REVIEW

Advancing sugarcane juice as a sustainable alternative to plant-based sports isotonic drinks: Innovations in preservation techniques

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Summary

Sugarcane juice has gained popularity for its refreshing taste and flavour, making it a traditional beverage cherished in various cultures. Rich in sugars, vitamins, minerals, antioxidants, prebiotics and bioactive compounds, sugarcane juice and its derivatives stand out as promoting health and rejuvenating, making it an appealing natural alternative to commercialised isotonic beverages. Augmenting sugarcane juice with probiotics enhances its health benefits and also elevates its commercial value. Despite its potential therapeutic effects, the limited shelf life of fresh sugarcane juice due to microbiological spoilage and enzymatic reactions necessitates effective preservation methods. Various emerging techniques, including processing with ultrasound, high-pressure or pulsed electric field, and other hurdle techniques, have been explored to extend its shelf life. These methods act by inhibiting enzymatic reactions and microbial growth. They replace conventional thermal treatment to ensure the safety and quality of sugarcane juice under milder while efficient conditions, though the adoption of advanced technologies may involve higher operational and processing costs. This review focuses on the potential of sugarcane juice as a health-promoting drink and explores emerging techniques for preserving its nutritional and physico-chemical values, paving the way for its commercialisation.

Keywords

hurdle technology; plant-based drink; ergogenic; probiotic; food safety; antioxidant

Sugarcane (*Saccharum officinarum* L.) is a pivotal industrial crop cultivated in numerous tropical countries, playing a crucial role as a primary source (accounting for 80 %) of the world's sugar raw material and serving as a key feedstock for ethanol production. In industry, the by-products of sugarcane processing, such as straw and bagasse, find versatile applications, further emphasising the plant's significance in promoting sustainable practices and resource utilisation [1].

Among its various cultivars, sugarcane is commonly distinguished by rind colour, including red, green, and purple varieties. Beyond sugar production, sugarcane is commonly consumed raw for its distinct sensory properties and affordability, especially in hot tropical countries where the sugarcane plantation is endemic. Classified under the kingdom Plantae, clade Angiosperms, order Poales, family Poaceae, genus *Saccharum* and species *S. officinarum*, this crop thrives in tropical and subtropical regions with abundant rainfall. The yellow rind sugarcane is preferred for commercial juice production due to its higher yield, good flavour, less fibrous texture and easier processing owing to its softer stalk [2]. Derived products from sugarcane processing find tradi-

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tional use in various tropical countries in America and Asia. For instance, it can serve as a sweetener, molasses, jaggery and bagasse [3].

Sugarcane's nutritional value is often overlooked due to perceptions of high reducing sugar content, which can be detrimental to health. However, moderate consumption of sugarcane juice, either raw or processed, offers excellent health benefits. Chewing sugarcane was linked with oral health [4], and sugarcane juice is rich in amino acids, minerals and antioxidants [5]. Moreover, sugarcane was implicated in various biological effects, including immune system stimulation, reduction of deoxyribonucleic acid (DNA) damage, anti-thrombosis, anti-inflammatory and anti-stress effects, vaccine adjuvants and acetylcholine modulation [5].

Despite its nutritional value, the commercialisation of sugarcane juice faces challenges due to rapid enzymatic, non-enzymatic and microbial deterioration impacting sensory qualities. Saccharose loss post-harvest stages are of significant concern, with degradation commencing upon harvesting and escalating during the delay between harvesting and milling. Factors such as ambient temperature, humidity, enzymatic activity (invertase, polyphenol oxidase and peroxidase), non-enzymatic chemical reactions (such as Maillard reaction), microbial contamination, cane variety and maturity influence these losses. Traditional post-processing methods, such as using machetes, and unhygienic practices during crushing and milling may introduce microbial contamination that lowers the juice's shelf life [6].

Currently, several preservation techniques using hurdle techniques have been explored by researchers and food technologists to inhibit enzymatic reactions and microbial growth in sugarcane juice. However, implementing these advanced technologies may incur higher operating and processing costs, while the use of traditional heat inactivation often results in lower nutritional qualities and lower efficiency in inhibiting enzymatic reactions and microbial growth, leading to shorter shelf life and compromised product quality. Therefore, this review aims to document recent advances in sugarcane juice research, emphasising its nutritional and functional qualities. Additionally, recent processing technologies to preserve and improve its quality will be discussed.

Physico-chemical and nutritional properties

Sugarcane juice is a nutrient-rich beverage containing natural sugars, vitamins (such as B-complex vitamins), minerals (including calcium, potassium, magnesium, and iron), antioxidants and bioactive compounds. These components contribute to its wide-ranging applications in food as a natural sweetener and functional ingredient as well as in health support for hydration, energy replenishment and potential therapeutic benefits, such as aiding digestion or supporting immune function [4, 5]. Its important physico-chemical attributes include total soluble solids, pH, total sugars, organic acids, pigments and inorganic salts. These attributes are influenced by factors like sugarcane variety, climate, cultivation and processing. The colour of sugarcane juice varies depending on the variety used, ranging from greenish yellow to light brown [7].

