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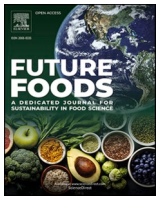

Exploring the potential of emerging thermal and non-thermal processing techniques for tomato juice preservation: A comprehensive review

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ABSTRACT

Tomato juice is a nutrient-rich beverage due to its high content of carotenoids, phenolics, and vitamin C, which increase its functional importance. However, its high perishability and enzymatic activity necessitate proper processing approaches to maintain safety. This review highlights the effects of thermal and non-thermal processing techniques on tomato juice. It focuses on safety, enzyme activity, functionality, storage stability, and retention of nutrients and bioactive compounds. Techniques discussed include pasteurization, hot break (HB), cold break (CB), ohmic heating (OH), microwave heating, ultrasound (US), high hydrostatic pressure (HHP), cold plasma (CP), pulsed electric field (PEF), hydrodynamic cavitation (HDC), ultraviolet light-emitting diodes (UV-LED), and dynamic high-pressure microfluidization (DHPM). Across studies, non- thermal techniques and hybrid approaches were consistent in better retention of bioactives, and antioxidant activity (AOA). These also resulted in preservation of color, and improvement of storage stability, while attaining microbiologically pure juice. Among all, HHP, CP, and US combined with heat effectively enhanced juice nutrients and bioaccessibility, as well as prolonged the storage life with limited resource usage, consistently. Combined strategies further enhanced microbial safety. In contrast, traditional thermal approaches were commonly used to guarantee microbiological safety. However, these lowered carotenoids, ascorbic acid (AA), and phenolic compounds. These also resulted in loss of color and flavor changes. In conclusion, novel thermal and non-thermal techniques, as well as their combination with other approaches, exhibit an eco-friendly and energy-optimized substitute for traditional processing. Future investigation should be carried out to explore the industrial scale-up, interactions of carotenoids, cost effectiveness, and intelligent hybrid or combined process strategies for the overall safety of tomato juice.

1. Introduction

Fruits and vegetable juices play a significant role in the human diet due to their rich nutritional value. These contain vitamins, minerals, and bioactives, which supports overall human health and well-being (Purwanta and Timur, 2024; Tharwat et al., 2024; Ullah, 2024; Wang et al., 2025). Among these, tomato (*Solanum lycopersicum* L.) is an economical, bright red, and sub-spherical-shaped berry, considered worldwide as both a vegetable and a fruit (Li et al., 2025; Zhang et al., 2024). It is recognized as the world's second most cultivated and consumed crop due to its high nutritional value and distinctive aroma. China alone contributes 30 % of global tomato production and consumption (Khalid et al., 2024; Salazar et al., 2025; Statista, 2023). According to the Food and Agriculture Organization, the worldwide tomato cultivation was 4.92 M ha, with a yield of 186.1 M tons in 2022 (Food and Agriculture Organization of the United Nations, 2024a). It is consumed fresh, boiled, or fried, or in processed forms, such as sauces, salads, juices, pastes, and ketchup, through the conditioning and milling of pulps after removing peels and pericarp (Al-Muslhi and Ali, 2024; Guo et al., 2025; Zhang et al., 2024). Tomato or its derivatives, mainly juice,

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are known for their richness in bioactives and nutrients (Nazir et al., 2024; Zhang et al., 2024). Bioactives, mainly lycopene, carotenoids, vitamins (A, C, and E), flavonoids, and phenolics, confer antioxidant and protective effects against cancer, metabolic syndrome, cardiovascular diseases, and inflammation in humans. On the other hand, nutrients such as potassium, folate, minerals, and dietary fiber improve nutrition and consequently have a significant impact on the global food industry (Li et al., 2025; Salazar et al., 2025; Wang et al., 2025). An overview of tomato fruit structure and its main nutritional components have been illustrated in Fig. 1. Globally, the trade volume of processed tomato juice has progressively increased to 79,768.95 tons in 2023. The processed tomato juice also offers micronutrients better than fresh tomatoes while preserving nutrition and bioactives (Food and Agriculture Organization of the United Nations, 2024b; Guo et al., 2025; Nazir et al., 2024).

However, fresh, unpasteurized tomato juice has a very limited shelf life of up to 3–5 days due to rapid microbial growth. The juice is susceptible to several pathogenic and spoilage microbes such as *Escherichia coli, Salmonella typhimurium*, and *Listeria monocytogenes. E. coli*O157:H7 exhibits acid adaptability, so the Food and Drug Administration mandates its 5-log CFU/ml reduction in juice (Kim et al., 2019; Ibrahim et al., 2021; Mahmood et al., 2024; Kusalaruk et al., 2024; Farooq et al., 2025; Al-Rawashdeh et al., 2024; Khan et al., 2025;). Polyphenol oxidase (PPO), lipoxygenase (LOX), polygalacturonase (PG), and pectin methylesterase (PME) activity cause changes in color, texture, nutrition, and total phenolic content (TPC) through oxidation, which consequently contribute to juice browning (Akdemir Evrendilek and Hitit Özkan, 2024; Musmalika et al., 2025). In China, tomato juice can get contaminated with *Alicyclobacillus acidoterrestris* (AAT) spores during pasteurization. It has become a potent challenge for juice deterioration and ultimately causes financial burden (Selim et al., 2024; Wahia et al., 2025a). The novel agricultural methods are also used to enhance the juice yield, which causes a negative impact on juice flavor, making flavor improvement a primary issue for juice processing (Guo et al., 2025). Conventional methods, including pasteurization, high-temperature short-time (HTST), and ultra-high-temperature treatment, effectively improve shelf life. But these can result in loss of heat-sensitive nutrients, color value, and off-flavor can also develop, consequently minimizing the market acceptability (Kusalaruk et al., 2024; Li et al., 2025). On the other hand, chemical preservatives are also being used widely. But these have lower consumer acceptability, because they insist on the use of chemical-free, minimally processed juices (Rathnayake et al., 2025). Tomato juice is the most sensitive one because it contains high levels of bioactive substances, which are easily degraded during the traditional processing. Enzymatic and microbial activity also pose a further threat to the quality of the juice (Salazar et al., 2024; Zhang et al., 2024; Yu et al., 2024). Thus, industrial and local juice producers are adopting alternative novel thermal and non-thermal approaches to obtain safe tomato juice while maximizing its nutritional value, bioactive compounds, and sensory characteristics (Akdemir Evrendilek and Hitit Özkan, 2024; Wang et al., 2025). These techniques provide microbiologically safe tomato juice with improved nutritional, bioactive, and sensory properties (Salazar et al., 2024; Zhang et al., 2024). These sustainable and effective approaches include OH, radiofrequency heating, microwave heating, HHP, US, PEF, CP, UV-LED, HDC, and DHPM (Kusalaruk et al., 2024; Salazar et al., 2024; Zhang et al., 2024).

Although the previous literature has focused on conventional and novel processing approaches, it covers general beverages such as pomegranate and watermelon juices but not tomato juice. To the best of our knowledge, no previous studies have covered individual and comparative impacts of thermal and non-thermal processing techniques on the quality and storage stability of tomato juice in a single comprehensive context. Previous studies have also not explored the mechanisms, scalability, and sustainability of novel non-thermal techniques. To address this gap, this review aims to provide an updated and detailed overview of both conventional and emerging processed tomato juices. Its primary focus is on the impact of processing techniques on safety, nutrition, physicochemical characteristics, and storage stability. It also briefly explains the basic heat mass transfer mechanisms, challenges, and future recommendations to provide for sustainability and quality in tomato juice.

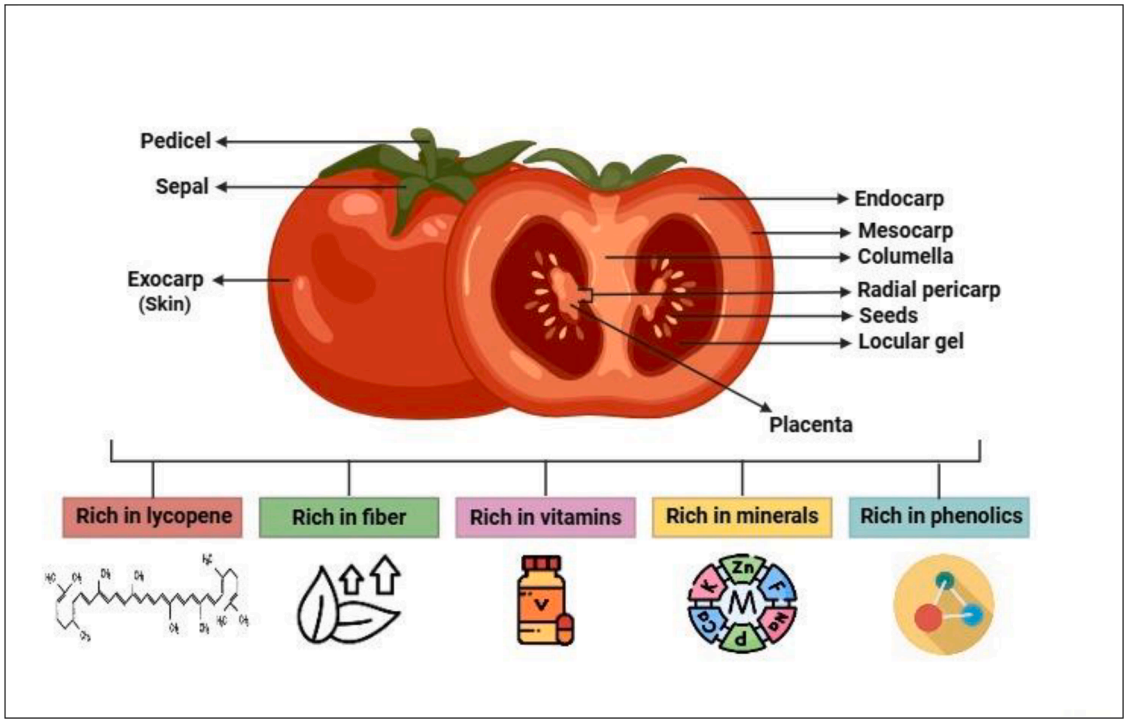

Fig. 1. Structure and main composition of the tomato fruit.

