

Research Article

Cactus Pear Juice as a Functional Beverage: Current Knowledge, Technological Developments, and Future Directions

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Abstract

Cactus pear (*Opuntia* spp.) is a drought-resistant fruit widely grown in arid and semi-arid regions of Africa, Latin America, and the Mediterranean. In recent years, cactus pear juice has gained growing interest in the food and nutraceutical sectors because of its high nutritional value, functional bioactive compounds, and potential health benefits. This narrative review summarizes the current scientific knowledge on cactus pear juice, including its nutritional composition, antioxidant properties, processing potential, and technological constraints. The review highlights factors affecting juice quality such as variety, maturity stage, extraction method, filtration, pasteurization, and storage conditions. Comparative studies show that cactus pear juice is rich in betalains, phenolic compounds, vitamins, and minerals, and demonstrates promising antioxidant, anti-inflammatory, and anti-diabetic properties. However, challenges remain related to its mucilage content, enzymatic instability, rapid color degradation, and microbial sensitivity during storage. The review identifies opportunities for industrial exploitation, especially in health beverages, functional food formulations, and value-added products for regions with limited water resources. Future research should focus on improving processing stability, optimizing extraction technologies, validating clinical health benefits, and developing standards for commercialization and quality control. Overall, cactus pear juice shows potential as a sustainable and high-value functional beverage, particularly for countries seeking to diversify their agro-food sectors and reduce post-harvest losses.

Keywords

Cactus Pear Juice, *Opuntia* Spp, Functional Beverage, Antioxidants, Nutritional Composition, Processing Technology, Food Innovation

1. Introduction

Cactus pear (*Opuntia* spp.), also known as prickly pear, is a fruit belonging to the Cactaceae family and is widely cultivated in arid and semi-arid regions across Africa, the Middle East, Latin America, and the Mediterranean basin [1]. The plant is recognized for its exceptional resistance to drought

and ability to grow in degraded soils where other crops cannot survive, making it a strategic agricultural resource for food security and climate resilience [2]. In many producing regions, cactus pear fruit is consumed fresh or processed into juices, jams, syrups, alcoholic beverages, and traditional medicinal

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products [3]. However, despite its availability and cultural importance, large quantities of the fruit remain underutilized or wasted, mainly due to its short post-harvest shelf-life, lack of efficient processing systems, and limited industrial valorization [4].

In recent years, growing scientific interest has focused on cactus pear juice because of its nutritional richness and potential health-promoting properties [5]. Several studies have reported that cactus pear juice contains significant levels of natural pigments such as betalains, as well as phenolic compounds, dietary fiber, vitamins (particularly vitamin C), and essential minerals including calcium, magnesium, and potassium [6]. These components are associated with antioxidant, anti-inflammatory, hypoglycemic, and anti-cancer effects, which support its classification as a functional beverage [7]. The increasing global demand for natural plant-based nutraceuticals and healthy beverages has positioned cactus pear juice as a promising candidate for the functional food and wellness markets [8].

Despite its potential, the industrial development of cactus pear juice faces technical challenges. The fruit contains high levels of mucilage, pectin, and seeds, which complicate extraction, clarification, and filtration during processing [9]. Furthermore, betalains, responsible for the vivid red, purple, or yellow color of the juice, are sensitive to temperature, oxygen, and light, leading to instability during pasteurization and storage [10]. Microbial spoilage, enzymatic browning, and phase separation further limit shelf stability [11]. These constraints require specific processing and stabilization strategies such as enzymatic treatment, controlled thermal processing, membrane filtration, or novel methods like high-pressure processing and pulsed electric fields to preserve juice quality [12].

Beyond technological aspects, market development and industrial adoption remain limited in many producing countries, particularly in Africa where cactus resources are abundant but processing capacity remains low [13]. However, there is increasing interest from both researchers and industry in exploring cactus pear juice as a value-added product that could support rural economies, reduce post-harvest losses, and contribute to agricultural diversification and climate adaptation strategies [14]. With appropriate processing technologies, quality standards, and market positioning, cactus pear juice could represent an opportunity for small and medium agro-food enterprises, especially in regions where the fruit is historically cultivated.

This review aims to summarize current scientific knowledge on cactus pear juice, focusing on its nutritional composition, bioactive compounds, technological processing considerations, product stability, and industrial potential. The review also highlights identified challenges and opportunities for scaling production, including research needs, innovative processing technologies, and future perspectives for commercialization. By synthesizing recent advances, this article provides a foundation for scientists, processors, and deci-

sion-makers interested in advancing cactus pear juice from a traditionally consumed product to an industrially viable functional beverage.