Comprising 75–82 % water and 18–25 % soluble solids, sugarcane juice is a good energy source that aids hydration. The juice's simple sugars (carbohydrates) rapidly replenish energy levels, assisted by the presence of electrolytes such as sodium and potassium with easy digestibility and sustainability due to its renewable sourcing [8]. In sports nutrition, studies indicated that consuming sugarcane juice yields effects akin to commercial sports drinks, enhancing endurance performance, elevating blood glucose levels and facilitating hydration [8, 9]. Moreover, an analysis comparing the consumption of sugarcane juice with a commercial sports drink during intense exercise indicated that sugarcane juice was more effective in maintaining stable blood glucose levels by providing a steady release of natural sugars. This suggests it could be a preferable alternative to sports drinks as a rehydration tool, offering both quick energy replenishment and sustained glucose availability for prolonged physical activity [9]. However, while sugarcane juice contains beneficial minerals, its composition may still lack the balance found in commercial isotonic drinks formulated with precision nutrition. Nonetheless, it remains a viable alternative for rehydration when needed and is more sustainable.

Nevertheless, being a plant-based drink, it provides additional benefits of micronutrients and fibres such as hemicelluloses, soluble gums and pectins [10]. The presence of better health-compatible indigestible oligosaccharides, such as fructooligosaccharides, in sugarcane drinks may further contribute to beneficial soluble fibre for robust bifidogenic and glycemic index properties, promoting a healthier gut and overall well-being [11]. However, individual preferences and nutritional requirements should be considered and consulting healthcare professionals is advised before making any abrupt dietary changes.

Beyond carbohydrates, sugarcane juice contains essential proteins and amino acids important for metabolic processes. A recent study revealed that sugarcane is abundant in various amino acids, with concentrations reaching up to 781.61 mg·l^{-1}, where glutamate emerges as the predominant amino acid [12], while another publication showed that up to 16 amino acids are present [13]. These amino acids play important roles in the human body, including protein synthesis, tissue repair and nutrient absorption. A recent finding also suggested the presence of γ-aminobutyric acid (GABA), a biologically active non-proteinogenic amino acid significant for the human nervous system. Foods containing this functional compound are proposed to have therapeutic potential, such as reducing anxiety, improving mood and enhancing relaxation, due to GABA's role as a major inhibitory neurotransmitter in the central nervous system [14, 15]. However, this is still a debated topic and contrasting views exist in scientific literature regarding the extent and consistency of these effects. Further research is needed to validate these claims and clarify GABA's functional impact when consumed through dietary sources.

Regarding lipids, minimal to negligible quantities are present, but the presence of plant sterols and terpenoids (stigmasterol, sitosterol and campesterol) is prominent, which is common in plant-based juice beverages [16, 17]. Plant-based sterols help maintain cell membrane structure and have cholesterol-lowering, anti-inflammatory and arthritis-reducing properties [18], which bodes well as a health-promoting drink.

From a sports nutrition perspective, the mineral content of sugarcane juice is notably robust. In a recent study, it was found that the electrolytes or minerals (referred to as ergogenic) in a functional sugarcane drink can be comparable to or surpass the traditional isotonic beverages in the market [16]. Featuring a rich assortment of nutrients including ammonium, phosphorus, sulfur, potassium, magnesium, calcium, zinc, manganese, copper and iron, sugarcane juice serves as an effective hydration tool [19]. Importantly, it contains lower levels of undesirable sodium compared to many commonly consumed foods [19]. Sugarcane juice contains organic acids such as aconitic, malic, citric, succinic, oxalic, tartaric or glycolic acids, which enhance the availability of minerals like phosphorus, calcium and iron [20]. These acids contribute to breaking down complex minerals, making them more easily absorbed and utilised by the body. These organic acids also contribute to the titratable acidity of the juice, influencing its taste, antioxidative and nutritional value [10, 20]. Certain organic acids, like succinic, malic, and citric, can be important in enhancing energy and reducing muscle fatigue during strenuous exercise [20]. Moreover, the inclusion of energy-regulating vitamins in sugarcane juice, such as those in the vitamin B complex, and the antioxidative-repair properties of vitamins A, C and E, can significantly enhance the quality of exercise [19].

Sugarcane juice and its derivatives (brown sugar, molasses and jaggery) also contain abundant plant phenolic substances, including phenolic acids, flavonoids, anthocyanins and other glycosides [5, 17]. Compared to other plant juices such as pomegranate, cranberry or red grape juices, sugarcane juice has a significantly higher total phenolics content, establishing its superiority as a health-promoting plant-based beverage [10]. The bioactive compounds in sugarcane juice derived from flavonoids and cinnamic acids like apigenin, luteolin, tricin derivatives, caffeic acid, sinapic acid and chlorogenic acid isomers, contribute to its antioxidant and functional properties [17]. Flavones, such as naringenin, apigenin, tricin, tannins, anthocyanins, syringic acid or luteolin derivatives, are also abundant in sugarcane juice [21]. These natural antioxidants play a crucial role in various biological and pharmacological properties, including anti-inflammatory, anticancer, antimicrobial, antiallergic, antiviral, antithrombotic and hepatoprotective activities [22–24]. Antioxidants play a crucial role in sports drinks due to their ability to mitigate oxidative stress, which is heightened during intense physical activity. Additionally, sugarcane juice contains policosanol and octacosanol, unique compounds implicated in regulating blood lipid levels and improving exercise quality [10]. Altogether, these properties make it a better alternative to traditional commercial sports drinks that commonly contain only sugar, electrolytes and artificial additives [19]. Overall, the nutritional composition of sugarcane juice is demonstrated in Tab. 1.

