hydrostatic pressure (HPP) | Whole | Excellent preservation of sensory and nutritional qualities | Expensive machinery; sensitive to juice composition | Chang et al. (2016); Evrendilek (2018); Li and Padilla-Zakour, (2021); Li and Padilla-Zakour (2024). |
| Pulp wash | Secondary | Low-cost; sustainable; valorizes pomace | Lower nutritional concentration; regulatory limits | Fernandes and Rodrigues, (2021); Kandemir et al., (2022); Dutra et al. (2025a). |

\*Definitions of juice types: Whole juice refers to a product made exclusively from the fruit's juice, with no addition of water, sugar, or additives. Clarified juice is obtained through a clarification process in which suspended particles are removed, resulting in a clearer product. Secondary juice is produced by washing the fruit pulp residue remaining after the primary juice extraction processes.

Therefore, although the traditional method currently plays a relevant role in the juice industry, its evolution is necessary. Process modernization through integration with milder and more sustainable technologies appears as a path to meet new market and regulatory demands without compromising the nutritional and functional quality of the final product. Thus, emerging technologies and by-product reuse methods have been considered promising to increase yield, add value, and reduce environmental impacts compared to the conventional model.

2.2 Enzymatic Juice Extraction

One alternative to optimize juice extraction is enzymatic extraction, which employs specific enzymes such as pectinases and cellulases to degrade fruit cell wall components, facilitating the release of bioactive compounds and increasing juice yield (Dal Magro et al., 2015). In grape processing, this technique has proven effective in recovering anthocyanins and other phenolic compounds present in the pomace, contributing to the production of juices with higher nutritional value and color stability. Studies indicate that the use of commercial enzymatic preparations can optimize the extraction of these compounds, making the process more efficient and sustainable (Dutra et al., 2025b).

The application of these enzymes improves juice extraction efficiency by reducing viscosity and increasing the release of soluble solids. This technique has been particularly advantageous in whole grape juice production, promoting higher yields compared to the traditional method and contributing to intensified antioxidant activity (Zubaidi et al., 2025). Additionally, enzymatic extraction has the potential to be integrated with processes like ultrasound, forming hybrid extraction systems. However, its application requires strict control parameters, such as temperature and pH, to ensure optimal enzyme activity and prevent degradation of sensitive compounds. Small variations in these parameters can compromise process efficiency and the quality of the resulting juice. Moreover, the cost of commercial enzymatic preparations can be high, limiting their use by small producers (Puri et al., 2012; Stanek-Wandzel et al., 2025).

Recent studies also discuss the possibility of reusing residual pomace from the enzymatic process, which still contains fibers and incompletely extracted phenolic compounds. Xavier Machado et al. (2021) suggest that the use of enzymes, associated with other separation techniques, such as microfiltration or centrifugation, can increase the yield and purity of the recovered compounds, as well as reduce the amount of waste generated during the process. This approach aligns with circular economy trends and by-product valorization in the wine industry.

Furthermore, there is growing interest in customizing enzymatic formulations for fruits, including grape varieties. Different cultivars exhibit specific resistance to enzymatic action, requiring adjustments in enzyme type and concentration. Adapting the technology to the profile of the fruit used is, therefore, essential to maximize efficiency (Pui and Saleena, 2023).

Based on these advancements, enzymatic extraction is a technology capable of optimizing the utilization of functional compounds and adding value to grape juice. Despite economic limitations, the nutritional benefits and the possibility of integration with other techniques position this method as a relevant alternative, especially for products with functional appeal and differentiated sensory quality.

2.3 Membrane Filtration

Membrane filtration is a non-thermal technology widely used in the juice industry for clarification, stabilization, and concentration. This technique employs semi-permeable membranes, such as microfiltration (pore size of approximately 0.1 micron), ultrafiltration (approximately 0.01 micron), and nanofiltration (approximately 0.001 micron), which allow selective separation of suspended particles, microorganisms, and even low-molecular-weight compounds, depending on the membrane type used. For grape juice, ultrafiltration has stood out for preserving phenolic compounds like anthocyanins and flavonoids while providing a product with better clarity and stability (Stoffel and Moreira, 2013).

