International Journal of Agriculture and Food Science 2026; 8(1): 273-281

ISSN Print: 2664-844X
ISSN Online: 2664-8458
NAAS Rating (2025): 4.97
IJAFS 2026; 8(1): 273-281
www.agriculturaljournals.com
Received: 13-11-2025
Accepted: 16-12-2025

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Advances in thermal and non-thermal preservation strategies for improving the storage stability of fruit juices

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DOI: https://www.doi.org/10.33545/2664844X.2026.v8.i1d.1152

Abstract
Fruit juices are consumed worldwide for their pleasant sensory attributes and nutritional value, although their high moisture content and sugar concentration make them highly susceptible to microbial growth, enzymatic reactions, and degradation of heat-sensitive nutrients during storage. Although conventional thermal processing is still very effective in causing microbial inactivation, several undesirable changes, such as colour loss, flavour deterioration, and lower vitamin retention, commonly occur. Non-thermal preservation technologies have recently received considerable attention due to growing consumer demand for beverages with minimal processing and clean labels. This review critically discusses the impact of thermal and non-thermal preservation strategies, such as high-pressure processing, pulsed electric fields, ultrasound, cold plasma, and pulsed light, on storage stability in fruit juices. The roles played by chemical preservatives, natural antimicrobials with special emphasis on chitosan, and various packaging materials in the prolongation of shelf-life are discussed. Special attention is paid to microbial behaviour under different storage conditions, including enzymatic stability, nutrient retention, colour preservation, and sensory quality. The review discloses that no single preservation method is going to give positive results concerning long-term stability; rather, integrating appropriate technologies of processing with natural preservatives, active packaging systems, and storage conditions yields better outcomes in preservation.

Keywords: Fruit juices, storage stability, thermal processing, non-thermal preservation, shelf life, natural preservatives, etc.

1. Introduction

Consumers highly value fruit juices for their sensory attributes and nutritional density, especially for their concentration of vitamins and bioactive compounds. However, their high moisture content and sugar profile, combined with their varying acidity levels, provide a favourable environment for microbial spoilage during storage. Integrated management of preparation and preservation treatments is essential to reduce microbial risk while preserving the organoleptic and nutritional quality of the product over time (Gómez-Gaete *et al*. 2024) [19]. One of the main causes of the quick deterioration of fruit juices is microbial multiplication, leading to the need for strong approaches to intervention. In particular, low-acid formulations and vegetable-based blends provide highly conducive substrates for pathogenic growth, resulting in accelerated quality loss and heightened safety risks. The kinetics of spoilage are influenced by a multifactorial matrix, including storage temperature, packaging specifications, and the thermal intensity applied during processing; consequently, the implementation of synergistic preservation techniques is critical for maintaining product stability (Guo *et al*. 2025) [20].

In addition to microbiological issues, basic biochemical elements like enzymatic activity play a major role in the degradation process. Shaik and Chakraborty's (2023) [42] study on sweet lime juice treated with pulsed light shows that leftover enzymes can hasten browning and quality degradation over time. This suggests that even when microbial loads are effectively decreased, enzyme stability is still strongly influenced by post-processing storage temperatures. The industry standard for lowering microbial loads and deactivating enzymes is still traditional thermal processing, such as pasteurisation using plate or tube heat exchangers.

Nevertheless, these treatments are linked to a number of detrimental effects on quality even though they guarantee microbiological safety. These include the degradation of vitamin C and various phytochemicals, a decrease in antioxidant capacity, colour deterioration, and the loss of sensory quality during subsequent storage. Long-term storage studies (180 days) of thermally treated tropical juice blends have reported significant vitamin losses and progressive flavour deterioration (Wurlitzer *et al*. 2019) [53]. Additionally, a range of thermally treated juices, such as grape, pomegranate, sour cherry, pomelo, and kinnow, have shown significant decreases in polyphenols, pigments, and free radical scavenging activity (Hooshyar *et al*. 2020; Kumar *et al*. 2023) [22, 28].

Chemical degradation of essential nutrients significantly impacts storage stability, with ascorbic acid (vitamin C) identified as one of the most labile components in fruit juice matrices. Vitamin C undergoes oxidative degradation during storage, a process frequently correlated with adverse colour shifts and a reduction in total antioxidant capacity. Similar instability has been documented for folates and phenolic compounds under equivalent storage conditions. In cold-plasma-treated kiwifruit juice, gradual losses of ascorbic acid were observed during storage, where the functional shelf life was found to be intrinsically linked to vitamin C retention and colour stability (Kumar *et al*. 2023) [28]. These results are in agreement with studies with pasteurised beetroot juice, where the optical characteristics of the packing (amber versus clear glass) and storage temperature had a significant impact on folate degradation. This study demonstrates that, in the absence of protective chemicals or efficient packing solutions, nutritional breakdown continues even under refrigeration (Mwaijibe and Vicent 2025) [33].