Probiotics play a significant role in supporting overall health, particularly in maintaining a balanced gut microbiota, which is essential for digestion and immune function [25–27]. Sugarcane juice can serve as an excellent substrate for the growth of probiotics due to its high sugar and prebiotics content [23], though the presence of phenolic compounds may be a concern as they might inhibit the growth of certain lactic acid bacteria that can act as probiotics. Holkem et al. [28] demonstrated that microencapsulated *Bifidobacterium animalis* subsp. *lactis* BLC1 and cinnamon extract in sugarcane juice yielded a probiotic-rich drink with elevated bioactive compound concentrations, crucially preserving the viability of probiotic bacteria. Similarly, Santos et al. [29]

Tab. 1. General nutritional composition of sugarcane juice, adapted with modifications from Arif et al. [23].

Organic compounds	Level
Carbohydrates	
Saccharose	130–150 g·l^{-1}
Non-reducing sugar	100–210 g·l^{-1}
Reducing sugars	~3 g·l^{-1}
Fibre (oligo- and poly-saccharides)	100–150 g·l^{-1}
Amino acids	
Total	5–25 g·kg^{-1}
Aspartic acid	0.6 g·kg^{-1}
Glutamic acid	0.8 g·kg^{-1}
Alanine	0.5 g·kg^{-1}
Valine	0.4 g·kg^{-1}
Aminobutyric acid	0.3 g·kg^{-1}
Threonine	0.4 g·kg^{-1}
Isoleucine	0.3 g·kg^{-1}
Glycine	0.4 g·kg^{-1}
Others	< 0.3 g·kg^{-1}
Lipids [kg·l^{-1}]	
Plant sterol	0.5–1.5 g·l^{-1}
Vitamins	
Vitamins A, B, C, and D	Not mentioned
Minerals	
Potassium	7.7–13.1 g·l^{-1}
Sodium	0.1–0.4 g·l^{-1}
Calcium	2.4–4.8 g·l^{-1}
Magnesium	1.0–3.9 g·l^{-1}
Iron	0.06–0.40 g·l^{-1}
Aluminium	0.05–1.70 g·l^{-1}
Copper	0.02–0.03 g·l^{-1}
Zinc	0.03–0.12 g·l^{-1}
Cobalt	0.07 g·l^{-1}
Silicon	0.0007 g·l^{-1}
Chloride	0.16–1.01 g·l^{-1}
Phosphate	1.6–2.7 g·l^{-1}
Sulphate	1.4–4.0 g·l^{-1}

The content of amino acid is expressed per kilogram of dry solid. Note that these values serve as a general guide only, as their actual level can vary depending on the analytical methods used, species, geographical location and other influencing factors.

introduced *Lactobacillus casei* as probiotics in sugarcane juice, achieving excellent viability but altered sensory attributes. Adding probiotics not only enriches the microbial profile of sugarcane juice [30] but also enhances its nutritional quality. This addition can potentially reduce sugars and convert saccharose into prebiotics such as oligosaccharides [11, 14], while also outcompeting unwanted microorganisms through selective substrate utilisation [31, 32]. In a recent study by Kumari et al. [33], native probiotic bacteria were isolated from fermented sugarcane juice and their high survival rates were demonstrated.

Transforming sugarcane juice into a probiotic-rich drink involves selecting probiotic strains capable of thriving in its acidic, high-sugar environment while withstanding inhibitory compounds like phenolic acids. Ensuring pH balance and providing additional nutrients, such as vitamins and minerals, can further support the growth of probiotics. Furthermore, controlling processing conditions, such as temperature and oxygen levels, was found important for preserving the viability of probiotic bacteria during production and storage. Emerging technologies, such as microencapsulation and nanoencapsulation, are being increasingly utilized to enhance the stability and efficacy of probiotics in functional beverages [34].

Quality degradation

Sugarcane juice undergoes enzymatic and non-enzymatic browning processes, affecting its colour and appeal. Enzymatic browning occurs due to the activity of peroxidase and polyphenol oxidase, which are enzymes that are activated during juice extraction when exposed to oxygen. These processes collectively contribute to colour change during storage, which is a significant hurdle for commercialisation. The primary mechanism is the transformation of phenolic compounds to quinines, which undergo additional polymerisation to form melanins, an insoluble dark brown polymer [35, 36]. *o*-Benzoquinone, which is formed by browning enzymes, may then combine with the amino groups of a lysine residue in plant proteins and diminish protein lysine availability [37]. In addition to its detrimental effect on phenolic antioxidants, it is hypothesised that polyphenol oxidase also contributes to the oxidative destruction of ascorbic acid, which is aplenty in sugarcane juice, due to quinone-mediated linked oxidation [37].

The non-enzymatic browning of sugarcane juice occurs via two primary mechanisms: caramelisation and Maillard reaction. Caramelisation occurs when sugars are heated to high temperatures, causing them to break down and form new compounds that impart a brown colour and characteristic flavour to the juice [38]. The Maillard reaction, which involves the reaction between sugars and amino acids to form brown pigments and a complex mixture of flavour compounds, can occur even at ambient temperatures, albeit much slower than at higher temperatures. The mechanism of browning and flavour development in sugarcane juice depends on several factors, including the temperature and duration of heating, the concentration of sugars and amino acids, as well as the pH value of the juice. Specific metal ions like copper and iron can catalyse the non-enzymatic browning, resulting in darker colouration and more complex flavours [39]. Non-enzymatic browning of sugarcane juice is a standard process in producing various sugarcane-based products, including molasses, caramel and rum.