The application of membrane filtration in grape juice offers advantages such as reduced turbidity and maintenance of sensory characteristics without the need for chemical additives or artificial clarifiers. Filtration can be performed as a final or complementary step to other methods, improving permeate flow and process efficiency and enabling the production of clarified juice. Considering that this technology requires high investments in equipment and continuous maintenance, especially due to progressive membrane clogging and the need for frequent cleaning, operational costs end up restricting its use to large companies or projects with specialized technical support. Before filtering, pre-treatments like centrifugation and decantation lower the solid content, extending the membrane's lifespan. (Bhattacharjee et al., 2017).

In addition to clarification, membrane filtration can be used to concentrate bioactive compounds and modify juice composition, favoring the production of functional beverages. Conidi et al. (2020) emphasize that selective fractionation enables the creation of customized juices with specific anthocyanin or polyphenol levels, expanding innovation possibilities in the sector.

The use of this technology also aligns with sustainability demands, as it avoids chemical products and generates less liquid waste. When well implemented, membrane filtration can improve overall production process efficiency and reduce losses of target compounds, positioning itself as a modern alternative to traditional thermal processing. Thus, membrane filtration establishes itself as a high-performance technology in juice production, with benefits ranging from sensory quality to bioactive compound valorization. Its application in grape juice has shown positive results, especially when combined with other techniques such as enzymatic extraction or ultrasound, enabling more efficient and sustainable processes in the beverage industry (Ghosh et al., 2015; Katibi et al., 2023).

**2.4 Ultrasound (US)**

Considered another important technology, ultrasound (US) uses high-frequency sound waves to induce acoustic cavitation in liquids, promoting the formation and collapse of microbubbles. This process generates microjets and shock waves that facilitate the rupture of fruit cell walls, intensifying the release of bioactive compounds and juice yield. In grape juices, US has demonstrated great efficacy in preserving polyphenols, anthocyanins, and other natural antioxidants while maintaining important sensory attributes like flavor and aroma (Comarella et al., 2022).

In addition to increasing extraction efficiency, the US offers relevant operational benefits, such as reduced processing time, lower energy consumption, and decreased need for solvents or chemical additives. These characteristics make the technology compatible with sustainable practices and the trend of offering more natural and healthy products. For Souto et al. (2024), the use of ultrasound allows the production of juices with greater stability during storage without compromising their nutritional value.

The technique's effectiveness, however, depends on factors such as frequency, sound wave intensity, exposure time, and medium temperature. These variables must be optimized to maximize benefits while avoiding damage to sensitive compounds.This technology thus requires rigorous technical monitoring, which can pose a challenge for small-scale adoption (Alvarenga et al., 2021).

Studies have highlighted the potential of combining US with other techniques, such as enzymatic extraction or membrane filtration, creating more efficient hybrid processes. This synergy can significantly increase juice yield and stability, especially concerning the preservation of thermosensitive phenolic compounds. Morata et al. (2021) reinforce that ultrasound use can improve enzyme dispersion during extraction and increase penetration into plant tissues, optimizing the release of antioxidant compounds. This integrated approach is promising for producing functional juices with higher added value, aligning technological innovation, industrial efficiency, and nutritional quality (Stanek-Wandzel et al., 2025).

It can be observed, therefore, that ultrasound stands out as one of the most significant emerging technologies in the juice industry, especially for grape processing. Its potential for industrial-scale application, coupled with the preservation of sensory and bioactive properties, justifies the growing number of research studies and investments aimed at its adoption in different production contexts.