Advanced non-thermal preservation technologies are of great interest due to the growing consumer demand for minimally processed foods that maintain "fresh-like" qualities. These techniques seek to accomplish microbiological safety without the harmful consequences of high-temperature processing. One of the most successful methods for reducing microbial burdens and postponing quality degradation is ultrasound processing, or sonication. It was discovered that ultrasound therapy extended the microbiological stability of sweet lime juice to roughly 35-37 days when stored in a refrigerator. When combined with multilayer polyethylene terephthalate (PET) packaging, the effectiveness of this treatment was further increased, indicating a potential synergy between advanced barrier packaging and non-thermal processing (Shaik and Chakraborty 2023) [42]. In comparison to traditional heat treatment, pulsed light treatment has demonstrated significant microbial reduction with little thermal damage, resulting in improved vitamin C and sensory quality retention (Shaik & Chakraborty, 2023) [42]. According to Kumar *et al*. (2024) [27], cold plasma technology has demonstrated great promise among new technologies by increasing the shelf life of kiwifruit juice to nearly 100 days at 5 °C while preserving low microbiological counts, colour stability, and nutrient retention.

The efficiency of pulsed electric field treatment in enhancing the extraction of nutrients and reducing microbial load in *Phyllanthusemblica* (AMLA) juice also justifies the potential of the non-thermal methods (Shaik & Chakraborty, 2023) [42]. High-pressure homogenization and microfluidization are some of the physical stabilisation techniques that reduce the size of particles, limit enzymatic activity, and contribute to better cloud stability. Such techniques have shown better nutrient retention and improved storage stability in fruit juice systems (Waghmare 2024) [50]. Along with all these processing technologies, chemical preservatives like sodium benzoate, potassium sorbate, sulphites, and nitrites remain widely used to control microbial growth in beverages and vegetable-based juices. The need for customers for clean-label products has led to interest in natural preservatives, including biopolymers and essential oils derived from plants. While chitosan has been found to be an effective natural stabiliser for citrus liquids, cinnamon, lemon, and clove oils have demonstrated potent antibacterial and antioxidant properties (Campolina *et al*. 2023; Shi *et al*. 2024) [11, 43]. Juice stabilisation is a complementary function of packaging solutions, primarily controlled by light and oxygen during storage. Ethylene Vinyl Alcohol (EVOH) and multilayer Polyethylene Terephthalate (PET) presented superior performance compared to conventional packaging for sweet lime juice subjected to pulsed light and ultrasound processing. Amber glass also presented improved maintenance of folate content in beetroot juice when compared to clear glass packaging during storage (Mwaijibe & Vicent, 2025) [33]. New approaches, like edible films, coatings, and encapsulation systems, enhance stability by protecting sensitive bioactive compounds; for instance, liposomal systems have been successfully applied for delivering and protecting vitamins C and E in fruit beverages (Chavan *et al*. 2023; Marsanasco *et al*. 2011) [13, 32]. Considering the literature reviewed, it appears that fruit juice stability during storage is controlled by multiple interactions of microbial, enzymatic, chemical, physical, and packaging-associated factors. In spite of all the advances made by advanced techniques of processing and preservation strategies, nutrient retention, enzymatic stability, and practical storage conditions pose problems that call for integrated and optimised methods for juice stabilisation.

2. Deterioration of fruit juices during storage

Fruit juices are highly susceptible to rapid deterioration during storage due to their intrinsic composition, characterized by high water activity (a_w), fermentable sugars, endogenous enzymes, and labile micronutrients. This spoilage is a multi-factorial process involving microbial proliferation, oxidative vitamin degradation, and enzyme-mediated browning, which collectively result in cloud destabilization and the loss of characteristic flavor and aroma (Leizerson & Shimoni, 2005; Shaik & Chakraborty, 2023) [29, 42]. Ultimately, the degradation of fruit juices during storage is the product of integrated biological, chemical, and physical pathways that progressively diminish the product's nutritional density, sensory profile, and visual integrity. Refrigeration significantly slows microbial growth, whereas storage at ambient or elevated temperatures (15-35 °C) accelerates spoilage, shortening shelf life. Research on citrus and associated juices shows that when microbial populations reach about 6 log CFU/mL, which is often utilized as an end-of-shelf-life indicator, spoilage becomes organoleptically undesirable. In addition to microbial spoiling, nutritional deterioration during storage, especially of heat-sensitive antioxidants, is a serious concern. Because of its extreme vulnerability to oxidative destruction, vitamin C has been examined in enormous depth. Vitamin C loss is accelerated by exposure to air, residual metal ions, high temperatures, and enzymatic activity. As a result, zero or first-order models are frequently used in shelf-life research to characterise the kinetics of vitamin C degradation. In addition to vitamin C, phenolic compounds, anthocyanins, carotenoids, and folates are reduced, which lowers nutritional quality and antioxidant activity. Both colour retention and flavour stability are impacted by these chemical alterations. Enzymatic activity also significantly influences juice deterioration during storage. Following processing, residual Polyphenol Oxidase (PPO) and Peroxidase (POD) activities encourage the oxidation of phenolic substances, which causes browning and the development of an off flavour. Juices that have undergone mild processing or goods that have been treated with non-thermal technologies that do not totally deactivate enzymes are more susceptible to these effects (Leizerson & Shimoni, 2005) [29].