2. Methodology

For this narrative review, we followed a systematic methodology. We first identified and defined the keywords relevant to thermal and non-thermal techniques for the preservation of tomato juice. We searched these keywords mainly on two databases, Scopus https://www.scopus.com and Google Scholar https://scholar.google.com, to screen relevant studies within the timeline of 2019–2025. We searched "thermal processing", "tomato juice", "non-thermal processing", "nutrition", "quality", "safety", "shelf life", "preservation", and "storage stability by combining them differently in each database." We also individually searched all techniques using the keywords "heat or pasteurization, or ohmic heating or microwave heating", "hydrodynamic cavitation", "ultrasound", "cold plasma", "high pressure processing", "high pressure microfluidization", "UV-LED", and pulsed electric field". After that, studies were selected based on inclusion or exclusion criteria. We included those research papers whose titles and abstracts were about the preservation of tomato juice by thermal and non-thermal techniques. While the exclusion criteria were as follows:

The study was irrelevant to the preservation of tomato juice by these techniques.

The full text of the study was not available.

The study was not in the English language.

The study was not in the timeframe of 2019 to 2025.

The study was a duplicate research article.

The study was a review paper, conference, proceeding, or book chapter.

Finally, the screened articles were synthesized in a narrative way, highlighting the effects of thermal and non-thermal techniques on the microbial and enzymatic inactivation, physicochemical properties, nutrition, sensory quality, and storage of tomato juice.

3. Thermal processing

Table 1 covers the effect of traditional and novel thermal techniques effect on the overall preservation of tomato juice. This comprehensive table also includes emerging non-thermal processing techniques and synergistic approaches.

Thermal processing (TP), conventionally known as pasteurization, is the most established method for stabilizing tomato juice through controlled heat application (Salazar et al., 2025; Tumbarski et al., 2021). TP, due to its realism and cost efficiency, is one of the most widely used treatments for tomato juice, while ensuring microbiological safety and enzymatic stability (Salazar et al., 2024; Zhang et al., 2024). Final pasteurization, such as heating at 100 °C for 7 min, is commonly applied to achieve commercial sterility (Pizarro-Oteíza and Salazar, 2022; Zdravković et al., 2019). The process functions by transferring heat into the juice, raising temperatures sufficient to denature microbial proteins and inactivate endogenous enzymes. OH is a novel thermal food processing technique in which electrical current passes directly through a product, generating heat internally due to its electrical resistance (Alkanan et al., 2021; Kim et al., 2019). The process works by applying alternating current across the product, converting electrical energy into heat (Kim et al., 2019). Microwave heating is a novel volumetric heating method that uses electromagnetic waves in the microwave frequency range (300 MHz-300 GHz) to rapidly heat foods or liquids. These waves lead to polar molecules oscillation in juices, resulting in even internal heating, which effectively inactivates microbes and enzymes, while maintaining nutrition and acceptability (Sofizadeh et al., 2023). HB (93–99 °C) is an enzyme inhibitor that fastens pectolytic enzymes, so that the enzymes cannot break down the pectin and yields a more viscous tomato juice. CB (67–77 °C) cannot completely inactivate such enzymes, and results in a less viscous juice. These two processes are based on the idea of disrupting the enzymes' structure thermally. It decreases the activity of pectinase and oxidase, while prolonging shelf life and enhancing consumer acceptability (Salazar et al., 2025). HTST quickly heats juice to around 92–95 °C within short periods of time. It inactivates the enzymes and denatures microbial proteins with minimal loss of nutrients and pigments (Polak et al., 2024). The most important bioactive compounds that define the quality and functionality of tomato juice are vitamin C, phenolics, flavonoids, tannins, and carotenoids like lycopene. Key quality parameters that affect flavor, texture, preservation, and shelf life include acidity and pH. Lycopene helps to provide the redness and AOA properties, whereas phenolic and flavonoid compounds help to improve nutritional and functional properties. So, their preservation by means of optimized processing guarantees high quality and health-enhancing prospects of tomato juice.

When tomato juice was processed with heat treatment, it caused cooked corn or potato, onion, and mushroom odor, resulting in cooked flavor due to the presence of volatile compounds (Liu et al., 2022). Similarly, in another study, the impact of TP on flavor and consumer response to tomato juice was investigated. At high temperatures, it resulted in the generation and degradation of cooked and green note volatile compounds, respectively, by the Millard reaction, carotenoids co-oxidation, and fatty acids oxidation, with a maximum overall liking of 6.15 (Koltun et al., 2022).

The impact of pasteurization on the carotenoids and AOA of tomato juice during storage was investigated. Samples stored at 4 °C in the dark did not change the levels of lycopene, β-carotene, and TA for two months. However, under such conditions, due to their non-stable nature, their losses reached ~ 45 %, 58, and 47 % by day and dark storage at 20 °C for 1 year. β-Carotene showed the lowest loss of >80 % under daylight storage at 4 °C, while TA activity was preserved >40 % (Zdravković et al., 2019). In contrast to previous study, when the combined post-processing impact of bacteriocin and pasteurization on tomato juice was evaluated, it improved the storage up to 24 days. At the end of storage, TP reduced pH (4.15), TA (0.81 %), TPC (7 mgGAE/100 g), AOA (21 mmol TE/100 g by 2,2-diphenyl-1-picrylhydrazyl DPPH assay), chlorophylls (15.4μg/g), carotenoids (12 μg/g), and organic acids (citric acid (17.5 mg/100 g), and fumaric acid (35 mg/100 g), while increasing the TSS (5 %). The reduction in acids can be a result of reduced microbes. The control samples exhibited the highest reduction and increment of pH (4.9) and TA (0.94 %). TP combined with bacteriocin exhibited the highest inactivation of bacteria (3×10^4 log CFU/mL) and yeast (1.9×10^2 log CFU/mL), without fungal decay (Tumbarski et al., 2021). The impact of microwave heating-assisted vacuum evaporation on the quality and process efficiency of tomato juice was evaluated. It resulted in lower degradation of AA (35.6 mg AA/100 g) and TPC (364.9 mg GA acid/100 g), with processing time 2.3–6.3 times and energy consumption 30–71 % lower than those of conventional heating. A higher heating rate reduced evaporation time, resulting in lower degradation of AA. While, a lower microwave power released phenolics bound to cell structures of tomato juice, resulting in reduced TPC degradation (Sofizadeh et al., 2023). However, these results were higher as comparable to the previous synergistic approach study.

The impact of TP and oil type on the lycopene bioavailability and oxidative stability of the tomato juice containing tomato seed oil. The juice was topped with tomato seed oil, which was extracted by using tomato seeds (a by-product of tomato processing) to increase the bioaccessibility of fat-soluble compounds like lycopene and oxidative stability of juice. TP of tomato juice without oil addition resulted in 17.8 % lycopene bioaccessibility by breaking down the cell structure and obstacles around lycopene. However, it was lower than when emulsified oil was added (44.8 %), because large emulsion molecules result in more repaid lipase digestion and larger micelle development resulting in more lycopene solubility. Oil addition better increases lycopene bioavailability than TP alone. Tomato juice without oil addition exhibited a similar color difference (L*=70.28, a*=13.42, b*=99.55) to the untreated ones. Heat in the presence of emulsion also presented the highest turbidity of almost 48,000 FNU because of white-opaque appearance of emulsion (Ghasemi Baghabrishami and Goli, 2023).

Table 1
. Impact of thermal and non-thermal processing techniques on the overall safety of the tomato juice.