**2.5 Pulsed Electric Fields (PEF)**

Gaining prominence in liquid food processing, especially fruit juices, Pulsed Electric Fields (PEF) represent a non-thermal emerging technology. The technique involves applying high-intensity electric pulses that cause electroporation of cell membranes. This physical effect allows more efficient release of intracellular compounds while inactivating spoilage microorganisms and enzymes, extending product shelf life without resorting to heat (Wang et al., 2024).

For grape juice and wine, PEF has shown promising results in enhancing the extraction of anthocyanins, polyphenols, and other antioxidant compounds. Morata et al. (2021) emphasize that this technique improves the release of these bioactive components, thereby contributing to greater color intensity, enhanced flavor, and improved functional properties. One of the main advantages of PEF is its ability to preserve the sensory characteristics of the final product, which is highly valued by consumers (Lee et al., 2024).

In addition to nutritional benefits, PEF also contributes to juice microbiological stability. Reducing microbial load without preservatives responds to the growing demand for more natural and minimally processed products. Li and Padilla-Zakour (2024) reveal that PEF use can significantly increase the juice yield, antioxidants contents and antioxidant activity compared to conventional thermal pasteurization methods.

Despite its potential, PEF adoption still faces challenges, particularly regarding high equipment costs and operational complexity. The technique requires fine adjustments in electric field intensity, pulse frequency and duration, and specific adaptation for each fruit or grape variety (Heinz and Knorr, 2007).

The integration of PEF with other techniques, such as high-pressure processing, has been explored as a strategy to increase yield and reduce operational costs. As observed by Li and Padilla-Zakour (2024), this technological combination can lead to highly efficient processes that are adaptable to industrial demands. In addition to improving processing efficiency, the integrated use of technologies offers multiple advantages, including increased juice yield and color intensity, enhanced nutrient retention and fresh flavor, extended shelf life, and greater consumer acceptability and purchase intent when compared to conventionally heat-pasteurized juice. Souto et al. (2024) note that, when well controlled, PEF contributes to conserving natural aromatic notes, offering more attractive products to end consumers.

Another relevant aspect is process sustainability. PEF offers a more environmentally friendly alternative to conventional heat pasteurization by minimizing thermal input and energy use. This makes it an advantageous option for industries seeking to align quality, safety, and environmental responsibility in their production chains (Koubaa et al., 2015).

Given these perspectives, PEF is identified as a relevant technology for modernizing juice processing, including grape juice. Given its high potential to elevate final product quality - combining nutritional preservation, microbiological safety, and production efficiency - the need for investments in research and technological adaptations to enable large-scale application becomes evident.

**2.6 High Hydrostatic Pressure (HPP)**

Used to treat packaged foods or liquids, High Hydrostatic Pressure (HPP) is a non-thermal process that applies pressures typically between 100 and 800 MPa for short times. This uniform pressure is transmitted through a fluid (usually water), promoting the inactivation of pathogenic and spoilage microorganisms, as well as enzymes responsible for degrading sensitive compounds. One of the technique's main advantages is that it does not use heat, preserving sensory characteristics and bioactive compounds, making it highly suitable for juices (Evrendilek, 2018).

For grape juice, HPP has proven effective in preserving anthocyanins, flavonoids, and other polyphenols, components that give the beverage not only its intense color but also high antioxidant activity. The HPP treatment results in juices with superior sensory and nutritional quality compared to traditional thermal pasteurization. The technology is also valued for meeting consumer demand for natural and minimally processed foods (Chang et al., 2016; Li and Padilla-Zakour, 2021).

The HPP application, however, involves technical and economic challenges. Initial equipment acquisition costs are high, and the process requires specific attention to juice composition, pH, and suspended solids content, which can affect microbial inactivation efficiency. These factors also directly influence juice stability during storage. Despite these limitations, the literature highlights efforts to optimize processing variables (Barba et al., 2015).

Another notable aspect of HPP is its versatility. The technique can be used to stabilize ready-to-drink juices, as well as concentrates or bases for mixed beverages. Muñoz et al. (2022) emphasize that HPP use does not significantly alter beverage volatile compounds, which is essential for maintaining grape juice's characteristic aromatic profile.

