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Thermal Treatments for Fruit and Vegetable Juices and Beverages: A Literature Overview

Leonardo Petruzzi, Daniela Campaniello, Barbara Speranza, Maria Rosaria Corbo, Milena Sinigaglia, and Antonio Bevilacqua

Abstract: Fruit and vegetable juices and beverages are generally preserved by thermal processing, currently being the most cost-effective means ensuring microbial safety and enzyme deactivation. However, thermal treatments may induce several chemical and physical changes that impair the organoleptic properties and may reduce the content or bioavailability of some nutrients; in most cases, these effects are strongly dependent on the food matrix. Moreover, the efficacy of treatments can also be affected by the complexity of the product and microorganisms. This review covers researches on this topic, with a particular emphasis on products derived from different botanical sources. Technologies presented include conventional and alternative thermal treatments. Advances toward hurdle-based technology approaches have been also reviewed.

Keywords: beverages, fruit, juices, thermal processing, vegetable

Introduction

The intake of fruits and vegetables decreases the occurrence of diseases related to oxidative stress (inflammation, cardiovascular diseases, cancer, and aging-related disorders) (Escudero-López and others 2016). Beneficial effects are attributed to dietary intake of some bioactive compounds (tocopherols, carotenoids, polyphenols, phenolics, and anthocyanins) (Kongkachuichai and others 2015), vitamins, minerals, and fibers (Liu 2013).

The 2010 Dietary Guidelines for Americans recommend in a 2000-kcal diet 9 servings of fruits and vegetables per day, 4 servings of fruits and 5 servings of vegetables (Liu 2013). The European Union supports the WHO recommendation for at least 400 g/d (Tennant and others 2014). Dietary guidelines around the world recommend increased intakes of fruits and nonstarchy vegetables for the prevention of chronic diseases and possibly obesity (Charlton and others 2014).

Despite these guidelines, the consumption of vegetables and fruit remains below recommended levels in many countries and a substantial burden of disease globally is attributable to low consumption (Mytton and others 2014). Therefore, the promotion of the consumption of fruit and vegetable is a key objective of food and nutrition policy (Rekhy and McConchie 2014). Juices, blends, smoothies, and fermented and fortified beverages are a popular way to consume fruits and fresh-like vegetables and contribute to a healthy diet and a healthy life style (Wootton-Beard and Ryan 2011; Corbo and others 2014; Marsh and others 2014; Ramachandran and Nagarajan 2014; Hurtado and others 2015).

Many approaches alternative to thermal treatments have been tested and successfully proposed for juices (Jiménez-Sánchez and others 2017), but thermal processing still remains the most cost-effective tool to ensure microbial safety and enzyme deactivation (Rawson and others 2011). Some drawbacks of thermal processes are the slow conduction and convection heat transfer (Baysal and Icier 2010), and the negative effect of overprocessing on the sensory, nutritional, and functional properties (Gonzalez and Barrett 2010). In most cases, these effects are strongly dependent on the food matrix (Rodríguez-Roque and others 2015, 2016). Moreover, the efficacy of thermal treatments can also be affected by the complexity of the product and microorganisms (Chen and others 2013b).

The preservation of the organoleptic scores of food is a key goal of the food industry. As a result, the optimization of heat treatments is a key tool to maintain an equilibrium between safety and nutritional quality of the raw material (Traffano-Schiffo and others 2014). Apart from the conventional thermal processing, there are some other nonconventional thermal approaches (ohmic and microwave heating (MHW)), characterized by some benefits, such as a better energy efficiency, a lower capital cost, and shorter treatment time (Salazar-González and others 2014; Lee and others 2015).

To the best of our knowledge, there are not comprehensive reviews on the thermal treatments applied to fruit and vegetable juices, juice blends, smoothies, and enriched and fermented beverages. This review is an update of the most important advances on this topic; Figure 1 offers an overview of the manuscript. A summary of the current state of knowledge about the factors enhanced or reduced by thermal processing is given in Table 1.

CRF3-2017-0017 Submitted 1/24/2017, Accepted 4/25/2017. *Authors are with the Dept. of the Science of Agriculture, Food and Environment, Univ. of Foggia, Foggia, Italy. Direct inquiries to author Bevilacqua (Email: antonio.bevilacqua@unifg.it; abevi@libero.it).*

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Table 1–Factors enhanced or reduced by thermal processing: summary of issues.