2. Nutritional Composition of Cactus Pear Juice

Cactus pear juice is recognized for its rich nutritional composition, which varies depending on the species, ripening stage, cultivation conditions, and processing method [15]. In general, the juice has a relatively high moisture content, typically above 85%, making it a refreshing low-energy beverage compared to many commercial fruit juices. Its caloric value primarily derives from natural sugars, predominantly glucose and fructose, which contribute to sweetness and sensory acceptance [16]. Compared with other tropical fruits, cactus pear tends to have a moderate sugar content, making it suitable for both direct consumption and formulation into reduced-sugar or functional beverages.

The juice also contains significant amounts of dietary fiber, particularly soluble fiber such as mucilage and pectin [16]. These polysaccharides contribute to the characteristic viscosity of the juice and have been associated with potential physiological benefits, including improved gut motility, cholesterol reduction, and modulation of glycemic response [17]. However, the same polysaccharide fraction may present technological challenges during processing due to difficulty in filtration, clarification, and stabilization [12].

Cactus pear juice is also a source of essential vitamins, particularly vitamin C, which contributes to antioxidant capacity and supports immune function [18]. Although vitamin content varies with storage and processing, fresh juice generally retains noteworthy levels [19]. Small amounts of vitamin E and several B-complex vitamins have also been reported in some studies, though their concentrations tend to be lower than in fruits such as citrus or guava [18].

From a mineral perspective, cactus pear juice contains notable levels of calcium, magnesium, and potassium, with potassium being the most abundant [20]. These minerals contribute to electrolyte balance, muscle function, and cardiovascular health and may support the positioning of the juice as a natural hydration beverage. Trace elements such as manganese and iron may also be present, though in varying concentrations depending on soil composition and environmental factors [21].

One of the distinguishing features of cactus pear juice is its content of bioactive compounds, particularly betalains, which include betacyanins and betaxanthins. These pigments contribute to the vivid red, purple, or yellow coloration of the juice and are responsible for much of its antioxidant capacity. In addition to betalains, cactus pear juice contains phenolic compounds such as flavonoids and phenolic acids, which further contribute to antioxidant activity and may provide additional functional health benefits.

Organic acids, including citric and malic acid, are also present, influencing both flavor and stability [22]. The pH of cactus pear juice is generally within a mildly acidic range, though typically less acidic than citrus fruits [23]. This moderate acidity may influence microbial stability and processing requirements, including pasteurization conditions necessary for shelf-life extension.

Overall, the nutritional composition of cactus pear juice indicates that it is a promising functional beverage rich in natural antioxidants, essential minerals, soluble dietary fiber, and health-relevant phytochemicals. These attributes support its potential use not only as a refreshing drink but also as a base ingredient in wellness and nutraceutical products. However, variability in nutritional content due to processing conditions and raw material differences highlights the importance of standardization and quality control for future industrial development [19].

3. Bioactive Compounds and Functional Properties

Cactus pear juice contains a wide range of bioactive compounds that contribute to its potential health benefits. These include betalains, phenolic compounds, flavonoids, carotenoids, and antioxidant vitamins, which work synergistically to support physiological functions and reduce oxidative stress [24]. Among these compounds, betalains are particularly noteworthy due to their strong antioxidant activity and their role in the vibrant natural coloration of the juice. Betacyanins (responsible for red-purple hues) and betaxanthins (yellow-orange tones) have demonstrated free radical scavenging capacity and potential anti-inflammatory effects in both in vitro and preliminary in vivo research [25].

The antioxidant properties of cactus pear juice have attracted growing interest because oxidative stress is associated with a wide range of chronic diseases including diabetes, cardiovascular disorders, metabolic syndrome, and certain neurodegenerative conditions [26]. Several studies report that consuming cactus pear juice or extracts may help reduce markers of oxidative damage by increasing endogenous antioxidant defenses or by directly neutralizing reactive oxygen species [27]. This antioxidant effect may be partly attributed to vitamin C and phenolic compounds, which are present in measurable quantities in the juice and remain active even after moderate processing.