In citrus juices, pectin methylesterase (PME) causes pectin demethoxylation, leading to particle aggregation and sedimentation, which manifests as cloud loss and reduced visual quality. Colour degradation is a visible indicator of quality loss during storage and arises from pigment oxidation, enzymatic browning reactions, and non-enzymatic interactions between sugars and proteins. In kiwifruit juice stored at 5, 15, and 25 °C, cold-plasma and thermally treated samples exhibited progressive increases in total colour change with storage time and temperature, accompanied by decreases in ascorbic acid content, total phenolic content, antioxidant capacity, and sensory acceptability (Kumar *et al*., 2024; Shaik & Chakraborty, 2023) [27, 42]. Although microbial counts remained below detectable levels for extended periods, quality deterioration was driven primarily by chemical and enzymatic changes. Shelf life decreased markedly at higher storage temperatures, and kinetic modelling showed that zero-order reactions combined with temperature-dependent models adequately described quality degradation. Overall, microbial growth, nutrient degradation, enzymatic reactions, and colour changes collectively contribute to declining sensory quality during storage. Attributes such as aroma, taste, acidity, and overall freshness deteriorate due to loss of volatile compounds, oxidation reactions, and compositional changes (Kumar *et al*., 2024) [27]. Even when microbial safety limits are maintained, sensory degradation often determines consumer acceptability. These deterioration mechanisms highlight the importance of appropriate processing, packaging, and low-temperature storage to preserve the microbiological, chemical, and sensory stability of fruit juices.

3. Thermal processing and storage stability of fruit juices

Heat treatment remains one of the most widely used methods for fruit juice preservation, primarily because it effectively destroys microorganisms and inactivates deteriorative enzymes. The diversity of thermal processing methods, ranging from mild pasteurization to ultra-high temperature sterilization, significantly dictates the final quality and shelf-life of the juice matrix. The technical parameters and specific quality impacts of these methods are summarized in Table 1. The principal objective of thermal processing is to ensure microbiological safety while retaining flavour and nutritional quality for an extended storage period. Traditional methods, including high-temperature short-time (HTST) and low-temperature long-time (LTLT) processing, are frequently used. To apply controlled heating, these procedures usually make use of flat-plate, tubular, or multilayer heat exchangers. However, quality loss during future storage is frequently directly caused by the high temperatures needed to inactivate pathogenic bacteria and enzymes that limit shelf life. Heat-treated fruit juices have routinely been shown to have better microbiological stability than untreated juices in storage trials, especially when kept in a refrigerator. By drastically lowering the initial microbial load, thermal processing lowers the chance of rapid spoiling and slows microbial re-growth during storage. However, over time, residual microbes may multiply, particularly at ambient or high storage temperatures, suggesting that storage conditions still affect product stability even after heat treatment (Leizerson & Shimoni, 2005; Kumar *et al*., 2024) [29, 27]. As a result, post-processing storage management has a significant impact on the shelf life of thermally processed juices. In terms of nutrition, heat treatment mostly impacts substances that are susceptible to heat, especially ascorbic acid (vitamin C). When compared to their non-thermally processed counterparts, heat-treated juices typically show faster vitamin C breakdown during storage. Thermal processing affects phenolic chemicals, carotenoids, and folates in addition to vitamin C, which causes a progressive reduction in overall antioxidant capacity over extended storage (Jafari *et al*., 2017) [23]. Juice shelf life is directly impacted by enzyme inactivation, which is largely dependent on thermal treatment. By reducing the activity of enzymes such as Polyphenol Oxidase (PPO), Peroxidase (POD), and pectin methylesterase (PME), the appropriate temperature and holding duration combinations minimise browning reactions and cloud instability during storage. PME is one of these enzymes that is especially crucial for citrus juices because it encourages the breakdown of pectin and the production of sediment. Studies indicate that thermally treated orange juice maintains better cloud stability and exhibits less colour change during refrigerated storage compared with mildly processed juice (Aghajanzadeh *et al*., 2018; Anthon & Barrett, 2002) [3, 6]. However, excessive thermal exposure can negatively affect flavour and mouthfeel, emphasizing the need for precise optimization of processing parameters.