Compound(s)/quality attribute(s)	Product	Thermal treatment	Reference(s)
Enhanced by thermal processing			
Anthocyanins	Juice	MTLT	Mena and others (2013b)
	Juice	HTLT	Elez Garofulić and others (2015)
Aromatic compounds	Nectar	HTLT	Šimunek and others (2013)
	Juice blend	OH	Dima and others (2015)
Carotenoids	Smoothie	MWH	Arjmandi and others (2016)
Enzymatic inactivation	Juice	MWH	Rayman and Baysal (2011) Demirdöven and Baysal (2015)
	Smoothie	HTLT	Hurtado and others (2015) Rodríguez-Verástegui and others (2016)
	Juice-blend mixed with soymilk	HTLT	Morales-de la Peña and others (2010)
	Mixed beverage	HTLT	Swami Hulle and Rao (2016)
	Juice	HTLT	Saeeduddin and others (2015) Chaikham and Baipong (2016)
	Smoothie	MTLT	Keenan and others (2012)
	Juice	HTST	Aguilar-Rosas and others (2013) Katiyo and others (2014)
	Nectar	HTST	Huang and others (2013)
	Nectar	MWH	Salazar-González and others (2014)
	Juice	MWH	Rayman and Baysal (2011)
Flavonoid content	Juice	MWH	Saikia and others (2015)
Microbial inactivation	Juice enriched with hydrolyzed collagen	HTLT	Bilek and Bayram (2015)
	Juice	HTLT	Farhadi Chitgar and others (2016) Bhat and others (2016) Suna and others (2013) Santhirasegaram and others (2015)
	Beverage	HTLT	de Oliveira and others (2011)
	Juice	HTST	Zhao and others (2013) Zou and others (2016)
	Juice	MTLT	Mert and others (2013) Saeeduddin and others (2015) Aganovic and others (2016)
	Juice blend	MTLT	Kaya and others (2015)
	Smoothie	MTST	Palgan and others (2012)
	Juice	MTST	Aganovic and others (2014)
	Juice	MWH	Piasek and others (2011) Dhumal and others (2015) Stratakos and others (2016)
	Juice	OH	Somavat and others (2013)
Overall quality	Juice	MTST	Sun and others (2016)
	Concentrated juice	OH	Tumpanuvatr and Jittanit (2012)
Phenolic content	Juice	HTLT	He and others (2016) Dereli and others (2015)
	Juice	MWH	Saikia and others (2015)
	Juice	HTST	He and others (2016)
	Juice	MTLT	Saikia and others (2015)
	Juice	MTST	Queirós and others (2015)
Viscosity	Juice	HTST	Chen and others (2012)
Reduced by thermal processing			
Anthocyanins	Juice	HTLT	Shaheer and others (2014) Pala and Toklucu (2011)
	Juice	HTST	Woodward and others (2011)
Antioxidant capacity	Juice	HTLT	Bansal and others (2015) Chen and others (2015b)
Aromatic compounds	Smoothie added with skim milk	HTLT	Andrés and others (2016c)
	Juice	HTLT	Zhang and others (2010)
	Juice	MTLT	Aganovic and others (2016)
	Juice blend	MTST	Caminiti and others (2012)
Ascorbic acid	Juice	HTLT	Bansal and others (2015) Chen and others (2015b)
	Juice-blend mixed with soymilk	HTLT	Rodríguez-Roque and others (2015)
	Blended beverage	HTLT	Radziejewska-Kubzdela and Biegańska-Marecik (2015)
	Blended beverage	HTST	Barba and others (2010)
	Juice blend	HTST	Mena and others (2013a)
	Drink	MTLT	Abioye and others (2013)
	Juice blend	MTLT	Profir and Vizireanu (2013)
	Juice blend	MTST	Mena and others (2013a)
Carotenoids	Juice	HTLT	Oliveira and others (2012)
	Juice	HTST	Uçan and others (2016)
Color	Juice blend	MTST	Caminiti and others (2012)
	Smoothie	HTLT	Andrés and others (2016b)
	Juice	HTLT	Guo and others (2011)
	Herbal-plant beverage added with rice	HTLT	Worametrachanon and others (2014)
Flavonoid content	Juice	MTLT	Saikia and others (2015)
Overall quality	Blended beverage	HTLT	Jayachandran and others (2015) Kathiravan and others (2014a)
	Juice	HTLT	Santhirasegaram and others (2015)
Phenolic content	Juice-blend mixed with soymilk	HTLT	Rodríguez-Roque and others (2015)
	Juice	HTST	Jiménez-Aguilar and others (2015)

(*Continued*)

Table 1–Continued.