Processing category	Processing technique	Processing parameters	Storage conditions	Effect on microbial safety	Effect on quality and functionality	Effect on Shelf Life	References
Thermal	Heat	96 °C and 30 s	4 °C for 22 and 40 days	LOX and HPL activity decreased	Volatile aldehydes decreased except (E)-2-hexenal Alcoholic content increased Lycopene content slightly increased	Extended shelf life up to 40 days	(Baenas et al., 2021)
	Heat	100 °C and 7 min	In the light and dark at 20 °C, and in the dark at 4 °C for 365 days	-	β-Carotene significantly decreased during 1 year of storage Lycopene decreased during 1 year of storage	Extended shelf life up to 365 days	(Zdravković et al., 2019)
	Heat	90 °C and 15 min	-	-	Resulted in cooked off-flavor	-	(Liu et al., 2022)
	Heat	85 °C and 30 s	-	-	Lycopene bioaccessibility increased Oxidative stability decreased during storage	-	(Ghasemi Baghabrishami and Goli, 2023)
	Heat	70–90 °C and 0–60 min	-	-	Carotenoids, vitamin C, and provitamin A decreased	-	(Ordóñez-Santos and Martínez-Girón, 2020)
	OH	88–98 °C and 5–20 min	-	Significant effect on the inactivation of *Byssochlamys fulva*	By increasing the temperature, pH and TSS increased TA decreased than at a lower temperature	-	(Mokhtari and Zia, 2024)
	Pasteurization	75 °C and 10 min	4 °C for 0–24 days	The fungi count significantly decreased At the end of storage, it reduced near to the detection limit Total plate count and yeast increased at the end of storage The combined treatment with bacteriocin exhibited lower counts than pasteurization	Non-significant change in pH and TA Increased TSS Organic acid levels and TPC decreased Decreased slightly in chlophylls and carotenoid contents Presented a lower AOA, which further decreased throughout the storage During storage, TA, organic acids, and TSS increased while pH and TPC, and bioactives decreased Combined treatment with bacteriocin presented somewhat similar results	Extended shelf life up to 24 days	(Tumbarski et al., 2021)
Non-Thermal	CP	3–5 min and 40 and 45 V	-	PME and TVC activity significantly decreased	TFC, AA, and AOC decreased	-	(Ali et al., 2024a)
	US	4–6 min; 57- 74 W and 50 % duty cycle	4 and 20 °C for 28 days	No effect on *Limosilactobacillus reuteri*	-	Non-significant improvement in shelf life	(Giordano et al., 2022)
	TS	20–60 °C; 0- 10 min; 250 W and 0–130 kHz	4 °C for 0–7 days	Microbial load decreased	Color attributes, polyphenol, lycopene, anthocyanin, and AOC retention increased than thermal treatment	Extended shelf life up to 7 days	(Lafarga et al., 2019)
	CP	25 °C; 0–5 min and 45 V	-	-	pH slightly decreased TSS and browning index increased A very low color change AOC, flavonoids, and TPC slightly decreased	-	(Ali et al., 2021)
	CAP	30–300 s; 40 W; 3.8 kV and 50 Hz	4 °C for 0–5 days	Total aerobic mesophilic counts decreased	Non-significant effect on dry matter and pH Lycopene slightly increased Vitamin C slightly decreased	Extended shelf life up to 5 days	(Starek et al., 2019)
	Mild heat	60 °C and 30 min	4 and 15 °C for 0–7 days	*Eschericia coli* significantly decreased when combined with 0.05 % clove extract	-	Extended shelf life up to 7 days	(Kusalaruk et al., 2024)

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Table 1 (*continued*)

Processing category	Processing technique	Processing parameters	Storage conditions	Effect on microbial safety	Effect on quality and functionality	Effect on Shelf Life	References
	US	2–10 min; 28 and 40 W cm^{-2} and 20 kHz	4 °C for 1–10 days	Free from microbes for up to 10 days of storage	Non- significant effect on pH A little effect on lycopene content Vitamin C slightly decreased	Extended shelf life up to 10 days	(Starek et al., 2021)
	HDC	35–62 °C; 15 min and 3–0.3 bar	5 °C for 1–14 days	Microbial inactivation increased	Particle size reduced Apparent viscosity increased Stability increased for up to 14 days No change in lycopene and phenolic compounds	Extended shelf life up to 14 days	(Terán Hilares et al., 2019)
	HDC	5–30 min and 5–15 psi	4 °C for 15 days	Lower inactivation of PME and total plate count than thermal treatment	Non- significant effect on lycopene content AA and TPC highly retained Little effect on stability and viscosity pH, TSS, and TA remained stable More retention of bioactives and better physicochemical properties for up to 15 days	Better shelf life than TP up to 15 days	(Vigneshwaran et al., 2022)
	CAP	25–29 °C and 0–600 s	4 °C for 1–10 days	Microbes inactivated significantly	Significant effect on pH, TSS, carotenoids, and AA	Extended shelf life up to 10 days	(Starek et al., 2020)
	CAP	29.6 °C and 30–600 s	6 °C for 10 days	TPC and Y&M slightly decreased	TSS, pH, lycopene, and vitamin C significantly increased During storage, slight changes in physicochemical properties	Extended shelf life up to 10 days	(Starek-Wójcicka et al., 2023)
	US	30 °C; 0–40 min; 480 W and 40 kHz	-	TVC, PG, and PME significantly inactivated	TFC, TPC, AA, carotenoids, lycopene, colloidal stability, and AOA significantly increased	-	(Faisal Manzoor et al., 2023)
	Microfluidizer system	0–120 MPa	-	-	Particle size decreased Stability increased for up to 28 days Lycopene content and bioaccessibility increased	-	(Dai et al., 2022b)
	TS	50–70 °C; 5–10 min and 480 W	-	Significant microbial inactivation similar to pasteurization	pH, TSS, and TA increased similar to pasteurization Highly significant effect on color retention and stability Lycopene, AA, and flavonoid content, AOA, sensory quality, and volatile compounds increased	-	(Li et al., 2025)
	Cold US	10 °C; 30 min and 87.52 W/cm^2	-	Microbes reduced significantly	Stability, TPC, viscosity, and carotenoids increased	-	(Gao et al., 2019)
	Power US	28 kHz; 10–50 °C and 33.33–100 % duty cycle	-	-	Increased aroma with the release of trans-2-hexenol and 6-methyl-5-hepten-2-one compounds	-	(Guo et al., 2025)
	UV-LED	250–350 min/mL and 5–20 min	-	Significant reduction of AAT spores	Bioactive compounds retention and AOA by DPPH decreased	-	(Wahia et al., 2025b)
	ISMS	33–62 °C and 30–120 MPa	4 °C for 28 days	-	Increased lycopene amount and bioaccessibility Decreased particle size Physical stability increased depending on the pressure Turbidity significantly decreased during storage	Extended shelf life up to 28 days	(Dai et al., 2022a)

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Table 1 (*continued*)

Processing category	Processing technique	Processing parameters	Storage conditions	Effect on microbial safety	Effect on quality and functionality	Effect on Shelf Life	References
	PEF	17.2–24.1 kV/cm; 130–1040.5 μs and 1.43–29.13 J/kg	-	Decrease in pH Increase in conductivity, TPC and AOC Non-significant change in TSS	Decreased pH Non-significant effect on TSS and color values Increased electrical conductivity, AOC, and TPC Decreased PPO and LOX counts	-	(Akdemir Evrendilek and Hitit Özkan, 2024)
Thermal and non-thermal	UV-LED irradiation and heat	UV-LED irradiation: 28.5 °C; 2–10 mW and 265–278 nm Heat: 70 °C and 14 min	4 °C for 0–28 days	*Listeria monocytogenes* and *E. coli* counts decreased than the heat-treated juice	-	Extended shelf life up to 28 days	(Salazar et al., 2024)
	UV-LED irradiation, HB, and CB	UV-LED irradiation: 28.5 °C; 5–15 min and 278 nm HB: 90 °C and 5 min CB: 60 °C and 5 min	-	Residual PME activity decreased significantly, similarly to CB Residual PG activity decreased, similarly to HB	pH and TA decreased Lycopene, AOC, TPC,° brix, and viscosity were similar to HB	-	(Pizarro-Oteíza and Salazar, 2022)
	HHP and HTST	HHP: 10 min and 550 MPa Heat: 110 °C and 8.6 s	4 °C for 28 days	-	Polyphenols, carotenoids, AA, and AOC increased than HTST After 1 week of storage, similar results to HTST Caffeic acid, quercetin, ferulic acid, and p-coumaric acid remain stable during storage than HTST	HTST Extended shelf life but less efficiency than HHP up to 28 days	(Wang et al., 2023)
	US and Heat	50- 70 °C and 48-120W	-	-	Lycopene and vitamin C increased	-	(Alaei et al., 2022)
	Microwave-vacuum heating	21 °C and 0–1000 W		-	AA and TPC slightly decreased		(Sofizadeh et al., 2023)
	HIPEF and heat	HIPEF: 1500 μs; 35 kV/cm; 4 μs bipolar square-wave pulses and 100 Hz Heat: 90 °C and 60 s	-	-	Vitamin C and TPC significantly decreased Non-significant effect on AOA Higher degradation than HIPEF	-	(Odriozola-Serrano et al., 2022)
	OH and UV-C irradiation	UV-C irradiation: 45.6 and 191.5 mJ/cm^2 OH: 60–63 °C; 50–210 s; 13.4 Vrms/cm; 0.05 duty ratio and 500 Hz	-	Microbes significantly reduced	Non-significant deterioration of color and lycopene content	-	(Kim et al., 2019)
	UV-LED irradiation, HB, and CB	UVB-LED: 46, 69, 92 mJ/cm^2 and 14- 28 min UVC LED: 167, 250, 333 mJ/cm^2 and 14- 28 min CB: 60 °C and 5 min HB: 90 °C and 5 min	-	Non-significant difference between HB and UVB-LED irradiation in PME inactivation UVC-LED exhibited the highest PME reduction	Non- significant change between UVB-LED and CB in TPC, TFC, and AOA	-	(Salazar et al., 2025)
	US and heat	37 kHz; 50–70 °C and 48–120W	-	-	Increased the lycopene and AA content than the thermal concentrator At lower power, particle size increased	-	(Alaei et al., 2022)
	HPH and US	25 Hz; 20 min; 200–600 W and 50 μm amplitude	-	-	Increased lycopene content and carotenoid bioaccessibility than HPH US increased a* and b* values while decreasing L* value than HPH	-	(W. Zhang et al., 2019a)

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Table 1 (*continued*)

Processing category	Processing technique	Processing parameters	Storage conditions	Effect on microbial safety	Effect on quality and functionality	Effect on Shelf Life	References
	HHP and TP	HHP: 400 and 600 MPa and 2–10 min TP: 65–115 °C and 2–10 min	-	-	Lycopene and β-β-carotene retention was higher than TP Exhibited higher degradation of vitamin C than TP a*b*, C*, and h* values exhibited similar trend as of TP	-	(Ibrahim et al., 2021)

Lipoxygenase (LOX); Hydroperoxide lyase (HPL); Ohmic heating (OH); Total Soluble Solids (TSS); Titratable acidity (TA); Total phenolic Content (TPC); Antioxidant activity (AOA); Cold plasma (CP); pectin methyl esterase (PME); Total viable count (TVC); Total flavonoid content (TFC); Ascorbic acid (AA); Antioxidant capacity (AOC); Ultrasound (US); Thermosonication (TS); cold atmospheric pressure plasma (CAP); Yeast and Mold (Y&M); Hydrodynamic cavitation (HDC); Total plate count (TPC); Total viable count (TVC); Polygalacturonase (PG); Ultraviolet- light emitting diode (UV- LED); Alicyclobacillus acidoterrestris (AAT); Industrial-scale microfluidizer system (ISMS); high-intensity pulsed electric fields (HIPEF); Hot Break (HB); Cold Break (CB); High hydrostatic pressure (HHP); High- temperature short-time (HTST); High pressure homogenization (HPH); Thermal processing (TP).