Ohmic heating represents an advanced thermal processing technique in which electric current is passed directly through the juice, generating rapid and uniform internal heating. This method minimizes temperature gradients and reduces the formation of localized hot spots commonly observed in conventional heat exchangers. Research has shown that fruit juices processed by ohmic heating retain superior sensory attributes, colour, and nutritional quality during storage, despite achieving microbial inactivation levels comparable to conventional thermal methods. These improvements are attributed to reduced overall thermal exposure, which limits chemical degradation reactions during shelf life (Leizerson & Shimoni, 2005; Achir *et al*., 2016) [29, 1]. The design and performance evaluation of heat exchangers significantly influence the storage stability of thermally processed juices. Plate and tubular heat exchangers with improved flow patterns and enhanced mixing promote faster heat transfer, thereby reducing treatment time while preserving thermo labile nutrients. Combined experimental and simulation studies demonstrate that more uniform temperature distributions result in lower nutrient degradation during processing and subsequent storage. Nevertheless, irrespective of technological advancements, storage studies consistently report progressive quality deterioration due to oxidative reactions and thermal stress, particularly when juices are stored without refrigeration.

Table 1: Thermal processing methods applied to fruit and vegetable juices and their effects on quality and storage stability

1	Orange juice	Continuous ohmic heating (OH)(90, 120, and 150 °C for 1.13, 0.85, and 0.68 s) and Thermal pasteurization (TT), (at 90 °C for 50 s)	OH ensured complete microbial and enzyme inactivation in orange juice with minimal vitamin C loss (~15%) and superior flavour and sensory retention compared to TT	Leizerson and Shimoni, (2005) [29]
2.	Cloudy apple juice	Low-temperature long-time (LTLT) vs high-temperature short-time (HTST)	HTST better kept the juice's color, aroma, and cloudiness than LTLT; HTST juice tasted closer to fresh juice	Katsch *et al*., (2025) [25]
3.	Carrot juice	Continuous ohmic sterilization; CFD-modelled heating & cooling simulations	The juice was heated more uniformly by Ohmic heating than conventional heating, and the results from the model indicated that conventional calculations were lower than the actual heating of the juice.	Rivera *et al*., (2024),
4.	Tomato juice paste	Shell-and-tube heat exchanger CFD simulation for industrial pasteurization	The CFD simulation was able to predict the heat transfer and the temperature and flow patterns, which aided in the design of heat exchangers for thick and viscous fluids.	Asadbeigi *et al*., (2023) [8]
5.	Beetroot juice	Batch thermal pasteurisation (90 °C, 15 s); storage in amber and transparent glass bottles at 4 °C and ambient temperature	Pasteurisation inactivated microbes but decreased folate, and folate was more stable during storage in amber bottles at 4 °C than at room temperature.	Mwaijibe & Vicent, (2025) [33]
6.	Orange beverage	HTST (indirect heat treatment); time-temperature schedule used to calculate F-values	Describe F-values are used to balance microbial safety with nutrient loss, showing that higher heat improves safety but reduces vitamin C and folate.	Rouweler, (2015)

While heat treatment initially stabilizes sensory quality, prolonged storage especially at elevated temperatures leads to noticeable declines in flavour and appearance, potentially limiting consumer acceptability before microbial spoilage becomes evident (Shaik& Chakraborty, 2023) [42]. Overall, thermal processing remains indispensable for ensuring microbial safety and enzyme inactivation in fruit juices. However, the retention of nutritional and sensory quality during storage is highly dependent on the careful optimization of processing parameters and stringent control of storage conditions. Although emerging techniques such as ohmic heating and improved heat exchanger designs mitigate some quality losses, thermal damage remains a fundamental limitation. Consequently, increasing attention is being directed toward alternative preservation strategies that operate at lower temperatures to extend shelf life while maintaining fresh-like quality attributes.

4. Non-thermal processing technologies and storage stability of fruit juices

Non-thermal methods have drawn growing attention from researchers as viable substitutes for traditional heat-based processes when aiming to extend shelf life of fruit juices while keeping taste and nutrition close to fresh. The operational mechanisms and specific qualitative advantages of these advanced non-thermal techniques are comparatively analyzed in Table 2. High-pressure processing has been one of the foremost non-thermal modalities investigated to retain the safety of fruit juice. These technologies essentially reduce microbial counts and enzyme activity by physical or combined physical-chemical mechanisms rather than the application of heat. The latter helps in preserving those heat-sensitive nutrients that are susceptible to deterioration at high temperatures. Practical confirmation exists to prove such methods may better retain vitamin C, antioxidants, colour, and aroma during cold storage than thermal approaches; however, results often depend on the treatment strength, type of juice to be treated, and other operating variables like time and temperature. It commonly uses 400-600 M Pa, killing microbes by damaging cell walls, changing protein shapes, or affecting enzyme structure without raising heat much. Many storage tests indicate treated juices grow fewer bacteria, hold colour longer, and preserve more vitamin C and phenolic content than heated versions, particularly when chilled. Since treatment happens after packaging, recontamination risk drops sharply, this extends usability. Still, some enzymes withstand pressure and stay functional; also, how cold it's stored at strongly affects freshness maintenance. PEF treatment has received similar attention in liquids like fruit juice. Short bursts of high voltage are used this damages microbe's outer layers, reducing their numbers. Stored juices treated this way tend to keep more vitamin C, antioxidants, and aroma chemicals compared to those heated even though both methods kill microbes well (Odriozola-Serrano *et al.,* 2016) [15]. However, PEF can often also fail to completely inhibit enzyme activity, especially in the case of polyphenol oxidase and pectin met. As a result, colour darkening and cloudy particles settling may still happen over time unless cooling, slight heating, or extra preservatives are also applied (Terefe *et al*. 2015) [45]. Cold plasma shows strong potential for cleaning surfaces and liquids because it generates active compounds without heat, damaging microbes effectively. While stored, treated items often show reduced microbial re-growth provided the processing settings are well adjusted alongside preserved antioxidant properties. Yet excessive plasma contact triggers oxidation, speeding up loss of vitamin C and altering appearance (Kumar *et al*., 2024) [27]. Therefore, killing microbes must go hand-in-hand with maintaining substance integrity over time (Fernandes & Rodrigues, 2021; Pipliya & Srivastav, 2024) [18, 27].