Moreover, postharvest processes invariably lead to saccharose losses, categorically falling into two significant stages: primary and secondary losses. Primary saccharose losses occur due to its inversion facilitated by enzymatic activities, often a consequence of delayed processing following sugarcane harvest. In contrast, secondary losses occur indirectly, giving rise to dextran, alcohol, organic acids and other substances, with the initial 14 h proving to be the most critical period responsible for 93 % of all microbe-related losses [10]. Enzymatic and acid degradation only contribute to 5.7 % and 1.3 % of losses, respectively. Secondary losses can further be classified into five major causes – biological and microbiological, chemical and biochemical, mechanical, physical and physiological, each playing a distinct role in the overall saccharose deterioration process [10].

Lactic acid bacteria, yeasts, filamentous fungi, *Xanthomonas* spp., *Aerobacter* spp., *Aeromonas* spp., *Pseudomonas* spp., *Bacillus* spp., *Escherichia coli* and other microorganisms are the common active contaminants during sugarcane juice processing [6]. Lactic acid bacteria, soil-borne and thrive in humid conditions, infiltrate sugarcane through cuts, causing saccharose metabolism. Notably, species like *Leuconotoc mesenteroides* and *Le. dextranicum* contributes to saccharose breakdown, yielding mannitol and organic acids, thus compromising juice quality. Their presence during harvesting and transportation reduces sugar recovery at mills by enhancing enzymatic activity, complicating processing. Similarly, contamination by *Xanthomonas* spp. occurs during plant growth, while *Aeromonas* spp. enters via contaminated water sources during processing, aligning with other common contaminants in sugarcane juice [6].

Processing and preservation

The manufacturing process begins with the harvesting of mature sugarcane, followed by cleaning, crushing, juice clarification and pasteurisation. Pasteurisation of fruit juices, although often skipped in traditional methods, is essential for reducing pathogens to safe levels for consumption as well as effectively inactivating polyphenol oxidase and peroxidase enzymes [40]. The heat denatures the protein structure of the enzyme, leading to a loss of its catalytic activity. Polyphenol oxidase's inactivation rate is much greater than of other enzymes under the same temperature conditions, such as peroxidase. However, although heat treatment is the most effective way to increase the shelf life, this method may reduce the quality of the juice due to the change in sensory, physico-chemical and nutritional properties [41, 42]. The use of low-temperature storage at 10 °C can extend the shelf life of raw sugarcane juice for more than a month [43, 44].

It is generally recommended to add preservatives before pasteurisation to ensure safety and effectiveness in extending the shelf life of sugarcane juice. However, the use of stabilisers or preservatives often presents a conflict with consumer preferences for reduced chemical additives in food products, aligning with the "clean label" movement, although it is proven safe in food products. Nevertheless, chemical preservatives are proven effective at reducing microbial and enzymatic deterioration. For example, the study by Mishra et al. [43] and Mansor et al. [16] found that sodium benzoate, sorbic acid and several other chemical preservatives were highly effective in prolonging the shelf-life of sugarcane juice. Kaavya et al. [45] also reported that ascorbic acid and potassium metabisulphite could preserve sugarcane juice, with potassium metabisulphite showing minimum changes in sensory qualities during storage. To minimise the amount while enhancing the effectiveness of the chemical preservatives, combinatory treatments with emerging techniques such as gamma radiation can be considered [43, 45]. Overall, although "culturally" undesirable, chemical preservatives may be the best approach in preserving sugarcane juice, due to their ability to suppress microbial growth, inhibit browning and oxidation reactions and stabilising the pH value while having little impact on the nutritional properties [16].

Recent innovations in processing focus increasingly on microbial and enzymatic inactivation, as well as on maximising juice yield and enhancing nutritional benefits [45]. The emerging methods for preserving sugarcane juice include microwave processing, membrane processing, high-pressure processing, spray-drying, pulsed electric field treatment, cold plasma, nanocomposite packaging films and ozonation (Tab. 2 [2, 36, 41, 46–71]). Arguably, some of these methods still generate a substantial amount of heat (such as microwaves), often at the expense of faster or greater efficiency compared to conventional heating methods.

Microwave treatment was shown to enhance the antioxidant activity of sugarcane juice. Studies demonstrated that microwave treatment, alone

Tab. 2. Preservation techniques for sugarcane juice.