Overall, TP can guarantee microbial safety and enzymatic inactivation. But it can result in loss of heat-sensitive nutrients, change in flavor, and reduction in turbidity based on the processing conditions. Heating method and processing conditions are the key factors in nutrient preservation. Different thermal treatments do not exhibit similarities, but similar trends are observed across studies in combined approaches such as oil addition and bacteriocin application along with thermal treatment and improves bioavailability and microbial stability. TP is considered to be safe when compared to the emerging non-thermal methods such as US and HHP. However, it is not much efficient in the retention of nutrients and the preservation of bioactive compounds.

4. Cavitation-based technologies

4.1. Ultrasound

US (sonication) is a non-thermal, sustainable food processing technology that applies high-power sound waves to enhance preservation and quality with low energy use (Faisal Manzoor et al., 2023; Qadeer et al., 2025). Its primary mechanism is acoustic cavitation, where rapid formation and collapse of microbubbles generate localized mechanical and chemical effects. These induce microbial inactivation through membrane disruption and free radical generation that aids in microbial safety and quality enhancement (Starek et al., 2021). Fig. 2 illustrates the same key mechanism of US to inactivate microbes. Tomato fruit and

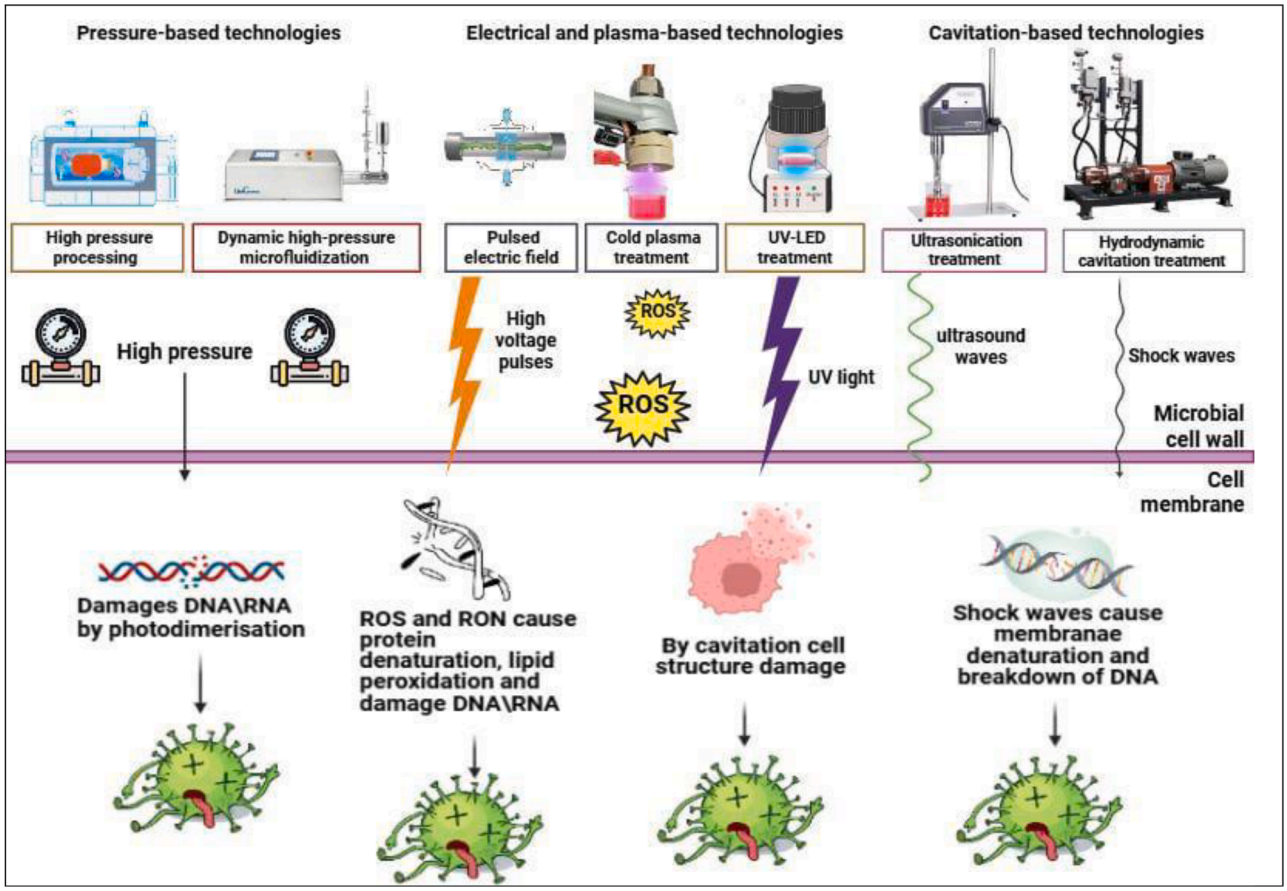

Fig. 2. An illustration of the general microbial inactivation mechanism of non-thermal techniques.

juice contain microorganisms that lead to spoilage and food-borne diseases, and thus conventional and new processing technologies are used to guarantee their safety. Pectolytic enzymes, such as PME, are also naturally occurring in tomatoes and are released during the extraction of the tomato juice, resulting in the breakdown of pectin and the formation of pectin precipitate, which adversely affects the stability and texture of tomato juice. Beyond decontamination, power US is also used as an innovative approach to enhance flavor quality by facilitating the release of nonvolatile glycosidically bound volatiles (GBVs) (Altarjami, 2025; Anwar et al., 2024; Guo et al., 2025). The US process also aids in improving the overall physical stability of products like juice by enhancing colloidal stability through reduced particle size distribution, while also contributing to the inactivation of spoilage enzymes (Faisal Manzoor et al., 2023; Khalid et al., 2025; Meng et al., 2024; Raza et al., 2025; Rueangsri et al., 2025).

US processing was compared with high pressure homogenization (HPH) to check the stability and bioavailability of tomato juice. US by cell collapse resulted in higher lycopene content (921 μg/100 g) and by promotion of all-trans lycopene isomerization, its higher bioaccessibility (1.76 times) than HPH, which exhibited a maximum of 777 μg/100 g lycopene and 1.43 times bioaccessibility. However, ζ-carotene bioaccessibility was slightly lower in US-treated (0.95 times) samples in comparison to HPH (1.06), due to microenvironment impact (Zhang et al., 2019a). The impact of the US on microbial safety and quality parameters of tomato juice was assessed. The US prolonged the storage of tomato juice by >10 days, because there were no spoilage microbes in it. While in untreated samples, *mesophilic aerobic* microbes, *Lactic acid bacteria* (*LAB), Coliforms*, and *Yeast* count increased to 6.8, 5.6, 3.1, and 3.9 log 10 CFU/g. Similar results were found for pH (4.55) in both treatments (TP and US), with a small reduction in lycopene (3.53 mg/100 g) and AA (12.30 mg/100 g) observed until the end of storage, whereas the untreated sample deteriorated (Starek et al., 2021).

The effect of sonication on the decline of fungicide and quality attributes of tomato juice was evaluated. It significantly reduced the total volatile count (TVC) up to 1.91 log CFU/mL. It also significantly decreased PG and PME up to 44.32 % and 64.2 %, due to reactive species generation, which results in the oxidation of amino acids, making the enzymes unstable and varying their catalytic activity. It significantly improved the overall quality attributes with a maximum improvement of TPC, total flavonoid content (TFC), AA, and carotenoids, as well as AOA, up to 488 GAE μg/mL, CE 424 μg/mL, 22.03 mg/100 mL, 33.03 mg/kg, 109.16 mg β-carotene/100 g, and 32.45 μM TE/g by oxygen radical absorbance capacity assay, respectively. While AA enhancement occurs by removing dissolved oxygen. The colloidal stability also significantly improved by decreasing viscosity, particle, size and stability, mainly due to pectin and cellulose collapse, and stronger interactions between small-sized particles, respectively (Faisal Manzoor et al., 2023). The impact of cold ultrasound treatment (CUT) on the safety and quality of unpasteurized tomato juice was evaluated. The CUT-treated sample presented a count of 10^3 CFU/mL, significantly lower than fresh juice (10^4 CFU/mL). Higher reduction in counts was due to abundance of carotenoid content and AOA of the sample as well as reduced temperature during CUT. On the other hand, there was a non-significant change in TSS, pH, and TA with values of 4.23 °Brix, 4.36, and 0.46 g/100 g. Such treated juice with a spatial-temporal nature showed a color difference of 2.55, with little reduction in redness due to oxidation or isomerization of the carotenoid content. Cloud stability significantly decreased to 34.69 % relative to the fresh sample (68.56 %). While apparent viscosity, AA, TPC content, AOA, and total carotenoids bioavailability increased to 175.63 mPa·s, 16.80 mg/100 mL, 21.60 mg GAE/100 g, 154.98 μmol TE/100 g wb by 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assay, and 18.81 %, compared to fresh ones (79.82 mPa·s, 13.76 mg/100 mL, 17.32 mg GAE/100 g, 111.63 μmol TE/100 g wb, and 8.95 %, respectively) (Gao et al., 2019).