Ultrasound works mainly through tiny bubbles forming and collapsing, which helps destroy microbes while improving how substances move inside juice. Studies on stored orange and similar fruit drinks show ultrasound can help keep antioxidants longer and lower early bacteria levels. Still, some enzymes stay active this becomes a problem during warm storage, since it leads to faster browning and loss of cloudy appearance. Because of these issues, ultrasound performs best when paired with cold storage, natural additives, or special packaging methods. UV-C light offers a cold method to preserve clear juices, working best when particles are minimal. It stops microbes from growing by altering their DNA, which helps keep juice safe without harming nutrients much. Still, cloudy liquids scatter the rays, so they don't reach deep, making disinfection weaker and risking germs coming back later. Even after UV exposure, how well the product lasts depend mostly on how cold it's kept, this holds true across similar chill-based techniques (Chemat *et al.*, 2011) [14]. High-pressure homogenization and micro-fluidization are being studied to boost shelf-life and maintain product consistency. These processes reduce droplet size, support even suspension, while improving hue stability via changes in internal structure.

Table 2: Advanced non-thermal techniques applied to juices

S.No	Product	Technology used & condition	Key findings	Reference
1.	Raspberry juice	Pulsed electric fields (PEF), High-pressure processing (HPP), and Thermal pasteurization (TT)	High-intensity PEF achieves optimal nutrient and sensory retention compared to TT and HPP.	Truong *et al.*, (2025) [48]
2.	Kiwi fruit juice	Cold plasma optimized (CPO)-(30 kV/5 mm/6.7 min) & Cold plasma Extreme (CPE), (30 kV/2 mm/10 min), thermally treated (TT) (90 °C/5 min) and untreated UT.	CPO showing the least disruption, lowest viscosity, highest ascorbic acid retention, and best sensory quality compared with CPE and TT	Kumar *et al.*, (2024) [27]
3.	Sweet lime juice	Ultrasound (US) storage at 4, 15, 25, 30,35 °C; EVOH vs ML-PET; Shelf-life of 37 days	US juice showed better bioactive retention, preserving ~89% vitamin C &antioxidant activity at 4 °C, with better shelf life in ML-PET than EVOH	Shaik & Chakraborty, (2023) [42]
4	Sweet lime juice	Pulsed Light (PL), (3000 J cm^{-2}) vs thermal conditions (TT) (95°C/5 min); storage at 4, 15, and 25°C; EVOH vs ML-PET; Shelf-life for 46 days	PL preserved sensory quality and nutrients better than TT, with shelf life extended to 46 days at 4 °C in ML-PET, while microbial growth limited stability at higher temperatures.	Shaik & Chakraborty, (2023) [42]
5.	Orange juice	High Hydrostatic pressure (HPP), (100-800 MPa, 30-60 °C); & Thermal treatment (TT), (50-80 °C)	High pressure and temperature worked together to inactivate PME and it followed first-order kinetics with minor residual activity.	Polydera *et al.*, (2003) [37]
6	Various fruit juices	ultrasound (US), pulsed electric field (PEF), cold plasma (CP), and high-pressure processing (HPP)	principles and applications of the technology; mechanisms of microbial inactivation and quality preservation; general trends in shelf-life extension and retention of sensory	Safwa *et al.*, (2024) [41]
7.	Apple-cranberry juice blend	UV (5.3 J cm^{-2}) + PEF (34 kV cm^{-1}, 18 Hz, 93 µs); HILP (3.3 J cm^{-2}) + PEF; UV/HILP + MTS (5 bar, 43 °C, 750 W, 20 kHz); compared with thermal pasteurisation (72 °C, 26 s)	UV + PEF and HILP + PEF preserved colour and flavour; HILP + PEF retained highest anthocyanins; MTS combinations negatively affected sensory quality	Caminiti *et al.*, (2010) [10]
8.	Tomato juice	High hydrostatic pressure (HHP) vs high-temperature short-time (HTST) thermal processing; cold storage study	HHP preserved better than HTST; redness and specific volatiles ((E)-2-heptenal, hexanal, (E)-2-octanal) were identified as markers to distinguish HHP-treated from TT during storage	Wang *et al.*, (2026) [51]