Another important functional characteristic of cactus pear juice relates to its potential anti-inflammatory effects. Some bioactive compounds, particularly betalains and flavonoids, have shown the ability to modulate inflammatory pathways by reducing pro-inflammatory cytokines and inhibiting oxidative inflammatory cascades [28]. Preliminary research suggests that regular consumption of cactus pear juice may support immune regulation and reduce low-grade chronic inflammation, which is a contributing factor to metabolic and cardio-

vascular disease progression [29].

The juice has also been studied for its potential role in glucose regulation and diabetes management [30]. Soluble dietary fiber, including mucilage and pectin, may help slow carbohydrate absorption and improve postprandial glycemic responses. Additionally, certain phenolic compounds found in cactus pear have demonstrated potential to influence insulin sensitivity and glucose metabolism in experimental models [30]. Although more clinical research is needed, these findings suggest cactus pear juice may support dietary strategies for glycemic control.

Cardiovascular health benefits have also been proposed based on the juice's mineral composition and bioactive content. The high potassium level may support blood pressure regulation, while antioxidants help reduce lipid oxidation, an important mechanism linked to atherosclerosis and heart disease. Some studies also suggest the juice may help improve lipid profiles by lowering LDL levels and reducing oxidative stress in vascular tissue [31].

Cactus pear juice may furthermore play a role in gastrointestinal health. Its soluble fiber fraction supports digestive function by promoting beneficial intestinal microbiota and improving stool consistency. The fiber also contributes to satiety and may assist in weight management when incorporated into a balanced diet. Additionally, some bioactive compounds possess mild antimicrobial activity against certain foodborne pathogens, although this effect varies depending on concentration and juice processing conditions [32].

Overall, the bioactive composition of cactus pear juice supports its classification as a functional food with potential antioxidant, anti-inflammatory, glycemic control, cardiovascular, and digestive health benefits [33]. While experimental and preliminary clinical findings are promising, further human studies are needed to validate dosage, bioavailability, and long-term health effects. Nevertheless, the existing evidence indicates that cactus pear juice could serve as a nutritionally valuable beverage and a natural ingredient for wellness-oriented food formulations [34].

4. Processing Technologies and Factors Affecting Quality and Stability

Processing cactus pear juice presents both opportunities and challenges due to the unique physical and biochemical characteristics of the fruit. The production process typically involves several stages including washing, peeling, pulping, filtration or clarification, pasteurization, and packaging. Each stage influences juice quality, nutritional content, stability, and suitability for industrial-scale production. Because cactus pear contains high levels of mucilage, seeds, and thermolabile pigments such as betalains, processing requires careful optimization to balance efficiency with product integrity.

Extraction is one of the most critical steps in processing cactus pear juice. Mechanical extraction methods such as cold

pressing or pulping are commonly used; however, the presence of seeds and mucilage can clog equipment and reduce efficiency [35]. To improve extraction yield and manage viscosity, some processors use pre-treatment methods such as mechanical deseeding, blanching, or enzymatic liquefaction with pectinases and cellulases. Enzyme-assisted extraction has been shown to enhance juice yield, reduce viscosity, and improve clarity without significant loss of nutritional compounds, making it a promising strategy for industrial adoption [12].

Clarification and filtration represent another major challenge due to the juice's natural thickness. Different technologies, including simple sieving, centrifugation, microfiltration, ultrafiltration, and membrane processing, may be used to achieve a stable and visually acceptable product [36]. While membrane filtration can produce a clearer juice with improved shelf stability, it may also remove some valuable antioxidant compounds bound to fiber. Therefore, clarification level must be determined based on the intended product: a clear beverage resembling fruit nectar or a thicker juice more aligned with functional or wellness-focused formulations [37].

Thermal processing is commonly applied to ensure microbial safety and extend shelf life. Pasteurization parameters vary depending on desired retention of color, flavor, and antioxidant compounds. Betalains are heat-sensitive, and excessive thermal exposure can result in pigment degradation, browning, and loss of antioxidant capacity [38]. Mild pasteurization, high-temperature short-time (HTST) treatment, and alternative non-thermal methods such as high-pressure processing (HPP) have been explored to mitigate these effects. HPP, although more costly, is particularly promising because it can inactivate microbes and enzymes while better preserving nutritional properties and sensory attributes [39].

Storage stability depends on several factors including temperature, oxygen exposure, packaging material, and initial composition [40]. Color degradation, associated with betalain breakdown, is one of the most visible quality changes during storage. Exposure to light, oxygen, and elevated temperatures accelerates pigment degradation, resulting in discoloration and reduced consumer appeal [41]. Use of oxygen-barrier packaging, controlled storage environments, and antioxidants such as ascorbic acid can help maintain product stability. Refrigerated storage generally provides better quality retention, although shelf-stable formulations are possible with optimized processing.