Compound(s)/quality attribute(s)	Product	Thermal treatment	Reference(s)
Protein content	Juice	HTLT	Deboni and others (2014)
Soluble solids	Juice	HTLT	Khandpur and Gogate (2015)
Viscosity	Juice	HTLT	Nayak and others (2016) Liu and others (2012) Deboni and others (2014)
	Juice	HTST	Aguiló-Aguayo and others (2010)

Thermal Treatments

High temperature-long time (HTLT)

Thermal processes can be classified according to the intensity of the heat treatment (Miller and Silva 2012). HTLT (temperature ≥80 °C and holding times >30 s) is the most commonly used method in the processing of juices and beverages; it can be classified as pasteurization (temperature <100 °C), canning (temperature ca. 100 °C), or sterilization (temperature >100 °C) (Miller and Silva 2012). Juice pasteurization is based on a 5 log reduction of the most resistant microorganisms. This method relies on heat generated outside and then transferred into the food through conduction and convection mechanisms (Chen and others 2013b). Exposure to high temperatures (strong stresses) can induce a continuous increase in membrane permeability caused by time-dependent changes such as lipid phase transitions and protein conformation changes, eventually causing cell death. Membrane fluidity changes may differ significantly, according to the type of thermal stress (Gonzalez and Barrett 2010). Juices with pH > 4.5 require stronger treatments to achieve the desirable shelf life. Table 2 provides a comprehensive summary of the most important outputs on HTLT thermal treatments.

Some examples of the effect of this technology on microbial quality of products include the total inactivation of native microflora in coconut-nannari blended beverage (Kathiravan and others 2014a), litchi (Guo and others 2011), mango (Santhirasegaram and others 2015), pear (Saeeduddin and others 2015) and tomato juices (Stratakos and others 2016), longan juice added with xanthan gum (Chaikham and Apichartsrangkoon 2012), and apple, grape, or orange juices enriched with hydrolyzed collagen (Bilek and Bayram 2015). Moreover, HTLT could control bacterial growth in açaí beverage (de Oliveira and others 2011), amla (Bansal and others 2015), asparagus (Chen and others 2015b), black raspberry (Suna and others 2013) and reduced-calorie carrot juices (Sinchaipanit and others 2013), papaya nectar (Parker and others 2010), as well as yeast growth in grape wine (Cui and others 2012). During the storage, thermal pasteurization assures the control of microbial growth in cupuaçu nectar (Vieira and Silva 2014), basil-bottle gourd juice blend (Majumdar and others 2011), grapefruit (Uckoo and others 2013), pennywort (Chaikham and others 2013), spinach and sweet lime juices (Khandpur and Gogate 2015), an herbal-plant beverage added with rice (Worametrachanon and others 2014), as well as in a juice-blend mixed with whole or skim milk (Salvia-Trujillo and others 2011), or mixed with soymilk (Morales-de la Peña and others 2010).

HTLT treatments could reduce or inactivate some enzymes, whose activities result in undesirable changes in sensory quality attributes and nutritive value of the products (Miller and Silva 2012), such as polyphenoloxidase (PPO), peroxidase (POD), pectin esterase (PE), and polygalacturonase (PG) (Marszałek and others 2016). PPO is responsible for the browning and degradation of natural pigments and other polyphenols, leading to discoloration and the loss of antioxidant activity. POD participates in several metabolic plant processes (catabolism of auxins, lignification of the cell wall, browning reactions which catalyze