Thermosonication (TS) was applied to anthocyanin-enriched tomato juice to obtain a safe and quality juice. TS reduced total aerobic mesophiles (0.64 log cfu/g) more than TP (3.3 log cfu/g), at the end of storage, because microbes became more sensitive to heat, pressure, and acidic environment as a consequence of US treatment. PG and PME activity were highest in TS-treated juice (~25.5 U/mL) than in TP (~ 1.5 U/mL) and the fresh sample (~ 21 U/mL). During 7 days of storage, TS retained physicochemical quality, with slight color change (ΔE) (0.7), pH (3.88), TA (4.55 g/L), and TSS (6.67°Brix), exhibiting better results than TP (3.4, 3.92, 4.26 g/L and 6.40°Brix) and fresh sample (3.92, 4.50 g/L and 6.63°Brix), respectively. TS presented the highest TPC (45.6 mg/100 mL), and AOA (~ 50 mg/100 mL by FRAP assay), in comparison to TP (~ 34 mg/100 mL and 45 mg/100 mL) and the fresh sample (~43 mg/100 mL and 37 mg/100 mL). Lycopene also reduced to 0.55 mg/100 mL, lower than the fresh sample (1.2 mg/100 mL), and higher than TP (0.52 mg/100 mL). While anthocyanin content showed similarity among treatments (~81–83 %) (Lafarga et al., 2019). The impact of TS on fresh tomato juice was evaluated. TS and pasteurization resulted in complete inactivation of total bacteria (1.05 log CFU/mL), yeast and mold (Y&M) (1.07 log CFU/mL), and *E. coli*(1.14 log CFU/mL), similar to previous studies. TS caused inactivation by chemical and mechanical effects, which contributed to cell damage and ultimately inactivation. However, it exhibited a non-significant change in pH, TSS, and TA, due to the escape of hydrogen ions within cells. It also better retained the color (a*= 2.4; b*≈ −1.25, and L*=29.38) than pasteurized (2.8, 0.28, and 24.83) and untreated juice (2.41, −1.42, and 26.58), respectively. Enhanced brightness by the US can be due to shear forces, which break down proteins and tissues, thereby enhancing the light transmission. It also significantly improved the lycopene, AA, flavonoids, and phenolics content to 42.13 %, 36.64 %, 33.94 %, and 34.06 %, attributed to the release of bound compounds from the cell wall and fibre. It also enhanced AOA 29.45 % by ABTS assay through intrinsic enzymes inactivation, sensory quality (overall acceptability 9.12), and volatiles than pasteurization (36 % and 7.87) and control samples (42.05 %), respectively (Li et al., 2025). Similarly, power US was applied to tomato juice for its flavor enhancement. It provided a better fruity and floral aroma than enzymatic or acid hydrolysis methods by releasing bound volatiles, mainly aglycones, including alcohols, esters, and alkenes at levels of 38,000, 28,700, and 24,200 μg/L, respectively (Guo et al., 2025).

4.2. Hydrodynamic cavitation

HDC is a non-thermal processing technology increasingly applied in food systems. It operates by forcing liquid through a constricted region, where the local pressure drops below the vapor pressure, leading to the formation of vapor-filled microbubbles. The rapid collapse of these bubbles' releases intense localized energy in the form of shock waves, microjets, and transient hot spots, as depicted in Fig. 2. This phenomenon results in microbial inactivation, particle size reduction, viscosity enhancement, and improved physical stability of products (Terán Hilares et al., 2019; Vigneshwaran et al., 2022).

The influence of the HDC process on the kinetics, shelf life, physicochemical properties, retention of bioactive compounds, and enzymatic activity of tomato juice was evaluated. HDC processing reduced only 15 % PME activity due to the mitigating impact during the cavitation process. TP exhibited better values of PME inactivation with 91.43 % reduction compared to HDC (2.72 %) due to enhanced dissolvable pectin. HDC exhibited a non-significant change in pH (4.4), TSS (5°Brix), TA (0.26 %), and lycopene compared to unprocessed juice. It also retained 93 % AA, 96.6 % TPC, and represented 89.2 % stability and 94.4 % viscosity. The reduced viscosity of the HDC compared to the control sample (5.91 cP) can be attributed to temperature rise, which increases molecular mobility. These values were significantly higher than heat treatment, which showed 61.4, 72.3, 37.7, and 83.2 % values, respectively. In terms of color, a maximum of 7.9 change in color values was observed, but a lower reduction than TP. HDC also retained better

quality than TP till 15 days of storage, although with a non-significant difference in TSS (4.9), pH (4.40), and TA (0.26). Viscosity remained stable (5.45 cP) but was higher than TP (4.90 cP) due to remaining PME activity. Sedimentation index (SI) and ΔE increased, but bioactive compounds decreased because of remaining O_2. HDC showed better results (41.52 %, 7.18, TPC: 41.19 mg GZE/100 mL, lycopene: 38.22 mg/kg, and AA: 10.01 mg/100 mL) than TP (29.23 %, 21.50, TPC: 30.41 mg GZE/100 mL, lycopene: 22.21 mg/kg, and AA: 6.13 mg/100 mL), respectively (Vigneshwaran et al., 2022). The impact of HDC on the physical characteristics and stability of tomato juice was investigated. It resulted in only 1 log CFU/mL inactivation of TPC, lower than TP (5 log CFU/mL). In comparison to study by Vigneshwaran et al. (2022), the PME inactivation was much lower and quality was less maintained. It also resulted in a maximum of 4.9 % PME inactivation, significantly lower than TP (92.2 %). Although both treatments exhibited a mild increase in their inactivation during 8 days of storage. The HDC reduced the particle size with diameters of >100 μm of $D_{[3,2]}$ and ≈ 250 μm of $D_{[4,3]}$, due to collapse of microbubbles, resulting in cell disruption and particle breakdown by excessive turbulence, compression waves, and fluid streams. It also enhanced the apparent viscosity, 3.7-fold greater than untreated samples, with no change in lycopene (35 mg/kg) and TPC (40.17 mg GAE/100 mL). HDC exhibited only >2 % SI for 14 days. That SI was significantly higher in stability as compared to control samples (68 %), through reduction of particle size, and huge biopolymer content, following Stokes' law (Terán Hilares et al., 2019).

Overall, cavitation-based technologies offer effective microbial and partial inactivation of enzymes and improve physical stability, color, and bioactive compound release. These preserve nutrients better, enhance antioxidant activity, and enable the bioaccessibility of compounds such as lycopene. That is why these techniques are more appropriate in high-quality and minimally processed tomato juice with enhanced sensory or functional properties compared to traditional thermal processing.

5. Pressure-based technologies

5.1. High pressure processing

HHP is a leading non-thermal preservation method in which foods packaged in flexible containers are subjected to uniform pressures ranging from 100 to 1000 MPa. Pressure disrupts non-covalent bonds in microbial proteins and enzymes, causing their inactivation as illustrated in Fig. 2 (Terán Hilares et al., 2019; Vigneshwaran et al., 2022). The preservation of covalent bond integrity is the reason HPP is superior at retaining the nutritional and sensory quality of juices compared to TP (Ahmad et al., 2024; Nadi et al., 2024). Beyond simple preservation, HPP also influences beneficial aspects of the product, such as promoting the bioaccessibility of key nutritional components (like phenols and lycopene) and modulating the volatile and non-volatile metabolite profiles (Hammoud et al., 2025; Wang et al., 2022, 2025).

The impact of HPP on bioactive compounds and AOA of tomato juice during storage was evaluated. HPP had higher carotenoids (137.41 μg/mL) as a consequence of protein–carotenoid complexes denaturation, TPC (49.85 mg GAE/100 g), AA (122.92 μg/mL), and AOA (188.37 mm Trolox/100 g) than HTST (107.90 μg/mL, 36.29 mg GAE/100 g, 111.07 μg/mL, 144.25 mm Trolox/100 g). After 7 days, TPC, AOA, lycopene, and carotenoids decayed to HTST levels. Carotenoid and lycopene content decreased as a result of Isomerization and oxidative degradation. During storage, decay in AA, TPC and polyphenols as well as pro-oxidant Millard products development results in reduced AOA. AA decreased due to non-enzymatic browning and oxidative degradation. After 4 weeks, AA (41.27 mg/mL), caffeic acid (8.31 μg/g), quercetin (4.77 μg/g), ferulic acid (1.86 μg/g), and p-coumaric acid (6.84 μg/g) remained higher in HPP. For 28 days, HPP and HTST treatments showed non-significant TVC (<2 log CFU/mL) and Y&M (<detection). HPP preserved Phenylalanine Ammonia-Lyase (76.79 %) and peroxidase (81.17 %), while PPO decreased 2.18 % due to phenolic product buildup, while HTST maintained only PAL (Wang et al., 2023). The effects of TP and HPP on the phytonutrients of tomato juice were monitored using analytical techniques and color measurement. HPP contributed to a lower decline of lycopene (3.6 %) and β-carotene (18.4 %) than TP (12 % and 23.3 %), respectively, further supporting the bioactives stability. But TP-treated samples exhibited lower breakdown of AA (35 %) in comparison to HPP (49 %). In juices containing only pulp, HPP showed only 4.68 ΔE with 30.63, 16.5, and 17.18 L*, a*, and b*-values, respectively, confirming previously reported color improvements. while TP resulted in a 6.18 value (Ibrahim et al., 2021). The impact of HPP and HTST on the metabolic profiling of tomato juice was determined. HPP slightly improved total carotenoids (1318 μg/g), mainly total lycopene (79.8 μg/g), by disrupting cell walls, which results in their weak bonding with the tissue matrix, similar to previous studies. HTST reduced these to 101 and 54.5 μg/g, respectively. HPP caused a non-significant change in AA (≈132 μg/g), but HTST significantly reduced it to ≈ 125 μg/g phytoene, exhibiting an effect of heat and pressure. Trans-lutein, and 13-cis-β-carotene exhibited similar results in fresh and treated juice samples with values of 21.5, 2.33, and 1.96 μg/g (Wang et al., 2022).