In addition to standalone applications, HPP can also be combined with other emerging technologies. Studies indicate that the synergy between HPP and ultrasound can intensify phenolic compound extraction, resulting in beverages with higher functional value (Sumere et al., 2018). This integration tends to increase yield and reduce thermal impacts, creating promising solutions for the beverage industry.

Finally, it is worth noting that HPP aligns with sustainable practices in the food sector, as it reduces preservative use and minimizes nutritional losses during processing. This makes it a competitive and modern alternative in response to market demands for safe, nutritious foods with preserved sensory attributes. Continuous advancements in equipment, cost reduction, and new application studies reinforce HPP as a potential technique for innovating juice processing, including grape juice.

**2.7 Pulp Wash Technology**

The pursuit of greater efficiency and sustainability in juice extraction has driven the development and application of technological innovations, such as pomace washing extraction, known as pulp wash. As a strategy that combines raw material utilization with reduced processing losses, this technique received greater emphasis in this review. Pulp wash enables the recovery of residual compounds still present in the remaining pulp after primary juice extraction, resulting in a product known as washed pulp juice or secondary juice. This approach has stood out for increasing production yield and contributing to grape production chain sustainability by minimizing waste and encouraging circular economy practices (Ospina-Maldonado et al., 2024). Thus, its technical-scientific relevance and industrial application potential justify this topic's in-depth exploration throughout the work.

In emerging countries, pulp wash adoption can have significant socioeconomic impacts, both in terms of increased production efficiency and access to lower-cost food products. This practice allows small producers to add value to juice industry by-products, creating new market opportunities and encouraging sustainable production. However, clear regulations are essential to ensure that juice obtained through this technique is properly labeled, preventing consumers from receiving lower-quality products without proper disclosure. Thus, public policies and certifications will play a key role in guaranteeing quality and promoting equitable access to pulp wash-derived products (Fernandes and Rodrigues, 2021).

Compared to the traditional method, pulp wash retains a higher quantity of bioactive compounds, preserving the final juice's antioxidant properties (Rezzadori et al., 2012; Silva et al., 2021). By recovering soluble solids from residual pulp, this technique not only increases production yield but also contributes to reducing the environmental impact associated with by-product disposal. Moreover, valorizing these by-products as functional ingredients in new food products reinforces the sector's economic and environmental sustainability (Kandemir et al., 2022).

Pulp wash is widely used in the citrus juice industry, particularly in concentrated orange juice production. Orange juice processing companies in Brazil and the United States employ this method to increase extraction yield. Thus, concentrated orange juice producers use advanced technologies and are among the successful examples of full agricultural product utilization. During processing, residual pulp is washed with water to recover soluble solids, resulting in a product that can be added to concentrated juice, as permitted by legislation. The citrus industry fully utilizes raw materials, transforming its waste into commercially valuable by-products. In addition to pulp wash, other derivatives such as D-limonene, extracted from fruit peels, citrus pulp meal used in animal feed, and essential oils employed in various industrial applications can be obtained. This reuse model reduces waste and adds economic value through full fruit utilization (Ashurst, 2001).

For grape juice, the pulp wash production flow chart would resemble orange juice production. The pulp wash process begins with fruit reception and selection, followed by washing and primary extraction, separating juice from pulp and peel. The residual pulp, composed of juice cells and peel fragments, is then collected and temporarily stored in suitable tanks. Subsequently, this pulp is washed with water in specific equipment called finishers, which separate soluble solids from the solid fraction. The resulting liquid is concentrated in multi-stage falling film evaporators, and through the combination of temperature and vacuum, the product is concentrated to the desired specification, i.e., until reaching the target solids content. Next, the product is cooled in heat exchangers and stored at low temperatures in refrigerated chambers until commercialization, typically in 200 L metal drums. At this stage, the juice is in base form, which can be considered the first stage of production planning. In the second stage, the various juice bases are blended to obtain final products (blends) (Munhoz and Morabito, 2010).