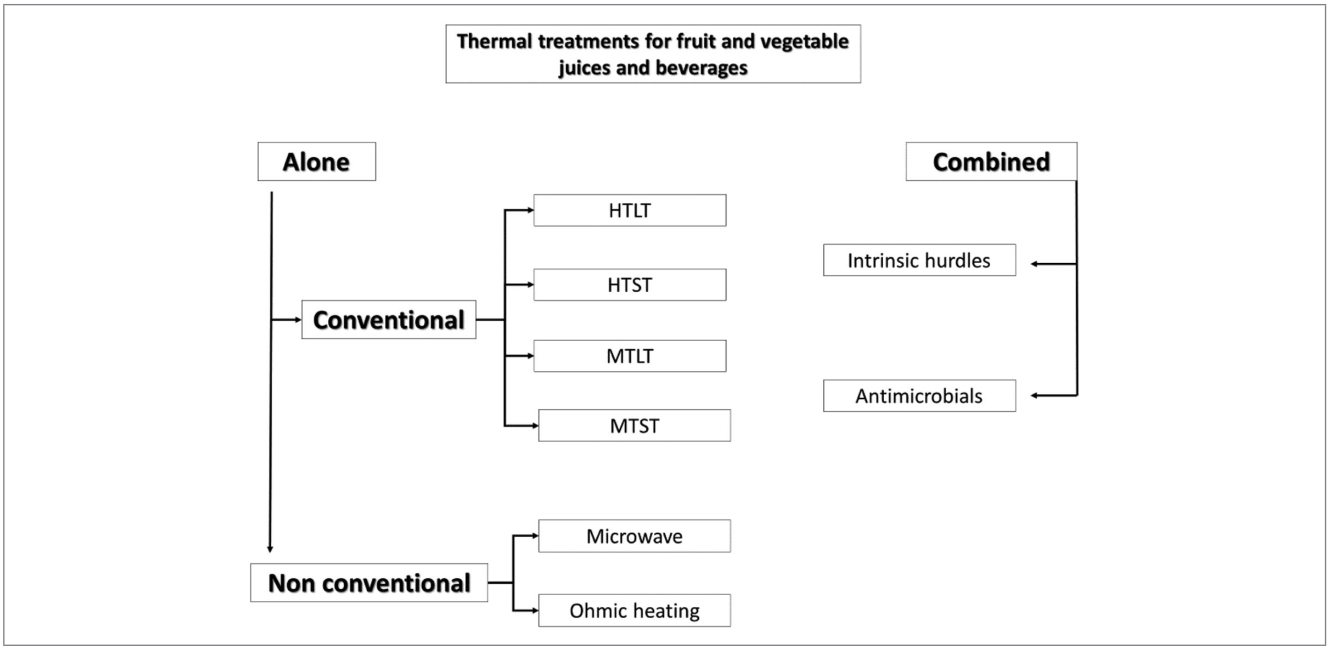

Figure 1–Roadmap of the manuscript.

Table 2–Conventional thermal processing: high temperature-long time (HTLT)

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Açaí	Beverage	80 °C/2 min	Reduction of naturally occurring microbiota	de Oliveira and others (2011)
Acerola, cashew apple, mango	Nectar blend	90 °C/1 min	Lower counts of lactic acid bacteria, yeasts and molds, coliforms, and *Salmonella* sp. below the detection limit	da Silva and others (2011)
Amla	Juice	90 °C/1 min	*Zygosaccharomyces bailii* (MTCC 257) reduced by 4.9 log CFU/mL; significant degradation of ascorbic acid and antioxidant capacity	Bansal and others (2015)
Aonla, bottle gourd, ginger, lemon	Juice blend	80 to 95/5 to 30 min	Minimum and maximum loss of ascorbic acid of juice blend were 22.97% at 80 °C for 5 min and 47.70% at 95 °C for 30 min, respectively	Gajera and Joshi (2014)
Aonla, carrot	Blended nectar	80 to 90 °C/30 s to 5 min	The treatment at 90 °C for 30 s retained significantly higher ascorbic acid content as compared to other treatments	Yadav (2015)
Apple	Juice enriched with oligosaccharides	80 and 90 °C/5 to 15 min	The carbohydrate fraction with a degree of polymerization ≥3 was stable in juice heated at temperatures up to 90 °C for 15 min	López-Sanz and others (2015)
Apple	Nectar	80 °C/2 min	More aromatic compounds in comparison with the untreated samples	Šimunek and others (2013)
Apple	Juice	80 °C/30 min	Increase of 39.8% and 69.1% in total phenolic content and radical scavenging activity value, respectively. No significant difference in the bioaccessibility of phenols	He and others (2016)
Apple	Juice supplemented with onion	96 °C/60 min	Improved overall quality	Lee and others (2016)
Apple, banana, blackberry, gooseberry, grape, lime, orange, strawberry	Smoothie	85 °C/7 min	Microbial quality in the smoothies kept at 4 °C for 28 d	Hurtado and others (2017)
Apple, banana, orange, strawberry	Smoothie	85 °C/7 min	Benefits regarding enzyme inactivation (POD, PPO, PME); limits connected to the development of cooked-fruit flavors	Hurtado and others (2015)
Apple, bilberry, blackberry, raspberry, red currant, grape, orange, strawberry	Smoothie	80 °C/1 min	Reduction of total aerobic mesophilic (3.4 log CFU/mL), lactic acid bacteria (3.3 log CFU/mL) and yeasts and molds (3.8 log CFU/mL)	Zacconi and others (2015)