5.2. Dynamic high-pressure microfluidization

DHPM is a non-thermal processing technology that applies extremely high pressures, typically 50–200 MPa for conventional HPH and up to 400 MPa for DHPM, to liquids through narrow channels or micro-orifices (Dai et al., 2022a; Zhang et al., 2019b). DHPM integrates multiple operations, including mixing, ultra-micro-crushing, and expansion, causing the liquid to split into fine streams and undergo vertical or Y-type impacts. This generates intense shear, turbulence, and cavitation, leading to ultrafine particle size reduction, improved colloidal stability, and uniform product structure (Zhang et al., 2019b, 2024). Fig. 2 also describes brief microbial inactivation mechanism through photodimerisation. DHPM is highly valued for its ability to achieve sterilization and superior product stability when compared to conventional thermal methods. DHPM also promotes the high retention of heat-sensitive bioactive compounds such as AA (Zhang et al., 2024), while the structural changes (like cell breakage and the promotion of lycopene isomerization) significantly increase the in vitro bioaccessibility of carotenoids like lycopene and β-carotene (Dai et al., 2022a; Vigneshwaran et al., 2022; Zhang et al., 2019b).

In a study by Dai et al. (2022a), the effect of microfluidizer pressure on the physicochemical characteristics and bioaccessibility of tomato juices was assessed. It significantly reduced the particle size to 30 μm as a result of cell structure breakdown by robust disruptive forces, by increasing pressure; consequently, lowering turbidity to >0.1. It significantly increased the carotenoids (33 μg/mL), lycopene (almost 28.2 μg/mL), and its bioaccessibility (14.1 %) due to their enhanced exposure to tissue, exhibiting consistent results with other pressure-based technique studies. The carotenoid accessibility was only >15 % in no lipid-rich foods mandatory for micelle solubilization. It exhibited a non-significant change in SI from 100 to about 93 %, due to reduced particle size, during 28 days of storage. The impact of DHPM and TP on the quality and volatiles of fresh tomato juice was determined. The impact of dynamic DHPM and TP on the quality and volatiles of fresh tomato juice was determined. Both treatments showed non-significant differences in pH, TA, and TSS; however, DHPM slightly increased pH (4.25) and TA (0.38 %), while decreasing TSS (4.22 °Brix), turbidity (24.58 NTU), lycopene (13.5 μg/mL), and browning (0.40) by inhibiting melanin free radicals generation. DHPM also enhanced juice brightness and AA (29 mg/mL, though lower than the control (35 mg/mL), and improved volatile compounds and SI, with a lower ΔE (0.89) than 1.88. The high juice brightness can be a result of reduction in particle size of the juice, which makes cellular matrix more uniform resulting in a better light reflection. While, volatile compounds

improvement can be a result of disruption of cellular material, which enhances porosity and facilitates escape of these compounds (Zhang et al., 2024).

Collectively, based on reviewed literature, pressure-based techniques are efficient in maintaining microbial and enzyme inactivation and retaining the heat-sensitive nutrients, bioactive compounds, and physicochemical properties. Such techniques are better in terms of retention of vitamins, carotenoids, and antioxidant properties, bioaccessibility, and colloidal stability. It makes them ideal in the preparation of high-quality and minimally processed tomato juice with high storage stability.

6. Electrical and plasma-based technologies

6.1. UV-LED

In the UV-LED technique, ultraviolet radiation emitting mainly from UVC type, provides a compact, energy-efficient, and mercury-free alternative to traditional UV lamps to ensure tomato juice safety. UV-LED cause microbial inactivation by damaging their DNA and hindering DNA replication as mentioned in Fig. 2 (Pizarro-Oteíza and Salazar, 2022; Salazar et al., 2025). UV-LED was applied to inactivate bacterial spores (*A. acidoterrestris*) in tomato juice. It reduced bacterial spores by 3.27 log CFU/mL, through extensive cell and DNA damage. This inactivation level was significantly higher than the conventional method, which contributed to <1logCFU/mL of inactivation (Wahia et al., 2025b). However, UV-LED was modeled, and its impact on inactivation kinetics as well as on the microbiological safety of the tomato juice was investigated. It exhibited a non-significant difference in counts of *E. coli*from 7 to 21 days of storage, after which they started to increase. While L. *monocytogenes* counts were stable from 7 to 14 days, after which they exhibited a non-significant change during storage, with 11.4 % lower counts in comparison to heat processing at the end of storage. UV-LED treatment exhibited lower counts than heat treatment from 14 to the 28th days of storage (Salazar et al., 2024).

UV-LED can achieve stability benefits while preserving and even increasing some bioactive compounds. The impact of UVC-LED irradiation processing on the enzymatic activity and quality of the tomato juice was determined. This technique contributed to a higher PME inactivation with 16.2 % residual activity, higher than CB (6.8 %) and HB (13.1 %), significantly dependent upon energy fluence and processing time. In the case of PG residual activity, it exhibited a maximum of 7.52 % residual activity, which was non-significant with HB but 49 % less than CB processing. The lower residual activity of both enzymes by UV-C-LED can be due to absorption of UV light, resulting in changes in the enzymes' configuration. Enzymes can also attach to chromophores outside their cells, so the development of an integrated backbone, cross-linking, and oxidized side chains can lead to modifications in enzymatic characteristics. It also resulted in 43.2 % and 57 % greater enhancement in lycopene levels in comparison to CB and HB, respectively. This processing exhibited non-significant change from CB processing in AOA (62.71 %) and viscosity (1.35Cp); however, 5.3 % more DPPH radical scavenging activity than HB. On the other hand, a similar case was with HB in TPC and TSS, and TA. This non-thermal processing caused a reduction in TPC (243.09 mg GAE /L) and TA (0.24 g citric acid/100 g) than CB (TPC=285.36 mg GAE/L; TA=0.25 g citric acid/100 g), but higher than control samples (TPC=216.73 mg GAE/L; TA=0.36 g Cctric acid/100 g). Higher TPC than control samples can be because of the build-up of polyphenolics or their collapse into smaller compounds. TSS value enhanced by the UV-LED technique (3.4 ^{o}Brix) than unpasteurized juice (3.3 ^{o}Brix). This irradiation processing also decreased pH (4.54) than the control (4.59) and TP (HB= 4.57 and CB= 4.56). However, there was a non-significant change in the case of density among all (Pizarro-Oteíza and Salazar, 2022). The impact of the UV-LED technique, optimized using response surface methodology, was evaluated in terms of modeling, inactivation kinetics, and activity of pathogenic microbes in tomato juice. UV-LED, dependent on energy fluence, resulted in a significant reduction of *E. coli*O157:H7 and L. *monocytogenes* up to 2.89 and 2.74 CFU/mL, correspondingly. However, TP exhibited higher inactivation, with 14 % and 2.7 % lower pathogens than UV-LED. UVB-LED and UVC-LED also exhibited performance similar to CB and HB, respectively, in quality. In contrast, UVB-LED achieved 22.7 % and 3.6 % higher AOA than UVC-LED (0.22 and 0.55 mmol TE/L) by DPPH and ABTS assays and had the lowest TPC reduction (8.9 %) than the untreated, followed by UVC-LED (16 %) and HB (21 %). Similarly, TFC increased with UVB-LED (12.18 % and 3.89 %) over untreated and CB-treated juice, whereas CB reduced TFC by up to 31.37 % compared to untreated juice. Carotene content enhanced by UVC-LED (30.50 %) and UVB-LED (14.41 %), though heat treatments presented higher values, with HB at 34.78 μg/100 mL and CB at 26.02 μg/100Ml. On the other hand, UVB-LED and HB presented non-significant results in PME activity with values of 38.5 and 45.3 %, higher than CB (63 %), significantly higher values than previously reported studies (Salazar et al., 2025).

6.2. Cold plasma

Among non-thermal techniques, CP is generated by electrical discharges in gases such as air or nitrogen, producing reactive oxygen and nitrogen species (RONS), ions, electrons, and UV photons that inactivate microorganisms and degrade chemical contaminants (Ali et al., 2021; Starek et al., 2019). These reactive substances oxidize lipids of membranes, denature proteins, and destroy the microbial DNA, resulting in the rupture of membranes and cell death. The acids produced by RNS also interfere with intracellular pH regulation to increase microbial inactivation (Naseem et al., 2025). A brief microbial inactivation description, aligned with text has also been illustrated in Fig. 2. Cold atmospheric pressure (CAP) plasma is normally generated with GlidArc reactors at ambient conditions, and forms long lived species such as NOx and H_2O_2, which allow penetration into liquid matrices deeper. In contrast, dielectric barrier discharge (DBD) plasma is generated by applying high voltage across electrodes separated by dielectric barriers. It generates strong electric fields and short-lived reactive oxygen species, including atomic oxygen and ozone (Ali et al., 2021; Starek-Wójcicka et al., 2023). These differences should be taken into consideration when choosing a plasma system to process juice. CP effectively extends shelf life and improves microbial safety while preserving heat-sensitive nutrients such as lycopene and vitamin C, making them advantageous over thermal pasteurization (Ali et al., 2024b; Starek et al., 2019).