Research shows treated juices tend to show reduced settling, along with steadier taste and appearance over time. Moreover, applying these methods in capsule formation can shield fragile components such as vitamin C or E from breaking down during storage, contributing to retained nutrient levels (Marsanasco *et al.*, 2011) [32]. Despite these benefits, non-thermal techniques are not necessarily always more effective than heat treatment methods. This depends on the juice's composition, initial microbial load, enzymes, and storage conditions. Usually, room-temperature shelf life stays limited without extra help from cooling, additives, or smart packaging solutions. Still, once fine-tuned, they preserve freshness and nutrients well over time making them key players in today's juice safety approaches.

5. Role of preservatives in enhancing storage stability of fruit juices

Preventing fruit juice from spoiling is a primary goal of food preservation, achieved by stopping microbial growth, preventing browning (oxidation), and deactivating natural enzymes that cause decay. While heat treatments kill off most bacteria early on, chemical preservatives like sodium benzoate and potassium sorbate are essential safeguards when consistent refrigeration isn't possible. The primary chemical agent utilized in the beverage industry, along with their specific regulatory limits and target organisms, are summarized in Table 3. These additives work best when they match the juice's specific acidity (pH) and storage temperature; for example, sodium benzoate is excellent at fighting molds, while potassium sorbate is better at stopping yeast. Research by Vignali *et al.* (2022) and newer studies by Shi *et al.*, 2024 [43]; confirm that these treatments help juice stay safe and fresh-tasting even at room temperature.

However, many modern shoppers prefer to avoid "lab-made" ingredients, scientists are now looking for natural alternatives to replace these traditional chemicals. With rising consumer preference for clean labels, attention has turned toward naturally derived alternatives in recent years. Certain plant-based options such as essential oils, phenolic substances and extracts from various peels inhibit microbial growth while also limiting oxidative damage, contributing to extended freshness.

Essential oils extracted from lemon and orange rinds effectively inhibit spoilage microbes and maintain stable antioxidant activity during storage (Shi *et al.*, 2024) [43]. However, their practical application is limited by potent sensory profiles that can overpower or alter the juice's natural flavor, as well as unpredictable performance influenced by juice matrix composition and storage variables (Gyawali & Ibrahim, 2014) [21]. Product shelf life hinges greatly on how preservatives behave under different processing methods.

Table 3: Chemical preservatives in fruit & beverage products

No.	Product / Matrix	Chemical preservatives	Level/Range	Purpose	Key finding	Reference
1	Soft drinks, energy drinks, fruit beverages	Sodium benzoate (SB), potassium sorbate (PS)	SB: 70-104 mg/L; PS: 23-118 mg/L	Antimicrobial	Detected levels were within Codex limits; health risk was acceptable (HQ < 1)	Muhammad Abdulla *et al.*, (2025)
2	Fruit juices, processed foods	Sodium benzoate (SB), potassium sorbate (PS), nitrates,	Regulatory limits	Preservation	Chemical preservatives are effective but long-term intake raises safety concerns	Shi *et al.*, (2024) [43]
3	Juices, jams, beverages	Sodium benzoate, potassium sorbate	General use	Antimicrobial	Widely used for yeast and mould control; excessive levels may pose safety risks.	Yazdanfar *et al.*, (2023) [54]
4	Orange juice	Sodium benzoate (SB), potassium sorbate (PS) vs. propolis extract	Industry levels; propolis ≈ 1 g/L	Preservation comparison	Propolis with mild heat provided microbial stability comparable to SB/PS.	Yang *et al.*, (2017)
5	Guava, mango, mixed fruit pulp	Sodium benzoate (SB), potassium sorbate (PS) citric acid	~0.05-0.10%	Microbial control	Acidification combined with SB/PS improved microbial stability during storage.	Latif *et al.*, (2022)
6	Multiple fruit juices (review)	Sodium benzoate (SB), potassium sorbate (PS), sulfites	Regulatory ranges	Antimicrobial	Reviews highlight effectiveness and growing preference for natural alternatives.	Shi *et al.*, (2024) [43]
7	Fruit beverages, jams	Sodium benzoate (SB), potassium sorbate (PS)	200-1000 ppm	Yeast/mould control	SB-PS combinations extend shelf life but may affect sensory quality at high levels.	Leizerson & Shimoni (2005) [29]; Shaik& Chakraborty (2023) [43]
8	General beverages	Sodium benzoate (SB), potassium sorbate (PS)	0.015-0.10%	Antimicrobial	Benzoate lowers intracellular pH; sorbate inhibits fungal metabolism.	Abdulla *et al.*, (2025)