Apple, carrot	Juice blend	98 °C/3 min	No effect on the antioxidant capacity	Gao and Rupasinghe (2012)
Apple, grape	Juice enriched with hydrolyzed collagen	95 °C/20 to 23 min	Inactivation of the naturally occurring microbiota	Bilek and Bayram (2015)
Apple, red cabbage	Blended beverage	90 °C/5 min	Significant reduction of ascorbic acid and glucosinolates. However, samples were found to be sensorially acceptable	Radziejewska-Kubzdela and Biegańska-Marecik (2015)
Aronia, cistus, green tea, nettle	Juice-herbal drink	85 °C/6 min	Slight increase of polyphenols content. Decrease of the total content of anthocyanin	Skąpska and others (2016)
Asparagus	Juice	121 °C/3 min	Reduction of the total mesophilic bacteria below the detection limit. Negative effects on aldehydes, alcohols and ketones concentrations, ascorbic acid, rutin, total phenolic contents, and total antioxidant activity	Chen and others (2015b)
Baobab	Drink	80 and 90 °C/0 to 180 min	95.99 and 98.90% ascorbic acid degradation after 180 min at 80 and 90 °C, respectively.	Abioye and others (2013)
Barberry	Juice	Approximately 90 °C/1 min	Complete inactivation naturally occurring microbiota. Significant reduction in total phenol content and antioxidant activity	Farhadi Chitgar and others (2016)
Basil, bottle gourd	Juice blend	95 °C/15 min	The blended juice was acceptable for 6 mo at room temperature and was microbiologically safe	Majumdar and others (2011)
Beetroot	Juice	96 °C/9 to 15 min	Thermal pasteurization for a total heating time of 12 min was able to produce microbiologically stable beetroot juice with the retention of quality attributes	Kathiravan and others (2014b)
Blackberry	Juice	80 and 90 °C/0 to 300 min	The antioxidant activity of juice was reduced as a result of temperature increase. However, the amount of cyanidin derivative slightly increased	Zhang and others (2012)
Black mulberry	Juice	107 °C/3 min	The total phenolic content, total flavonoid content monomeric anthocyanin content, and total antioxidant capacities were all significantly higher in the final pasteurized juice sample as compared to the starting raw fruit material. However, during *in vitro* simulated gastrointestinal digestion, monomeric anthocyanins in the fruit matrix had a significantly higher bioavailability than in the juice matrix	Tomas and others (2015)
Black raspberry	Juice	100 °C/25 min	Microbial safety	Suna and others (2013)