In a study, DBD plasma was applied to tomato juice to determine its effect on a fungicide (thiram) decline and safety, as well as on quality parameters. It significantly reduced the TVC to 1.38 log CFU/mL, which is higher than the control samples (5.63 CFU/mL). DBD plasma, dependent upon voltage and processing time, significantly decreased the AA, TPC, and AOA of the juice to 17.82 mg/100 mL, 406.23 GAE μg/mL, and 17.60 μM TE/g DWμg/mL, respectively. DPD plasma results in TPC reduction because reactive species and ozone at higher voltages cause depolymerization of plant cell wall components, while breaking down polyphenolic compounds through breakage of aromatic rings. TPC reduction further decreases AOA which can also be attributable to increased temperatures. AA reduced due to enzymatic browning or interaction of reactive species with bioactives, at higher processing time and voltage (Ali et al., 2024a). CAP plasma treatment was applied to fresh tomato juice to improve its shelf life. CAP for 600 s extended the shelf life up to 10 days, significantly reducing the total microbial and LAB count by 4.2 and 5.0 log10 CFU/g than untreated samples (5.8 and 5.6 log10 CFU/g). The highest reduction can be attributable to the generation of antimicrobial potent substances, which combine with the low sugars of the juice, compromising microbial protection, resulting in augmented cell death. In terms of quality, there was a non-significant difference in pH between treated and control samples, with pH in

CAP-treated juice increasing to 3.99. The plasma produces reactive substances which oxidize aldehydes into acids and then nitrogenous acids, resulting in enhanced pH. There was less AA degradation (11.70 mg/100 g) similar with previous studies, TSS remained at 4.10 °Brix due to loss in moisture, and carotenoids were slightly reduced to 74.90 mg/100 g due to oxidative effect of CAP and prolonged storage (Starek et al., 2020).

In a study by Starek-Wójcicka et al. (2022) the effect of CAP on the tomato juice was assessed. TPC significantly reduced below the detection limit in control and CAP-treated juice samples, in contrast with previously reported literature. Only CAP reduced Y&M counts below the detection limit. During storage of 10 days, TPC and Y&M count of CAP-treated samples remained stable. No significant reductions were observed in mesophilic aerobic microbes and Y&M, with values below 0.5. It improved TSS, pH, lycopene, and AA in comparison to untreated juice similar to other plasma-based studies except AA. During refrigerated storage of 10 days, its physicochemical parameters deteriorated less than the untreated ones. In CAP-treated samples, at the end of storage, pH and TSS increased to 4.57 and 4.10 °Brix due to water loss. Lycopene content remained unchanged at 66.43 mg/100 g due to trans-to-*cis* isomerization, and AA significantly decreased to 268.55 mg/100 g due to UV- radiation generation. In terms of color values, a non-significant change in L-value (29.70) occurred, while a* and b* values decreased to 2.96. Similarly, Ali et al. (2021) determined the impact of DBD Plasma on the safety, thiram reduction, and physicochemical properties of the tomato juice. It increased the TSS to 6.70°Brix because of a minute loss of water, and the browning index to 4.54 than untreated samples (5.83°Brix and 0.78), due to AA loss. It also enhanced the color values (a*=1.61 and b*15.64) except for the L value, which was 60.01. However, in contrast to previous study, it resulted in a minor reduction in pH from 4.28–4.18 due to the dissolution of hydroxyl radicals, which led to lower acidity. It also somewhat decreased TPC (393.41 μg/mL of gallic acid), TFC (388.94 lg/mL of catechin), and AOA (244.24 lg/mL of AA). TPC reduction was attributable to reactive O_2 molecules, which consequently reduced AOA. It also significantly reduced the PME activity from 23.12 to 11.24 mmol/min/g.

6.3. *Pulsed electric field (PEF)*

PEF is a non-thermal technology that applies short, high-voltage pulses (10–80 kV/cm) to liquids or semi-solids, including tomato juice. The pulses cause electroporation of cell membranes for microbial inactivation, enhanced extraction, and improved mass transfer. A general microbial inactivation mechanism through DNA/RNA damage has been discussed in Fig. 2. Depending on pulse intensity, pores in membranes may reseal (reversible) or cause permanent damage (irreversible). PEF systems can be batch or continuous flow (Akdemir Evrendilek and Hitit Özkan, 2024).

PEF was applied to different fruit juices to inactivate enzymes and evaluate their quality parameters. PEF significantly improved the conductivity (3.90 mS/cm), TSS (3.99°Brix), TPC (53.98 mg/100 mL), and AOA (89.41 %), as well as decreased the pH (4.16) of tomato juice samples. While untreated samples exhibited 4.45 pH, 3.28 mS/cm conductivity, 3.77°Brix TSS, 50.42 mg/100 mL TPC, and 80.79 % AOA. PEF resulted in a non-significant impact on the color of tomato juice, with L*, a*, and b* values of 29.93, 39.89, and 22.99, respectively. It significantly inactivated PME, PPO, and LOX enzymes up to 97.97, 97.90, and 94.69 %, respectively. Inactivation occurs through the disruption of hydrogen bonds, which results in conformational modifications in their structures. That's why their biological activity changes and they get inactivated (Akdemir Evrendilek and Hitit Özkan, 2024). Odriozola-Serrano et al. (2022) screened the AOA of different fruit juices after thermal and high-intensity PEF treatment. PEF reduced AA and TPC to 110 mg of AA/L and 154 mg of GA/L in tomato juice, then untreated samples (128 mg of AA/L and 167 mg of GA/L), and higher than TP, which resulted in 102 mg of AA/L and 149 mg of GA/L, respectively. However, PEF presented a lower AOA of 3.26 mmol Trolox/L than TP (3.28 mmol Trolox/L) in tomato juice. This reported literature exhibited inconsistency with previous study with lower physicochemical properties retention.

In conclusion, electrical and plasma-based techniques are effective in inactivating microbes. These can partially inactivate enzymes without causing nutrient degradation or alteration of physicochemical quality. UV-LED enhances the level of lycopene and antioxidants, and CP maintains a longer shelf life with a low level of quality alteration. PEF results in high enzymatic inactivation and improvement in TSS, conductivity, and AOA. In general, such non-thermal approaches provide a balance between the safety of microbes, nutrient preservation, and the enrichment of functional properties. This makes such techniques appropriate in high-quality and minimally processed tomato juice.

7. Combined approaches

The combined impact of OH and UV-C irradiation processing on food-borne pathogens in buffered peptone water and tomato juice was evaluated. The synergistic treatment significantly reduced *E. coli, S. typhimurium*, and L. *monocytogenes* up to 3.83, 2.19, and 2.70 log CFU/mL, respectively, with 8.37 % and 6.77 % low time and temperature usage, through cell membrane damage by lipid peroxidation. Although they differently targeted microbial inactivation, UV-C irradiation facilitates cell membrane damage after the pore formation by OH. In contrast, when applied separately, UV and OH resulted in smaller reductions of only 0.23–0.48 and 0.43–1.84 log CFU/mL. Simultaneous treatment exhibited intermediate reductions of 0.86 to 2.32 log CFU/mL. The color and lycopene content were not affected by any of these treatments due to their non-critical level in this study (Kim et al., 2019). Similarly, the antimicrobial activity of ethanolic clove extract and mild heat processing on the tomato juice was evaluated. This combined treatment decreased the *E. coli*population below detection levels, significantly higher than single processing by mild heat (2.5 log CFU/mL), clove extract (5.42 log CFU/mL), and the control sample (5.44 log CFU/mL). Mild heat treatment enhances the reducing impact of the extract by increasing its retention in the medium and improving the solubility of its volatile compounds, which in turn increases cell membrane permeability and targets the DNA, ribosomes, proteins, and enzymes of the cells (Kusalaruk et al., 2024). The US-heating method with vacuum pressure was applied and optimized to concentrate tomato juice. Its impact on the bioactive compounds was also evaluated. In contrast to previous literature, this synergistic approach under reduced pressure significantly increased the lycopene and AA content up to 49.20 and 22.10 %, respectively due to less heat damage to escaped lycopene content cells, with a reduction of 28.42 and 4.94 % in concentration time and energy usage (Alaei et al., 2022). Non-thermal treatments in combination with mild thermal and other techniques have synergistic antimicrobial effects and show a greater reduction of pathogens compared to single treatments. These methods also improve or conserve important bioactive compounds such as lycopene and AA. These combined approaches decrease processing time and energy consumption, which makes them useful in high-quality, minimally processed tomato juice.