Parameters of preservation technique	Findings	Ref.
Microwave processing		
30 W, 50 W, 80 W and 100 W for 15 min	Microwave processing at 100 W power for 15 min, achieves concentrated sugarcane juice at 750 $kg\cdot m^{-3}$ with 1.3 times less energy consumption compared to other power levels, while retaining sensory properties and antioxidant activity.	[46]
120 W, 400 W and 700 W for 5 min	120 W completely reduced microbial loads, preserved total phenolics concentration (3.53 $g\cdot l^{-1}$), maintained antioxidant activity (21.6 % inhibition of radical-scavenging activity), and minimised colour changes (colour difference ΔE of 4.76).	[47]
Thermosonication (20 kHz, 70% amplitude, 5 min, 10 min, 15 min) and microwave (90 °C, 400 W, 120 s)	Sonication of sugarcane juice blend at 15 min, 70% amplitude and 20 kHz frequency, combined with 120 s of microwave heating at 90 °C and 400 W, resulted in the highest retention of total phenolics content, total flavonoids content and antioxidant activity during 90 days of storage.	[48]
Spray-drying		
Presence of citric acid, 10–50 % of carriers (maltodextrin, arabic gum, liquid glucose, carrot fibre), varying operating conditions of inlet and outlet temperature and feed concentration	Maltodextrin (30 %), inlet air temperature of 150 °C, outlet temperature of 100 °C and 14 % total soluble solids, yielded the best sensory properties and product yield, with spray-dried powder without citric acid exhibiting superior porosity, flowability and reconstitution properties.	[49]
300 $kg\cdot m^{-3}$, and 500 $kg\cdot m^{-3}$ different carriers (maltodextrin, arabic gum and dietary fibre), temperature (130–170 °C)	The concentration of sugarcane juice at 300 $kg\cdot m^{-3}$, addition of minimum 15 % maltodextrin and temperature at 170 °C, resulting in an effective energy cost of 0.77–2.06 USD per kilogram of powdered sugarcane juice.	[50]
Inlet air temperature (130–180 °C), outlet air temperature (75–90 °C), atomizer disk speed (2 199.11–2 722.71 $m\cdot s^{-1}$), and whey protein concentration contribution in the feed (40–90 %)	Optimal conditions: Inlet temperature of 130 °C, outlet temperature of 88 °C, atomizer disk speed of 2 199.11 $m\cdot s^{-1}$, and 78.8 % whey protein. These conditions resulted in effective yield of 80.1 %, powder moisture content of 4.3 %, water activity of 0.2014, solubility of 91.6 % and bulk density of 0.44 $kg\cdot l^{-1}$.	[51]
8–14 % maltodextrin, 150–170 °C inlet temperature	Parameters at inlet temperature of 170 °C, outlet temperature of 75 °C, feed rate of 2.33×10^{-7} $m^3\cdot s^{-1}$ and 12 % maltodextrin led to good sensorial properties and storability.	[52]
Pulsed electric field		
Field strengths (30 $kV\cdot cm^{-1}$ and 50 $kV\cdot cm^{-1}$), pulse numbers (150, 300), temperature (4 °C, 31 °C), ginger and lemon addition	30 $kV\cdot cm^{-1}$ and 150 pulses showed stability after 30 days. Sugarcane juice with added lemon and ginger at 20 $kV\cdot cm^{-1}$ and 150 pulses extended the shelf life to 14 days, maintaining sensory attributes and achieving enhanced microbial reduction.	[53]
220 V and 110 V	The optimal parameters for the laboratory-scale pulsed electric field pasteurisation equipment are 110 V voltage, achieving a 1.42-log reduction of microorganisms in non-sterilised Czapek medium after 30 s of treatment at temperatures below 60 °C and a 1.2-log reduction of native microorganisms in fresh sugarcane juice.	[54]
Sonication		
40 kHz, power 240 W, 10–40 min	Increased phenolic (18 %) and flavonoid (16 %) compounds, preserved pH and colour decreased viscosity and decreased microorganisms.	[41]
90 °C for 5–15 min, sonication for 30 min at 40 °C or 60 °C	Sonication preserved sugar content but changed colour (became darker) and reduced microbial load to zero.	[2]
10–50 °C in different systems (saline, nutrient broth, and sterilised sugarcane juice)	Thermosonication at 50 °C resulted in a significantly higher reduction of viable bacteria, achieving a 5-log reduction faster than sonication alone.	[55]
Nanocomposite films		
Various compositions of nanoclay, compatibiliser and thickness using polypropylene and polyethylene	Optimal parameters for storing sugarcane juice in nanocomposite films are 100 μm thickness, composed of 93 % linear low-density polyethylene, 5 % compatibilizer and 2 % nanoclay, which provides superior shelf life, minimal quality changes and the least microbial population.	[56]
Ozonation		
Ozone (2×10^{-3} $kg\cdot m^{-3}$ to 6×10^{-3} $kg\cdot m^{-3}$), gas flow rate (4–8 $l\cdot min^{-1}$), exposure time (5–12 min)	Optimal parameters for ozone treatment of ultrafiltered sugarcane juice, based on browning, are gas flow rate of 4.58 $l\cdot min^{-1}$, ozone concentration of 3.12×10^{-3} $kg\cdot m^{-3}$ and exposure time of 8.2 min.	[57]