Flavor stability is another consideration. Cactus pear juice has a mild taste that can be influenced by processing conditions. Excessive heat treatment or prolonged storage may lead to flavor deterioration or development of off-notes associated with oxidation. Formulation strategies such as blending with other fruit juices, adding natural flavors, or incorporating functional ingredients may help enhance sensory acceptance while maintaining the unique identity of cactus pear.

From an industrial perspective, processing feasibility de-

pends not only on technological considerations but also on cost, equipment availability, and local expertise. Small and medium enterprises may face constraints in implementing advanced technologies such as membrane filtration or HPP [42]. Therefore, scalable and cost-effective solutions, including optimized extraction, controlled pasteurization, and appropriate packaging, are essential for enabling wider commercial adoption.

Overall, advances in processing technologies have improved the feasibility of producing high-quality cactus pear juice. Yet, achieving industrial consistency requires balancing technological sophistication with practicality, ensuring that nutritional and sensory quality are preserved while maintaining economic viability.

5. Comparison with Other Fruit Juices

When compared to commonly consumed fruit juices such as orange, apple, pineapple, and pomegranate juice, cactus pear juice presents a distinctive nutritional and functional profile. While most commercial fruit juices provide vitamins, minerals, and natural sugars, cactus pear juice stands out due to its high concentration of soluble dietary fiber, natural pigments such as betalains, and bioactive compounds with antioxidant and anti-inflammatory potential. These characteristics place it closer to functional beverages like pomegranate or beetroot juice rather than traditional refreshing juices such as apple or orange.

Nutritionally, cactus pear juice contains lower acidity than many commercial juices, making it gentler on the stomach and suitable for consumers who avoid acidic beverages for health reasons. While orange and pineapple juice are known for their high vitamin C content, cactus pear juice provides moderate but meaningful levels of this vitamin, complemented by unique components, including betalains and mucilage, that are not present in most traditional juices. Compared with grape or pomegranate juice, which are recognized for their polyphenol content, cactus pear juice offers a different class of antioxidant molecules, primarily betalains and flavonoids, that have shown similar or greater radical scavenging capacity in some laboratory studies.

In terms of sensory attributes, cactus pear juice has a mild sweetness and a low acidity, resulting in a delicate flavor profile that differs from the strong and sometimes astringent taste of pomegranate or cranberry juice. This mild character may be advantageous for product development, allowing cactus pear juice to serve as a neutral base for functional beverages, blends, nutraceutical formulations, or flavored drinks. However, its subtle flavor may also be perceived as less intense or distinctive, which could require formulation adjustments or blending with more aromatic juices to meet consumer expectations in competitive markets.

From a market positioning perspective, cactus pear juice fits well within the growing category of natural, plant-based, and health-promoting beverages. Consumer interest in func-

tional ingredients and sustainable agriculture aligns closely with the characteristics of cactus pear, particularly its drought resilience and ecological benefits. Compared with globally established fruit juices, cactus pear juice remains relatively unknown in international markets, presenting both an opportunity and a challenge. Its uniqueness and nutritional benefits provide strong selling points, but low consumer awareness may slow adoption unless supported by education, marketing, and product innovation.

Functionally, cactus pear juice may compete with juices like aloe vera and beetroot, which are marketed primarily for wellness benefits rather than traditional refreshment. Its potential anti-inflammatory, antioxidant, and glyce-mic-regulating properties could position it as a premium functional beverage in the health and wellness sector. Moreover, its natural pigmentation offers potential as a clean-label coloring agent in beverage formulation, further increasing its value beyond direct consumption.

Economically, cactus pear juice may offer strategic advantages in regions where the plant grows naturally and with minimal inputs. In comparison, fruit juices such as apple, orange, and grape require intensive cultivation systems, irrigation, and advanced industrial supply chains. Cactus pear, being highly resilient and requiring little water, represents a sustainable alternative crop that may support local value chains, reduce production costs, and diversify revenues for rural communities.

In summary, cactus pear juice occupies a unique position among fruit juices. Its nutritional and functional characteristics make it more comparable to emerging health-focused beverages than to mainstream juices. With appropriate marketing, processing optimization, and product development strategies, cactus pear juice has the potential to become a recognized functional beverage with strong identity, particularly in health-oriented markets.