In the extractive sector, the pulp-containing juice phase is transported to the filtration and centrifugation sector, where excess pulp and other defects incorporated into the juice are removed, in addition to adjusting the product's pulp content to desired standards. The pulp removed from the juice in this stage is used to produce the by-product known as pulp wash, which is a secondary juice (Munhoz and Morabito, 2010).

After the primary extraction of juice or wine, fruit pomace (composed of skins, seeds, and residual pulp) can follow multiple utilization paths, depending on the intended final product. When used for pulp wash, the pomace is internally conveyed or pumped to washing equipment to recover additional soluble solids. Alternatively, for applications such as animal feed, bioenergy, or biorefinery processes, the pomace is pressed, dried (often in rotary dryers), and subsequently pelletized before storage and commercialization. Proper handling, transportation, and storage are essential throughout these steps to prevent microbial spoilage and deterioration prior to final processing, thereby maximizing the valorization of this agro-industrial by-product (Del Mar Contreras et al., 2022).

The pulp wash process requires specific equipment to ensure extraction efficiency and final product quality. Key equipment includes centrifugal filters (finishers), used to adjust juice pulp content; pulp washing systems, responsible for recovering soluble solids; multi-effect evaporators, which concentrate the juice obtained after pulp washing; and heat exchangers, which cool the pulp wash after concentration. These devices ensure the process is efficient and safe for the food industry (Tetrapak, 2025).

Quality control during the pulp wash process is crucial to ensure final product safety and acceptability. Steps include microbiological analysis for contaminant detection, soluble solids content measurement (°Brix) to ensure proper concentration, and sensory evaluations assessing aspects like flavor, aroma, and color. Additionally, monitoring enzyme activity such as polyphenol oxidase is essential, as it can affect juice stability, color, and quality during storage (Sádecká et al., 2014). In the United States, pulp wash incorporation into concentrated orange juice is regulated by agencies like the Food and Drug Administration (FDA), which establishes quality and labeling standards to ensure consumer safety. North American companies adopt advanced equipment for pulp wash extraction and quality control, guaranteeing a market-appropriate final product (FDA, 2025).

Pulp wash has various applications in the food industry, as it can be incorporated into concentrated juice, provided legal specifications are met, or used in lower-concentration beverages like nectars and mixed drinks. Additionally, it can be employed in sweets, jams, and other food products, utilizing washed pulp nutrients and flavor. This versatility makes pulp wash a sustainable and economically viable alternative for the citrus juice industry (Casas Cardoso et al., 2022; Skwarek and Karwowska, 2023).

This technology stands out as a viable alternative in juice extraction, especially when compared to emerging non-thermal methods. These technologies, such as ultrasound (US), pulsed electric fields (PEF), and high hydrostatic pressure (HPP), have been explored to improve extraction efficiency and preserve bioactive compounds. However, implementing these technologies requires considerations regarding costs and infrastructure, areas where pulp wash offers significant advantages (Jadhav et al., 2021).

Thus, pulp wash implementation can bring significant benefits to small and medium producers, providing a low-cost alternative to increase yield and profitability. By transforming waste into marketable products, this technique enables product diversification and new revenue streams, strengthening local economies and promoting sustainable development in juice production chain communities. Moreover, Rezzadori et al. (2021) indicate that the implementation of pulp wash in citrus juice industries leads to an increase in the final juice production volume at a low cost, highlighting the favorable cost-benefit ratio of this technology and reinforcing the concept of converting waste into marketable, higher-value products.