(*Continued*)

Table 2–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Bottle gourd	Juice	121 °C/5 to 7 min	A reduction of 49.14% and 51.97% was observed in ascorbic acid content for 6 and 7 min, respectively. Bacteria, yeasts, and molds were reduced below the detection limit	Bhat and others (2016)
Blueberry	Nectar	80 °C/2 min	Decrease of the consistency coefficient for pasteurized samples	Šimunek and others (2014)
Blue-berried honeysuckle	Juice	100 °C/60 to 300 min	Reduction of anthocyanins, degradation of bioactive phytochemicals, and decrease of antioxidant activity	Piasek and others (2011)
Broccoli	Juice	90 °C/1 min	Reduction of bioactive compounds and thus diminution of antioxidant capacity	Sánchez-Vega and others (2015)
Broccoli, carrot, red pepper, tomato	Smoothie	80 °C/3 min	Thermal treatment totally inactivated PPO, POD, and PME which activities were minimal during storage up to 40 and 58 d at 20 and 5 °C, respectively	Rodríguez-Verástegui and others (2016)
Cactus	Juice	100 °C/20 min	Pasteurization process affected viscosity and protein content	Deboni and others (2014)
Carrot	Juice	90 °C/10 min	Increase of the total phenolic and hydroxycinnamic acids contents	Dereli and others (2015)
Carrot	Reduced-calorie juice	80 °C/1 min	*Salmonella* sp. or *Staphyloccoccus aureus* below the detection limit. Reduction of yeasts, molds, and total coliforms	Sinchaipanit and others (2013)
Carrot, grape	Blended nectar	80 to 90 °C/30 s to 5 min	The total sugars content was significantly higher at 80°C for 5 min	Yadav (2015)
Carrot, melon, orange, papaya	Smoothie	80 °C/3 min	Color degradation	Andrés and others (2016b)
Carrot, melon, orange, papaya	Smoothie added with soymilk	80 °C/3 min	Heat treatment did not produce any major variations in bioactive compounds. The bioactive compounds of treated smoothies were relatively stable after 45 d of refrigerated storage compared to the fresh product, although the loss of ascorbic acid resulted in decreased antioxidant capacity	Andrés and others (2016a)
Carrot, melon, orange, papaya	Smoothie added with skim milk	80 °C/3 min	Total reduction in microorganisms. Aroma and acceptability scores significantly decreased	Andrés and others (2016c)
Carrot, pomegranate	Blended nectar	80 to 90 °C/30 s to 5 min	Decrease of vitamin A because of the increase of processing temperature and heating time.	Yadav (2015)
Chokeberry	Juice	90 °C/10 min	Loss of cyanidin 3-arabinoside and cyanidin 3xyloside (69%), cyanidin 3-galactoside (58%), and cyanidin 3-glucoside (50%)	Wilkes and others (2014)
Coconut	Water	90 °C/1 min	Increase in aldehydes, ketones, and 2-acetyl-1-pyrroline, an aroma compound active at low odor thresholds and characterized by "popcorn" and "toasted" odor descriptors	De Marchi and others (2015)
Coconut, lemon, litchi	Blended beverage	95 °C/10 min	Loss in ascorbic acid. Low retention of nutritional quality attributes	Jayachandran and others (2015)
Coconut, nannari	Blended beverage	96 °C/6 min	Total inactivation of native microflora. Decrease of radical scavenging activity and overall acceptability	Kathiravan and others (2014a)
Cranberry	Nectar	80 °C/2 min	Significant decrease in the consistency coefficient	Šimunek and others (2014)
Cupuaçu	Nectar	90 °C/3 min	Reduction of mesophilic bacteria, yeasts and molds; stability for 45 d	Vieira and Silva (2014)
Elephant apple	Juice	80 °C/1 min	Decrease in viscosity during the storage	Nayak and others (2016)
Ginger	Ready-to-drink beverage	95 °C/10 min	The beverage remain microbiologically safe for 6 mo, with a good retention of active components	Dadasaheb and others (2015)
Grape	Juice	80 °C/30 min	Increase of 67.4% and 216.9% in total phenolic content and radical scavenging activity. The bioaccessibility of the total phenolics increased by 33.9%	He and others (2016)
Grape	Wine	80 °C/15 min	Lethality of 89.40% for *S. cerevisiae* (QA23)	Cui and others (2012)
Grape, orange	Juice blend enriched with hydrolyzed collagen	95 °C/18 min	Inactivation of the naturally occurring microbiota	Bilek and Bayram (2015)
Grapefruit	Juice	85 °C/45 s	No microbial growth during 21 d of refrigerated storage. Negative effect on the levels of ascorbic acid and color characteristics	Uckoo and others 2013
Guava	Juice	85 °C/1 min	Ascorbic acid decreased by 20% to 26%	Sinchaipanit and others (2015)
Guava, mango, papaya, roselle	Juice blend	82.5 °C/20 min	Ascorbic acid, total monomeric anthocyanins, total phenols, and antioxidant activity decreased significantly during storage	Mgaya-Kilima and others (2014)
Indian borage	Ready-to-drink beverage	95 °C/10 min	The beverage remained microbiologically safe for 6 mo, with a good retention of active components	Dadasaheb and others (2015)
Jamun	Juice	80 °C/5 min	High anthocyanin degradation	Shaheer and others (2014)
Jaboticaba	Juice	80 to 90 °C/15 to 90 min	Low stability of the monomeric anthocyanins (degradation of 1% to 2% after 60 min)	Mercali and others (2015)

(*Continued*)