6. Industrial and Economic Potential of Cactus Pear Juice

The industrial and economic potential of cactus pear juice is influenced by a combination of its nutritional properties, availability of raw materials, market trends, and technological requirements [43]. As consumer interest continues to shift toward natural and functional beverages, cactus pear juice offers opportunities for product diversification and value-added processing. The economic potential of cactus pear is significant, especially in arid regions where other crops struggle. In Sicily, Italy, it is estimated that cactus cultivation could utilize 14% of the land (about two million hectares), potentially supplying 15% of Italy's natural gas demand through biogas production in co-digestion with animal manure and slurry [44]. The increasing demand for natural colorants and functional foods, particularly in Europe, is driving annual growth rates of 10–15% for coloring foodstuffs, with

cactus pear juice and extracts being used for their nutritional and health benefits [45].

Despite its potential, industrial-scale production of cactus pear juice faces technological challenges. The high pH (5.3–7.1) and low acidity (0.05–0.18% citric acid) of the pulp affect storage life and processing, making the juice susceptible to microbial spoilage and limiting shelf life [46].

7. Knowledge Gaps in Cactus Pear Juice Research

7.1. Insufficient Industrial and Chemical Characterization

Current knowledge on the chemistry and industrial utilization of cactus pear juice is insufficient. There is a need for further investigation into the chemical composition of cactus pear and its potential as a raw material for food products, especially in relation to its nutritional and health benefits. This gap hinders accurate assessment of the plant's value in human nutrition and health, and limits its industrial exploitation [47].

7.2. Processing Technology Challenges

Cactus pear juice processing faces several technological challenges:

Microbial Spoilage and Shelf Life: The fruit's low acidity and high soluble solids make the juice susceptible to microbial spoilage and result in a short shelf life. Traditional thermal treatments can ensure microbiological stability but often lead to undesirable changes in color, flavor, and nutritional value, reducing health-promoting properties [48].

Non-Thermal Preservation: Emerging non-thermal preservation methods, such as cross-flow microfiltration and sonication, show promise for maintaining juice quality and antioxidant properties while reducing microbial counts. However, further research is needed to determine their effectiveness in extending shelf life and preserving health benefits [49].

8. Conclusion

Cactus pear juice represents a promising functional beverage due to its rich nutritional profile, unique bioactive compounds, and potential health benefits. Its high content of antioxidants, soluble fiber, minerals, and phytochemicals supports its relevance within the growing global market for natural and health-enhancing beverages. Advances in extraction and stabilization technologies have improved processing feasibility; however, challenges remain associated with viscosity, pigment stability, microbial sensitivity, and production costs. Although early evidence suggests several health benefits, further clinical research is required to substantiate functional claims and provide dosage recommendations.

From an industrial perspective, cactus pear juice offers economic opportunities, particularly in regions where the crop is abundant and resilient. To fully realize its commercial potential, efforts should focus on improving processing technologies, establishing regulatory frameworks, promoting consumer awareness, and supporting value-chain development. Overall, cactus pear juice shows strong potential as a sustainable, nutritious, and market-relevant product, provided existing scientific, technological, and market barriers are addressed.

Abbreviations

LDL Low Density Lipoprotein
HTST High-Temperature Short-Time
HPP High-Pressure Processing

Author Contributions

Abdoulaye Tamba is the sole author. The author read and approved the final manuscript.

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The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Abdoulaye Tamba is a senior food scientist and specialist in agro-food processing technologies. He earned his PhD in Agro-food Process Engineering from Cheikh Anta Diop University (Dakar, Senegal), following a Master's degree in Food Technology and a Bachelor's degree in Food Science. His

research focuses on post-harvest technology, food dehydration processes, food quality and safety, and the valorization of local agricultural resources such as mango, cactus pear. He has contributed to several scientific and technical initiatives aimed at improving food processing practices in West Africa, notably through innovation in drying processes, process optimization, and technology transfer for SMEs. He currently serves as Senior Technological Referent and Operational Lead for the youth insertion and industrial support program implemented by GINDI (www.gindi.sn), where he works closely with food industries, academic institutions, and development partners to strengthen technical capacity, promote innovation, and support industrial transformation in the agro-food sector.

Research Field

Abdoulaye Tamba: Food Process Engineering; Post-Harvest Technology; Preservation of Tropical Fruits; Food Quality; Agro-Industrial Innovation and SME Technology Transfer.