Tab. 2. *continued*

Parameters of preservation technique	Findings	Ref.
3.33 × 10^{-7} kg·s^{-1} of ozone for 10 min, lactic acid (1–10 g·l^{-1})	Optimal parameters for preserving pasteurised sugarcane juice are ozone at 3.33 × 10^{-7} kg·s^{-1} for 10 min and lactic acid at 5 g·l^{-1}, which reduced the total bacterial counts by 4.3-log, reduced polyphenol oxidase by 60 % and peroxidases by 72 %.	[58]
Ohmic heating		
Various fractions of sugarcane juice (liquid, solid, or concentrated), ohmic heating (75 °C and 7.8 V·cm^{-1} for 25 min)	Optimal parameters for ohmic heating to inactivate peroxidase in sugarcane juice are 75 °C and 7.8 V·cm^{-1} for 25 min, achieving 78% inactivation in the liquid fraction and 100% inactivation in the solid fraction.	[59]
Electric field strengths (2 400, 3 200, 4 800 V·m^{-1}) and holding times (0.25, 0.50, 0.75, 1.0, 1.25 min) at a temperature of 80 °C	3 200 V·m^{-1} and 1 min holding time inactivated polyphenol oxidase, growth of yeasts and filamentous fungi, reduced *Leuconostoc mesenteroides* growth and extended sugarcane juice shelf-life by up to 25 days, retaining physico-chemical properties.	[60]
High hydrostatic pressure		
300–600 MPa, 1 s to 25 min	Lowered microbial counts with increasing pressure and treatment time following first-order kinetics, with 600 MPa for 20 min inactivates vegetative microorganisms with minimal changes in physico-chemical properties. Coliforms are the most sensitive while aerobic mesophiles are less sensitive.	[61]
300 MPa, 3 min or 5 min	300 MPa for 5 min effectively retains physico-chemical properties (total soluble solids, pH, and colour) and increases antioxidants content (phenolics and flavonoids).	[36]
300–500 MPa, 40–60 °C, 10–20 min	400 MPa, 30 °C, and 15 min resulted in a 17% increase in ascorbic acid content with inactivation of polyphenol oxidase (79 %) and peroxidases (72 %) enzymes.	[62]
523 MPa, 50 °C, and 11 min, compared to conventionally pasteurised sugarcane juice	Retained colour, antioxidants and phenolics content better than thermal treatment. Shelf-life at 25 °C estimated to be 25 days based on sensory qualities, ascorbic acid retention and colour difference.	[63]
200–600 MPa for 6 min at 20 °C	600 MPa for 6 min significantly reduced bacterial and yeast counts. By day 28 of storage, high hydrostatic pressure-treated juice showed no significant differences in acidity, pH or soluble solids compared to fresh juice.	[64]
300–600 MPa, 30–60 °C, 10–25 min	Optimal parameters for maximum polyphenol oxidase inactivation (98 %) in sugarcane juice are 600 MPa, 60 °C and 25 min. Isothermal inactivation of polyphenol oxidase followed first order kinetic, but introduction of pressure led to deviation from log linear kinetics.	[65]
Membrane processing		
Multiple parameters – type of membrane, pore size, permeabilty range, pressure range	Membrane processing techniques, such as microfiltration, ultrafiltration, nanofiltration or reverse osmosis, effectively clarify, concentrate and purify the juice while preserving its sensory and nutritional qualities.	[66]
Hollow spiral wound ultrafiltration membrane with a 10 kDa pore size at 0.1 MPa pressure as pretreatment. Pulsed electric field parameters included field strengths of 20 kV·cm^{-1}, 30 kV·cm^{-1} and 40 kV·cm^{-1}, with pulse widths of 100 μs, 150 μs and 200 μs	Membrane-assisted pulsed electric field technology extends the shelf-life of sugarcane juice by reducing enzyme activity and microbial counts. The treatment achieved a 92% reduction in polyphenol oxidase, 80% in peroxidase and 3-log microbial reduction, while preserving ascorbic acid content and enhancing antioxidant capacity.	[67]
Polysulphone-based hollow fibre membrane with a 30 kDa molecular weight cut-off, at 10 MPa transmembrane pressure and a 30 l·h^{-1} cross-flow rate	Ultrafiltration of sugarcane juice using a 30 kDa polysulphone-based hollow fibre membrane achieved 98% saccharose and 80% polyphenols recovery, with significant reduction of enzymes and bacterial counts. The clarified juice remained stable for up to 9 weeks at 4 °C, indicating enhanced shelf-life and improved product quality.	[68]
Varying concentrations (0.25 %, 0.5 %, 1 %) of polypyrrole-chitosan into the polysulfone matrix	Polysulfone-based hollow fibre membrane modified with polypyrrole-chitosan composite demonstrated improved properties, achieving 71.2% reduction of polyphenol oxidase and 5.4-log reduction of bacteria, with superior antifouling capabilities.	[69]
30 kDa polysulphone-based hollow fibre with 10 MPa transmembrane pressure at 30 l·h^{-1} cross flow rate.	A combination of ultrafiltration and ozone treatment effectively inactivated key enzymes, bacteria and filamentous fungi, while preserving flavonoids. Storage tests confirmed microbiological stability for up to 90 days.	[70]

[47] or in combination with sonication [48], increases the levels of phenolics and flavonoids, which are known to scavenge free radicals and provide antioxidant properties. However, the heat generated during microwaving poses a challenge, as it can lead to the loss of certain nutritional characteristics of sugarcane juice, particularly heat-sensitive organic compounds like vitamins. Microwaving may also alter certain sensory properties such as colour due to caramelisation and browning, impacting the overall sensory properties of the juice [47]. Flavour profiles may shift due to the breakdown of certain compounds and uneven heating can leave some microorganisms alive, affecting the microbiological safety of the juice [47].

Another thermal technique that has shown effectiveness in sugarcane juice preservation is spray-drying. This method might be the most effective for extending the shelf-life due to the significant reduction of moisture content. Most of the research on sugarcane juice preservation using spray-drying focuses on finding the most effective parameters such as inlet and outlet temperature, as well as the type of carrier [72]. However, the addition of carriers and the process may alter the sensorial and physico-chemical properties. Therefore, many studies were undertaken with spray-drying to improve the reconstitution, flowability and sensorial properties of sugarcane juice [49, 52, 72]. One of the most commonly used carrier agents in the spray drying of sugarcane juice is maltodextrin, due to its versatility and suitability for a wide range of juice-based products [49, 73]. However, the addition of citric acid negatively affected the powder reconstitution and morphology [43]. In a different study, microencapsulation using orthophosphoric acid achieved stable powder with similar sensory qualities to fresh sugarcane juice, enhancing its market potential and shelf life [52].