Table 2–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Kiwifruit, mango, orange, pineapple	Juice-blend mixed with soymilk	90 °C/1 min	Decreased bioaccessibility of ascorbic acid and phenolic compounds	Rodríguez-Roque and others (2015)
Kiwifruit, mango, orange, pineapple	Juice-blend mixed with whole or skim milk	90 °C/1 min	Thermal processing ensured the microbial stability of the beverages during 56 d at 4 °C without significant changes on pH, acidity, and soluble solid content values. Thermal treatment did not inactivate PG enzymatic activity	Salvia-Trujillo and others (2011)
Kiwifruit, orange, pineapple	Juice-blend mixed with soymilk	90 °C/1 min	POD and LOX of heat treated beverages were inactivated by 100% and 51%, respectively. Thermal treatment ensured the microbial stability of the beverage for 56 d	Morales-de la Peña and others (2010)
Litchi	Mixed beverage	95 °C/5 min	Inactivation of PME, PPO and POD (83%, 79%, and 78%, respectively); loss of ascorbic acid of 31%. Shelf life 80 d	Swami Hulle and Rao (2016)
Litchi	Juice	90 °C/1 min	Total inactivation of naturally occurring microbiota. Negative effects on color. Decrease of the total free amino acids	Guo and others (2011)
Litchi	Probiotic juice	95 °C/1 min	Probiotic *Lactobacillus casei* at 8.0 CFU/mL log after 4 wk at 4 °C	Zheng and others (2014)
Longan	Juice	100 °C/1 min	Significant loss in physicochemical properties and flavor compounds	Zhang and others (2010)
Longan	Xanthan-added juice	90 °C/2 min	Complete inactivation of naturally occurring microorganisms and PPO significant decrease of total phenols and antioxidant activity	Chaikham and Apichart-srangkoon (2012)
Longan, pennywort	Herbal-plant beverage added with rice (*Oryza sativa* L.)	90 °C/2 min	No microbial growth for 3 wk at 4 °C. Negative impact on color and bioactive compounds	Worametrachanon and others (2014)
Mandarin	Juice	85 °C/5 to 15 min	The highest nonenzymatic browning during 6-mo-refrigerated storage was observed in juice processed at 85 °C for 15 min	Pareek and others (2011)
Mango	Juice	90 °C/1 min	Complete inactivation of occurring microbiota. Detrimental effects on the overall quality	Santhirasegaram and others (2015)
Mango	Nectar	100 °C/10 min	Negative impact on color	Tribst and others (2011)
Maoberry	Juice	90 °C/1 min	Complete inactivation of mesophilic bacteria, and PPO. Negative effects on color attributes	Chaikham (2015)
Maqui berry	Juice	85 °C/2 min	Reduction of anthocyanin	Brauch and others (2016)
Orange	Juice	90 °C/1 min	High retention of ascorbic acid. Low preservation of total polyphenol content and antioxidant capacity	Velázquez-Estrada and others (2013)
Orange	Juice enriched with hydrolyzed collagen	95 °C/21 min	Inactivation of occurring microbiota	Bilek and Bayram (2015)
Papaya	Nectar	80 °C/5 min	Reduction pectinesterase activity, *E. coli* K12, *L. innocua*, *Salmonella* Typhimurium, *Clostridium sporogenes*	Parker and others (2010)
Passion fruit	Juice	90 °C/1 min	The levels of ascorbic acid, anthocyanins, and carotenoids were slightly affected	Fernandes and others (2011)
Peach	Juice	90 °C/5 min	Significant reductions in total carotenoids, protocatechuic acid, zexanthin and β-cryptoxanthin	Oliveira and others (2012)
Pear	Juice	95 °C/2 min	Complete inactivation of PPO, POD, PME, and natural occurring microbiota. Reduction of ascorbic acid, total phenols, flavonoids, and antioxidant capacity	Saeeduddin and others (2015)
Pennywort	Juice	90 °C/3 min	Naturally occurring microbiota below the detection limit for 4 mo at 4 °C. Negative effects on ascorbic acid, total phenolic compounds, and antioxidant capacity	Chaikham and others (2013)
Physalis	Juice	90 °C/2 min	Preservation of the valuable attributes of the juice	Rabie and others (2015)
Pindo palm	Juice	85 °C/20 min	The physicochemical properties of juice, excluding color, and their proportion of ascorbic acid and β-carotene, was not affected	Jachna and others (2016)
Pineapple	Juice	90 °C/1.5 min	Adverse effect on ascorbic acid, total phenolic, and radical scavenging activity	Zheng and Lu (2011)
Pitahaya	Juice	80 and 85 °C/10 to 30 min	High reduction of betacyanin content at 85 °C for 30 min.	Wong and Siow (2015)
Pomegranate	Juice	90 °C/2 min	15.4% to 28.3% loss of anthocyanin	Pala and Toklucu (2011)
Pomegranate	Nectar	95 °C/45 s	Loss of 76% and 42% to 77% for flavonoid and antioxidant activity	Surek and Nilufer-Erdil (2014)
Rabbiteye blueberry	Juice	80 °C/0 to 3000 min	Half-life time of 5.1 h for anthocyanin.	Kechinski and others (2010)
Red-fleshed apple	Juice	80 °C/10 min and 90 °C/5 min	0.02 and 0.12 for PPO and POD residual enzyme activity at 80 °C, and 0.00 and 0.10 at 90 °C, respectively.	Katiyo and others (2014)

(*Continued*)