Non-thermal techniques such as ultrasound, cold plasma, and pulsed electric fields usually fail to fully stop enzymes, so extra chemical agents often become necessary. When combined with these physical treatments, additives cut down surviving microbes while slowing oxidation effects, which helps retain freshness over time (Terefe *et al.*, 2015) [45]. Although preservation agents play a constant role, using them wisely matters to avoid harm, taste shifts, or health concerns. Too much additive alters smell, ruins mouth feel, since balance determines whether people will accept the food. Warmth reduces how well certain ingredients work, so cooling is needed alongside them to keep products fresh. Still, clever wrapping helps food last longer even when the surroundings are far from ideal.

6. Packaging materials and their influence on the storage stability of fruit juices

While chemical and natural additives provide internal stability, the choice of packaging is the final determinant of a product's shelf life, as categorized in Table 4. Effective containers protect juice by blocking oxygen, light, and moisture, preventing the nutrient loss and off-flavors that occur even in perfectly processed beverages. Research indicates that material selection significantly dictates quality; for instance, amber glass and multilayer PET (ML-PET) have been shown to superiorly retain color and vitamins like folate and Vitamin C by mitigating light-induced and oxidative degradation (Shaik & Chakraborty, 2023; Mwaijibe & Vicent, 2025) [42, 33].

Table 4: Packaging techniques applied to juices

S. No.	Product / Juice	Packaging Type	Purpose / Function	Key Finding	Shelf-Life Effect	Citation
1	Sweet lime juice (ultrasound & pulsed-light treated)	Multilayer PET (ML-PET) vs EVOH	Compare packaging influence during storage	Packaging material significantly influenced quality degradation during storage; oxygen exposure affected vitamin C and colour stability	ML-PET showed longer quality retention under refrigerated storage	Shaik & Chakraborty (2023) [42]
2	Beetroot juice	Amber vs transparent glass bottles	Light protection	Amber glass reduced light-induced degradation of folate and colour during refrigerated storage	Improved folate retention and colour stability at 4 °C	Mwaijibe & Vicent (2025) [33]
3	Fresh fruits & vegetables	Polymeric films for MAP	Atmosphere modification	Polymeric films regulate O_2 and CO_2 transmission, slowing respiration and delaying senescence of fresh produce	Shelf-life extension reported for fruits and vegetables	Mangaraj *et al.* (2009) [31]
4	Juices & other foods (review)	Biobased& biodegradable films	Sustainable packaging	Barrier and mechanical properties depend on polymer type; potential to replace conventional plastics in food packaging	Shelf-life improvement reported in several food systems	Nilsen-Nygaard *et al.* (2021) [31]
5	Fruits, fish & other foods (review)	Marine biopolymer films & coatings	Active packaging	Incorporation of bioactive compounds provides antimicrobial and antioxidant functionality	Shelf-life extension reported in coated products	Oliveira *et al.* (2025) [36]
6	Fresh-cut fruits	Edible coatings (chitosan, alginate, starch)	Reduce browning and moisture loss	Edible coatings act as semi-permeable barriers to gases and moisture, delaying browning and dehydration	Storage stability improved compared to uncoated samples	Chavan *et al.* (2023) [13]

Beyond traditional barriers, industry standards are evolving to include Modified Atmosphere Packaging (MAP) to regulate gas transmission and biobased films to address sustainability concerns (Mangaraj *et al.*, 2009; Nilsen-Nygaard *et al.*, 2021) [31, 34]. Furthermore, emerging "active" systems, such as marine biopolymer films and edible coatings, offer functional benefits by releasing antioxidants or creating semi-permeable shields that delay browning and dehydration (Chavan *et al.*, 2023; Oliveira *et al.*, 2025) [13, 36]. Ultimately, these packaging advancements must be paired with consistent temperature control, as the protective benefits of even the most advanced materials are quickly compromised under harsh storage conditions.

7. Influence of storage conditions on fruit juice stability

Storage conditions often impact fruit juice quality more than the initial processing, with temperature being the most critical factor. Refrigeration (around 4 °C) is essential because it slows down the "clocks" of spoilage; it delays microbial growth, keeps enzymes from turning the juice brown or cloudy, and protects sensitive nutrients like Vitamin C. In contrast, room temperature or high heat (30-35 °C) acts as an accelerator, causing rapid loss of colour, flavour, and vitamins through oxidation and chemical reactions that even advanced processing cannot fully fix (Rawson *et al*., 2011) [38]. To predict exactly when a juice will expire, scientists use math models like the Arrhenius modelto calculate how fast Vitamin C disappears or how quickly browning occurs at different temperatures (Jafari *et al*., 2017) [23]. Ultimately, even the best-packaged juice requires a stable, cold environment to maintain its fresh taste and nutritional value until it reaches the consumer.