Sonication is a technique that leverages powerful sound waves to manipulate liquids. Unlike traditional thermal techniques, which can compromise the juice's nutritional and sensory aspects, sonication has proven effective in maintaining quality while minimising colour alterations and preserving its physico-chemical properties, with little heat generation. However, the treatment tends to be less effective than other emerging techniques in extending the shelf life of sugarcane juice [2]. As a result, sonication of sugarcane juice is often combined with other techniques to enhance efficiency, such as with heat [41, 48, 55] or microwave technology [47, 48].

The high oxidizing potential of ozone, compared to chlorine and oxygen, provides a potent antimicrobial activity. It rapidly decomposes into oxygen, leaving no harmful residues, and is generally recognized as safe in the food industry [57, 58]. Although promising for juice disinfection, ozone treatment faces challenges like reduced efficiency in the presence of suspended solids [57]. Combining ozone with other hurdles could enhance its preservation effects [58], indicating a need for further research to optimize its use in sugarcane juice preservation and extend its potential in commercial applications.

Ohmic heating, another innovative thermal treatment, is a promising food processing technology for sugarcane juice, yet still very much in the infancy stage. In conventional heating processes, uneven thermal distribution due to internal resistance often leads to additional thermal deterioration in the quality of food products. At ohmic heating, alternating electric current coupled with the resistance of the food causes the generation of heat. This leads to the inactivation of microorganisms and enzymes in liquid foods such as sugarcane juice [59]. The electrical field during ohmic heating influences biochemical reactions by changing the molecular spacing and increasing inter-chain reactions in enzymes, while also causing electroporation in microbial cell membranes [67]. In a study by Brochier et al. [59], the effects of moderate electric field strengths associated with ohmic heating on peroxidase inactivation in various fractions of sugarcane juice were examined. Ohmic heating caused higher inactivation of enzymes compared to conventional heating across solid, liquid and concentrated juice fractions, suggesting that thermal effects influenced enzyme conformation, particularly in low-sugar environments. The mechanism remains incompletely understood, possibly involving the prosthetic centre of the enzyme-containing metal ions. Commercial peroxidase experiments similarly demonstrated ohmic heating as efficient, with saccharose addition enhancing enzyme stability and thus reducing the effectiveness of the process, which was particularly noted in the liquid fraction of sugarcane juice [59].

Other emerging methods at low temperatures (below 60 °C), such as high-pressure processing and nanocomposite film packaging, showed effectiveness in reducing microbial activity and enhancing sugarcane juice safety and quality [56, 61]. However, it is important to note that these techniques require specialised expertise for implementation and involve significant capital investments, which may limit their widespread adoption [74, 75]. Another interesting low-temperature

Tab. 3. Overview of emerging techniques in preserving plant-based juices [74-77].

Technique	Advantages	Disadvantages	Setup	Relevant Information
Microwave heating	Uniform heating, rapid process, energy-efficient	Possible uneven heating, high initial cost	Requires specialised microwave equipment	Effective for microbial reduction and enzyme inactivation, suitable for juices containing water and ionic salts
Ohmic heating	Uniform and rapid heating, energy-efficient, environmentally friendly, low capital cost	Limited to products with sufficient electrical conductivity	Requires electrical current and electrodes	97 % of electrical energy is converted to heat, maintains nutritional and sensory properties
Pulsed electric field	Maintains fresh-like qualities, effective microbial inactivation	Requires precise control of electrical parameters, potential for temperature rise	High-voltage pulse generator and treatment chamber	Induces electroporation in microbial membranes, effective in maintaining nutritional and sensory attributes
High-pressure processing	Preserves nutritional quality, effective microbial inactivation, non-thermal	High equipment cost, potential for mild temperature rise during compression	High-pressure vessel and pump	Uses hydrostatic pressure, minimal impact on flavour and nutrients
Ultraviolet light	Easy to use, effective at low cost, non-thermal	Limited penetration depth, potential for uneven treatment	UV lamps, power supply, treatment chamber	Effective for surface microbial inactivation. UV-C (254 nm) is most effective
Pulsed light	Microbial inactivation, short treatment time	High energy consumption, potential for uneven treatment	High-energy capacitors and flash lamps	Uses intense light flashes, effective due to photochemical, photothermal and photophysical effects
Sonication (high-intensity ultrasound)	Effective microbial inactivation, preserves sensory and nutritional qualities	Limited penetration, potential for equipment wear and tear	Ultrasound generator, transducers, and probes	Utilizes mechanical vibrations, effective for liquid foods
Pressure change technology	Effective microbial inactivation, minimal impact on enzymes and nutrients	Requires precise pressure control, high equipment cost	High-pressure pump, inert gas mixing, relief valve	Utilizes dynamic decompression with inert gases
Supercritical carbon dioxide	Effective microbial and enzyme inactivation, preserves sensory and nutritional qualities	High equipment cost, specific processing conditions required	CO_2 tank, pressure vessel, temperature control system	Uses CO_2 in a supercritical state, effective at low temperatures and moderate pressures, suitable for various juices, limited adoption in the food industry
Ozonation	Non-residual nature, high oxidation potential, effective at low temperatures, maintains the nutritional quality of produce	Instability in water with ozone-resistant molecules, high production cost, negative consumer perception, and need for optimized dosage	Ozone generators, reaction chambers, UV light or high-voltage electrical discharge for production, temperature control units	Capable of reducing enzyme activity (polyphenol oxidase), without significant impact on food flavour or texture
Cold plasma	Non-thermal process, effective enzyme inactivation, minimal impact on nutritional properties, eco-friendly	Limited to surface inactivation, possible reduction of firmness, increased acidity, potential lipid oxidation, expensive setup	Atmospheric pressure plasma jet, dielectric barrier discharge (DBD), microwave-driven systems, voltage and frequency controls	Suitable for surface decontamination, generates reactive oxygen species, requires careful control of gas composition and plasma exposure time
Membrane processing	Low energy consumption, minimal heat damage	Membrane fouling, lower permeate flux over time	Can involve multiple setups of ultrafiltration, nanofiltration or reverse osmosis systems, with various choices of membrane types	Highly efficient in energy consumption although the initial setup is expensive