8. Limitations and future trends

Despite the several advantages, limitations of each processing technique persist. An overview of the main processing techniques and their limitations has been described in Fig. 3. The limitations or challenges are discussed together with future recommendations in this section. DBD plasma and UV-LED technologies are potentially effective, but they need additional research on the system design and a clear understanding of the effects of chemicals on nutritional compounds in large-scale processing of tomato juice. Their effects on pathogenic microbes, storage stability, and AOA should also be investigated. The unexplained

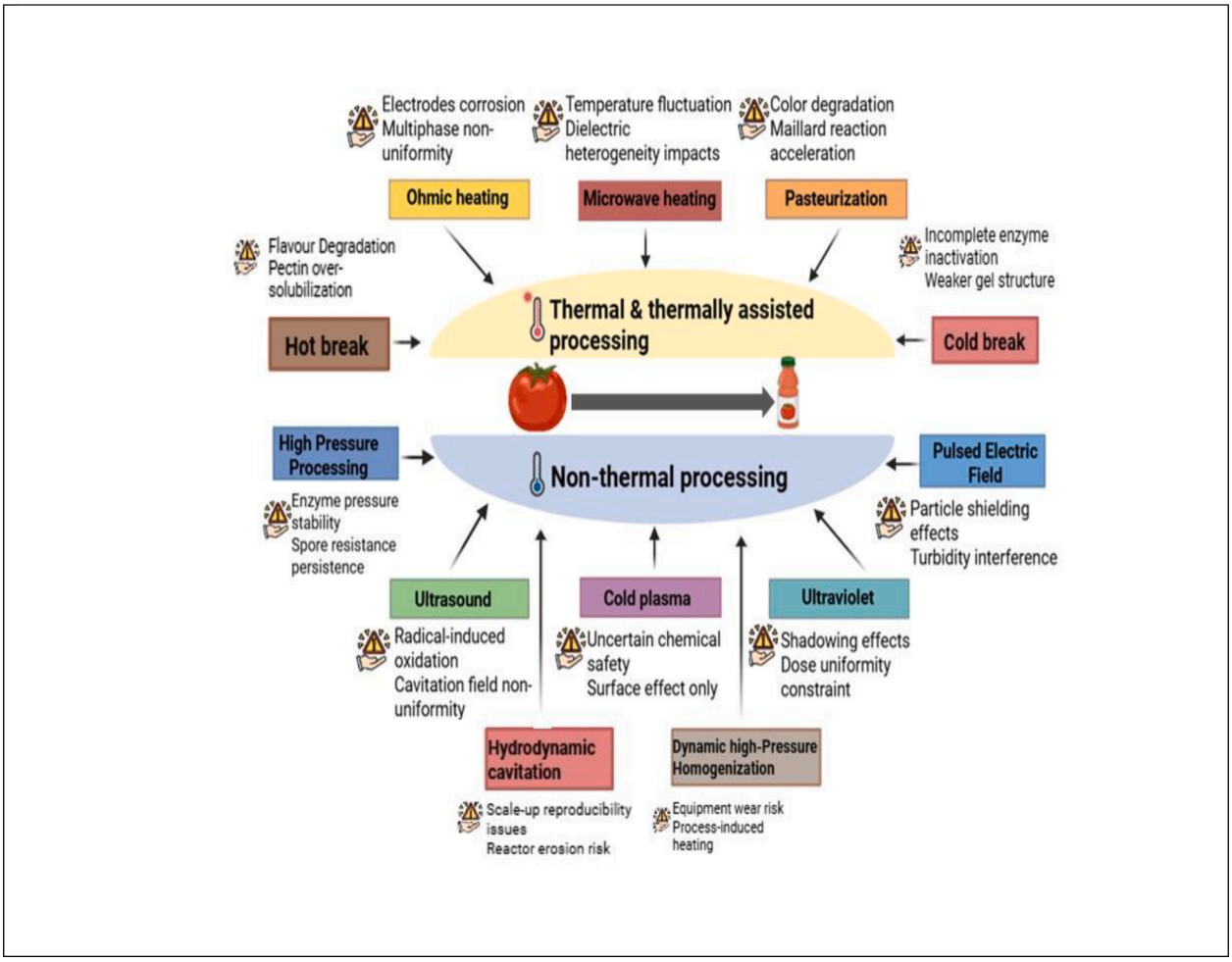

Fig. 3. An overview of the key processing techniques and their limitations.

microbial survival mechanisms, particularly during non-thermal processing conditions, at cellular and molecular levels, should be investigated in the future.

Carotenoids alone are not enough to elaborate the mechanisms of HPP and US. Hence, further research is required on the interaction of carotenoids with proteins and colloidal ingredients like pectin. It is also necessary to do research on metabolite markers linking tomato flavor and perception of consumers. The existing literature also fails to cover every condition of processing and thus it is suggested that further investigation be performed to understand how different pressures of HPP and the parameters of heat treatment affect the antioxidant bioavailability. Research in the future should also be done at extended treatment times to adequately determine its effects on enzymatic activity. There are still certain difficulties in HPP associated with high resource consumption and homogenizer wear, which restricts the feasibility of long-term industrial viability. The combined effect of US on green volatile compounds (GVBs) should also be evaluated in the future. More effort also needs to be put into maximizing the changing microwave source power and temperature during processing to enhance product quality, performance, and sustainability.

With the increasing market interest in new processing technologies, there is a need to conduct industrial-scale studies to determine the effects of the UV-LED technology on bacterial pathogens in plant-based liquid food products. LED scale-up is not easy due to the high cost of capital and insufficient light absorption in cloudy foods. Thus, optimization of operating conditions on the basis of food composition is needed. Experimental plasma systems and the combined effects of CP and the synergistic bactericidal effect of OH and excimer lamps also should be studied. The use of emerging technologies like CP, regulatory approval, and acceptance is variable across regions. As an example, safety issues, such as potential reactions of reactive species with the allergens to cause molecular changes or cause a conformational change in the allergens, have been communicated and discussed during recent toxicology evaluations (Deng et al., 2025; Zhang et al., 2022). Thus, additional safety validation further safety validation under real food-processing conditions is necessary before its large-scale application. Clear regulatory frameworks and guidelines should also be established to protect consumers and to provide food safety.

Future studies should also be extended into establishing carotenoid metabolic pathways, to eliminate heat-induced cooked flavor to tomato juice, as well as to assess AOA by yeast reporter model, with metabolomics literature. The kinetic models should also be implemented on tomato juice to gain a better insight into the enzymatic inactivation process during PEF treatment. The research needs to be conducted on sensory studies of tomato juice to understand how the GVBs are related to consumer perception and their impact on the quality of the flavor. Approximately 10^2 AAT spores/mL can result in juice spoilage, so synergism of UV-LED with other non-thermal techniques, such as US, and advances in plasma technology, has potential in improving safety and shelf life, so it should be investigated in the future. The future research should also focus on better interpretation of CUT results with well-established values, rather than normative findings.

9. Conclusion

Tomato juice is nutritionally desirable but very perishable, which

means it has to be processed in a way that it balances acceptable microbial safety with maintaining color, flavor and heat-sensitive bioactives like vitamin C, lycopene, and phenolics. This review demonstrates that the emerging non-thermal and hybrid methods have the potential to significantly minimize thermal damages and enhance retention and bioaccessibility to target compounds, although each has particular trade-offs in microbial efficacy, enzyme inactivation, sensory outcome and scalability. TP can preserve the juice while ensuring microbiological safety, but it may result in loss of sensory value and nutrition. HHP and US with mild heat (TS) are among the emerging non-thermal methods that improve nutrition, retention of antioxidants and carotenoids, and bioavailability. These also extend shelf-life and require less energy and time. DBD, CAP, and UV-LED are environmentally friendly, efficient, and scalable. These can provide microbial and enzymatic inactivation without adversely affecting physicochemical and nutritional quality. Hurdle techniques such as the use of mild thermal or antimicrobial preservatives, mild heat with clove, UV with hydroxyl radicals, are better methods of enhancing microbial safety and stability of storage by their synergistic effects. Other novel technologies, including HDC, PEF, microfluidization, and microwave-vacuum heating, assist in preserving bioactives and lowering enzyme activities. While PEF alone has little effect on physicochemical characteristics. Of the approaches reviewed, HPP, properly designed thermos-sonication regimes and confirmed CP or UV hybrid approaches are currently the most promising in terms of both quality retention and commercial viability when used as a component of an established hurdle strategy. However, most of the published research is exclusively on a laboratory scale, are heterogeneous in their approach and do not provide full validation data with regulatory microbial targets. This makes them inapplicable to direct industrial-scale applications without additional scale-up and validation studies. To accelerate safe, industrial deployment we recommend the following prioritized actions for researchers and industry: (i) Validate hurdle approaches against relevant pathogens and spoilage microbes for the exact formulation and packaging (ii) Standardize process windows at specific storage times, and sensory results; (iii) Scale-up and techno-economic evaluation, otherwise claims of sustainability and scalability remain unsubstantiated; (iv) Regulatory acceptance and labeling when recommending processing technologies for commercial use; (v) Targeted research gaps on longer storage trials, mechanistic investigation of carotenoid interactions with matrix components and systematic evaluation of spore inactivation and enzyme kinetics under non-thermal and hybrid treatments. The fulfillment of these gaps will enable the development of nutritious, safe tomato juice and promotion at industrial scale.

Declarations of interest

None.

Data availability

No data was used for the research described in this review article.

Abbreviations

HB: Hot break
CB: Cold break
OH: Ohmic heating
US: Ultrasound
HHP: High hydrostatic pressure
CP: Cold plasma
PEF: Pulsed electric field
HDC: Hydrodynamic cavitation
UV-LED: Ultraviolet light-emitting diodes
DHPM: Dynamic high-pressure microfluidization
AOA: Antioxidant activity
AA: Ascorbic acid

(*continued on next column*)

(*continued*)

PPO: Polyphenol oxidase
LOX: Lipoxygenase
PG: polygalacturonase
PME: Pectin methylesterase
TPC: Total phenolic content
HTST: High-temperature short-time
TP: Thermal processing
TSS: Total soluble solids
Y& M: Yeast and mold
AAT: *Alicyclobacillus acidoterrestris*
TS: Thermosonication
TVC: Total volatile count
CUT: Cold US treatment
HPH: High-pressure homogenization
DPPH: 2,2-diphenyl-1-picrylhydrazyl
ABTS:2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
RONS: Reactive oxygen and nitrogen species
CAP: Cold atmospheric pressure plasma
LAB: Lactic acid bacteria
GVBs: Green volatile compounds

Ethical Statement - Studies in humans and animals: NA

CRediT authorship contribution statement

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Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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