8. Comparative assessment of preservation strategies and future perspectives

No single approach is perfect for keeping fruit juice quality; therefore, there needs to be a balance between safety and taste. The industry standard for removal of harmful bacteria and inhibition of enzymes is thermal treatments. These not only make sure the juice has a long shelf life, but they can also break down heat-sensitive components like Vitamin C and change the juice's natural flavour. On the other hand, non-thermal methods like high-pressure processing or pulsed electric fields keep the juice closer to its fresh state. However, these juices can still turn brown or lose their texture if they are not kept strictly refrigerated (Shaik & Chakraborty, 2023) [42]. To get these problems resolved, recent research is looking toward hurdle technology, which combines processing with protective packaging and chemicals. Synthetic preservatives are efficient, but using natural antimicrobials like essential oils and improved packaging (like EVOH layers) that keep oxygen and light out without compromising the drink's "clean label" status is better. In the end, the temperature at which the juice is stored is the most important thing; even the best methods don't work if the juice is maintained in high heat. Scientists utilise kinetic models, such as the Arrhenius or Weibull models, to figure out these breakdown rates. This lets them guess how long the juice will last and ensure that the way it's processed, packaged, and cooled keeps it fresh until it arrives to the customer (Jafari *et al*., 2017) [23].

9. Identified research gaps and future directions

There are still many practical and unsolved challenges with preserving fruit juices, especially the stability and shelf life of juices from citrus fruits like oranges and mosambis. One of the biggest gaps is that juices don't stay stable in storage following thermal and non-thermal processing, especially when they're stored at room temperature. Many of the reports on rapid quality deterioration have been driven by microbial growth, enzymatic activity, and oxidation, which suggests that processing alone, can hardly assure an acceptable shelf life. One of the major pending issues is related to the role and necessity of preservatives in stabilized juices. While preservatives are commonly used with the objective of prolonging shelf life, some agreement on the type of preservative (chemical versus natural) that is most appropriate for different juice matrices and storage conditions remains limited. Furthermore, the interaction between preservatives and processing methods is still not well known, particularly for non-thermally processed juices where inactivation of enzymes may not be fully achieved. This makes the selection and dosing of the right preservatives that will confer stability without affecting sensory quality quite complex. A key missing insight concerns how juices are handled prior to processing. Methods such as enzyme use, filtering, clearing, or spinning differ widely between experiments so it's hard to judge exactly how each affects shelf life when used alone. In particular, limited information exists on the impact of pre-treatments on microbial load, enzymatic activity, cloud stability, and nutrient retention during storage in citrus juices. This call for the systematic evaluation of pre-treatment strategies under controlled conditions of storage. What could be the specific function of homogenization in stabilizing juices remains understudied yet? While homogenization and micro-fluidization are reported to decrease particle size and enhance cloud stability, results with respect to microbial stability indicate that it increases the rate of oxidation by increasing the surface area of exposure. Clear guidelines on whether homogenization is required, at what stage it needs to be done, and the effect on shelf life are not available, particularly for orange and mosambi juices. Furthermore, most of the existing literature on microbial stability, enzyme activity, oxidation rate, and nutrient degradation during storage are not consistent among different works. In some cases, while homogenization may enhance physical stability, it may negatively influence chemical stability. Most studies investigate preservation strategies under optimal refrigerated storage, while realistic distribution conditions often involve temperature abuse or ambient storage. The interactions among pre-treatment, homogenization, preservatives, and storage temperature relative to the stability of juice are seldom investigated together; thus, research findings may hardly be applicable to commercial juice processing in a practical way. Future studies aim at combining several preservation methods together. Important work now links gentle heat or non-heat techniques with natural antimicrobials, better packaging, along with regulated storage to boost shelf life while keeping food's taste and nutrients intact. Researchers are focusing more on how these combined steps interact, fine-tuning settings using predictive models, besides creating simple-label options that match what buyers want.

10. Conclusion

Fruit juices remain difficult to stabilize due to their high moisture content, active enzymes, and sensitive nutrients like Vitamin C. This review concludes that quality loss is a system problem caused by the combined forces of microbial growth, enzyme activity, and oxidation. While traditional heat processing ensures safety, it often sacrifices taste and nutrition. Newer non-thermal methods preserve fresh-like quality much better, but they frequently fail to fully deactivate enzymes. This means that processing alone is rarely enough to guarantee a long shelf life, especially if the juice is not kept cold. To achieve a truly stable, premium product, an integrated "hurdle" strategy is required. This involves pairing optimized processing with essential pretreatments like homogenization for cloud stability alongside high-barrier packaging and suitable preservatives. The study highlights that even the most advanced techniques are rendered useless by temperature abuse; therefore, refrigerated storage remains the most critical factor. Future progress in the industry depends on refining these combined methods to maintain high nutrient levels and fresh flavor while remaining practical for large-scale production and real-world handling.

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