emerging technique, dense phase carbon dioxide or supercritical carbon dioxide (SC-CO_2), utilises CO_2 at low temperatures (20–50 °C) and moderate pressures (below 50 MPa) for 5–30 min to inactivate microorganisms. While this technology showed effectiveness in preserving various juices, research on its impact on shelf-life, sensory properties and consumer acceptance is still in its infancy, and it has yet to gain widespread attention in the food industry [75].

Membrane processing techniques like ultrafiltration, microfiltration and nanofiltration were also extensively studied for refining sugarcane juice, offering benefits such as enhanced clarity, reduced viscosity and minimized use of chemicals while preserving its nutritional value [66]. Innovative approaches combining membrane technology with advanced techniques showed significant promise. Membrane-assisted pulsed electric field achieved a 92% reduction in polyphenol oxidase, 80% in peroxidase and a 3-log reduction in microbial counts, extending sugarcane juice shelf life while enhancing antioxidant properties [68]. Ultrafiltration with a 30 kDa polysulphone-based hollow fibre membrane delivered 98% recovery of saccharose, 80% of polyphenols and microbiological stability for up to 9 weeks at 4 °C [69]. A modified polysulfone membrane demonstrated superior antifouling and antibacterial performance, achieving a 5.4-log bacterial reduction [70]. Additionally, combining ultrafiltration with ozone treatment effectively inactivated enzymes, bacteria and filamentous fungi, while preserving key flavonoids, ensuring microbiological stability for up to 90 days [71]. Nevertheless, most research on membrane processing focused on optimizing engineering parameters and physico-chemical properties rather than on microbiological quality or shelf-life extension [74].

Consideration in the application of emerging technologies for sugarcane juice preservation

In evaluating various food processing technologies for the preservation and treatment of sugarcane juice, it becomes clear that energy efficiency, cost-effectiveness and product quality are key determinants of the optimal method (Tab. 3 [74–76]). Conventional indirect thermal treatment and microwave heating have the highest energy demands and operational costs, especially when heat recovery systems are not integrated. This often results in significant nutrient degradation, compromising the juice's quality [76]. Concurrently, emerging non-thermal technologies such as ultraviolet light, pulsed light and pressure-based methods are being actively explored as potential alternatives that may help preserve the nutritional and sensory qualities of sugarcane juice while offering more processing options. High-pressure processing, pulsed electric fields and supercritical carbon dioxide are recognized for their superior capabilities in microbial inactivation and preservation of nutritional and sensory qualities. Despite their effectiveness, these technologies come with higher energy consumption and complex equipment requirements, making them less cost-effective for large-scale operations [75, 76].

Membrane processing technologies, such as ultrafiltration and nanofiltration, have gained attention for their ability to clarify and stabilize sugarcane juice while maintaining its natural colour, flavour and nutritional content. Membrane systems like polymeric and ceramic membranes are highly efficient in removing suspended solids, reducing microbial load, and decreasing enzyme activity, leading to an extended shelf life [68–71]. They are advantageous due to their continuous processing capabilities, low energy consumption, and reduced need for chemical additives. However, membrane fouling and the initial setup cost of advanced filtration systems can be limiting factors in their widespread adoption [74].

Adding to this landscape, ozone and cold plasma technologies showed promising results in the preservation of sugarcane juice. Ozone effectively inactivates pathogens and enzymes in sugarcane juice without leaving harmful residues, though its instability in water and need for precise dosage control are limitations [77]. Cold plasma technology effectively inactivates microbes and enzymes in sugarcane juice while preserving its quality, but its surface-specific action and higher operational costs are notable drawbacks [77].

CONCLUSIONS

Sugarcane juice is a nutritious and aromatic plant-based drink that offers essential vitamins and minerals for overall health. To counter its rapid deterioration, adopting economic hurdle technologies is vital for maintaining freshness. Particularly beneficial for active individuals, sugarcane juice provides a natural energy boost due to its high sugar content, making it a suitable alternative to commercial energy drinks especially when consumed in appropriate amounts to support energy needs without excess sugar intake. Beyond its health effects, sugarcane is a sustainable and renewable resource, while by-products like bagasse can be used as biofuel, promoting environmental sustainability. Employing green preservation techniques, such as high-pressure processing or pulsed electric fields, can effectively extend the shelf life of sugarcane juice without compromising its nutritional value or sensory properties. These emerging methods utilise minimal heat and are environmentally friendly processes, ensuring the freshness and integrity of the product while aligning with sustainable practices.

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