It should be noted that although pulp wash increases production efficiency, there are concerns regarding the nutritional impact of juice obtained through this process. During pulp washing, some bioactive compounds such as polyphenols and anthocyanins may be diluted, resulting in lower concentrations of these nutrients compared to first-extraction juice. However, Silva et al. (2021) indicate that the reuse of pulp and other fruit by-products in the production of juices still retains considerable levels of dietary fiber, anthocyanins and antioxidant compounds, especially when the process is performed under controlled temperature and extraction time conditions. Therefore, although nutritional quality is slightly inferior, the technology remains a viable alternative, provided it is accompanied by process and quality control (Dutra et al., 2025a).

**2.8. Other Technologies**

In addition to the methodologies already discussed for grape juice production, the literature highlights other innovative approaches with potential for industrial application. Among them, particular attention has been given to the use of ultraviolet (UV) radiation, especially UV-C, and supercritical carbon dioxide (SC-CO₂) processing.

Fredericks et al. (2011) emphasized the efficacy of UV-C radiation (254 nm) as a non-thermal alternative for the inactivation of microorganisms in grape juice and wine. The authors reported that the application of UV-C resulted in a significant reduction of yeasts, lactic acid bacteria, and acetic acid bacteria in both must and wine, indicating its potential for microbiological stabilization of these products while allowing the use of reduced amounts of sulfur dioxide (SO₂). It is important to note, however, that the effectiveness of UV-C can be influenced by factors such as the color and turbidity of the beverage, which should be considered during process development in order to maximize its efficiency.

Another emerging technology is supercritical carbon dioxide (SC-CO₂) processing, as explored by Amaral et al. (2018). In a study involving mixed whey and grape juice beverages treated with SC-CO₂, improvements were observed in physicochemical properties and sensory acceptance, along with advantages over conventional thermal treatments. SC-CO₂ allows processing at near-ambient temperatures, thereby minimizing nutrient loss and sensory alterations. This makes it a promising approach for preserving grape juice-based beverages and related products.

Therefore, these technologies should be further encouraged and investigated, as they represent non-thermal alternatives capable of preserving the nutritional and sensory quality of beverages while ensuring the microbiological safety of vitivinicultural products.

4. Conclusion

The emerging technologies applied to grape juice extraction and processing represent significant advancements in the search for more sustainable, efficient methods capable of preserving product nutritional and sensory quality. Techniques such as enzymatic extraction, membrane filtration, ultrasound, pulsed electric fields (PEF), and high hydrostatic pressure (HPP) demonstrate superior ability to preserve bioactive compounds and sensory characteristics compared to exclusively traditional thermal methods. However, their adoption may face economic obstacles, particularly for small and medium producers, due to high implementation and operational costs.

Among the analyzed methodologies, the pulp wash technique emerges as a particularly advantageous solution for sustainable by-product reuse. Already widespread in the citrus industry, its adaptation for grape processing presents itself as a strategic alternative to increase production yield, minimize waste generation, and foster circular economy practices. However, its implementation requires care regarding process standardization, proper by-product valorization, and maintenance of final product sensory and nutritional characteristics.

As future perspectives, it is important to explore the combination of different grape juice extraction methods to optimize operational efficiency, sustainability, and product quality. Additionally, the integration of emerging extraction technologies with innovative packaging and storage solutions, such as active or intelligent packaging and modified atmosphere systems, may further enhance juice quality and extend shelf life by reducing oxidation and preserving nutritional value. However, limitations remain, including the lack of clear regulations for certain techniques (notably pulp wash) and the absence of long-term studies on shelf life and nutritional stability of juices processed with these technologies. Addressing these gaps requires multidisciplinary research, along with investments in studies evaluating economic viability at different production scales, consumer acceptance, and adaptation to specific grape varieties, to ensure the safe, effective, and equitable implementation of these innovations.

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Details of the AI usage are given below:

(1) ChatGPT (OpenAI), GPT-4 version, was accessed through the official platform (chat.openai.com);

(2) The tool was employed exclusively for language editing and text refinement purposes;

(3) Its use was limited, ethical, and strictly confined to enhancing writing quality, without contributing to the generation of scientific content or data.

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