Table 2–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Red raspberry	Juice	80 °C/15 min	The content of the ascorbic acid was reduced by 47% and 31% in fresh and processed juice after 20 d of refrigerated storage	Yang and others (2015)
Sea buckthorn	Juice	90 to 120 °C/0 to 300 min	Significant effect on ascorbic acid content.	Xu and others (2015a)
Sour cherry	Juice	80 °C/2 min	Increase in anthocyanins and phenolic acids	Elez Garofulić and others (2015)
Sour orange	Juice	70 to 80 °C/5 to 25 min	12.10% PME residual activity at 80 °C for 5 min	Koshani and others (2014)
Soursoup	Juice	60 °C/60 min	Significant decrease of naturally occurring microbiota during storage (30 to 31 °C; 2 wk). Decrease in titratable acidity from 23.25 to 21.92	Nwachukwu and Ezeigbo (2013)
Spinach	Juice	80 °C/10 min	No microbial growth during the storage at 4 °C for 10 wk. Degradation of color pigments. Significant loss of soluble solids	Khandpur and Gogate (2015)
Strawberry	Juice	90 °C/1 min	No effect on the antioxidant activity	Odriozola-Serrano and others (2016)
Strawberry	Nectar	85 °C/15 min	Moderate loss of anthocyanins during the refrigerated storage	Marszałek and others (2011)
Sweet lime	Juice	80 °C/10 min	No microbial growth during the storage at 4 °C for 10 wk. Degradation of color pigments. Significant loss of soluble solids	Khandpur and Gogate (2015)
Tamarillo	Nectar	80 to 95 °C/10 min	Increasing temperatures led to significant loss in some carotenoids, such as zeaxanthin and β-carotene.	Mertz and others (2010)
Tomato	Juice	85 °C/5 min	Inactivation of natural microorganisms. Moderate effect on physicochemical and color characteristics	Stratakos and others (2016)
Tomato	Fermented juice	100 °C/5 to 120 min	The lycopene content of tomato juice after heating at 100 °C for 5 min was significantly increased from 88 to 113 μg/g.	Koh and others (2010)
Twistspine pricklypear	Juice	95 °C/3 min	Low preservation of antioxidant activity	Moussa-Ayoub and others (2011)
Yellow mombin	Juice	90 °C/1 min	25% and 2.5% residual activity for PME and POD	De Carvalho and others (2015)
Watermelon	Juice	95 °C/1 min	Decrease of cloud stability	Liu and others (2012)
White mulberry	Juice	95 °C/1 min	14% reduction of α-glucosidase inhibitory activity	Yu and others (2014)
Wild cherry	Juice	90 °C/1 min	PPO was completely inactivated	Chaikham and Baipong (2016)

PME, pectin methyl esterase; PG, polygalacturonase; LOX, lipoxygenase; PPO, polyphenol oxidase; POD, peroxidase

the oxidation processes). PE and PG are involved in the breakdown of pectin and other cell wall materials, resulting in a product with reduced viscosity and undesirable organoleptic properties (Marszałek and others 2016). Therefore, several studies were performed to evaluate the effect of HTLT treatments on these activities. Examples include: (1) the reduction of PME enzymatic activity by 75% to 83%, respectively, in yellow mombin juice (de Carvalho and others 2015) and litchi-based beverage (Swami Hulle and Rao 2016), or its complete inactivation in pear juice (Saeeduddin and others 2015), and broccoli/carrot/red pepper/tomato smoothie (Rodríguez-Verástegui and others 2016); (2) the reduction of PPO enzymatic activity by 79% in litchi-based beverage (Swami Hulle and Rao 2016), or its total inactivation in smoothie (Rodríguez-Verástegui and others 2016), pear juice (Saeeduddin and others 2015), and longan juice added with xanthan (Chaikham and Apichartsrangkoon 2012); (3) the reduction of POD enzymatic activity by 78% and 97.5% in litchi-based beverage (Swami Hulle and Rao 2016) and yellow mombin juice (de Carvalho and others 2015), respectively, as well as its complete inactivation in pear juice (Saeeduddin and others 2015), in a juice-blend mixed with soymilk (Morales-de la Peña and others 2010), and a vegetable-based smoothie (Rodríguez-Verástegui and others 2016); and (4) the reduction of LOX enzymatic activity by 51% in kiwifruit/orange/pineapple juice blend mixed with soymilk (Morales-de la Peña and others 2010).

HTLT might affect many antioxidant compounds, thus reducing their beneficial health effects. The reduction of the antioxidant capacity was generally due to a loss in total anthocyanins and vitamin C (Miller and Silva 2012). Some of these studies reported: (1) the degradation of ascorbic acid in amla juice (Bansal and others 2015), apple/red cabbage (Radziejewska-Kubzdela and Biegańska-Marecik 2015) and coconut/lemon/litchi blended beverages (Jayachandran and others 2015), grapefruit juice (Uckoo and others 2013); (2) the degradation of anthocyanins in jamun (Shaheer and others 2014), maqui berry (Brauch and others 2016), and pomegranate (Pala and Toklucu 2011) juices; (3) the degradation of carotenoids in peach (Oliveira and others 2012) and pindo palm (Jachna and others 2016) juices; and (4) the reduction of antioxidant capacity in amla (Bansal and others 2015), asparagus (Chen and others 2015b), orange (Velázquez-Estrada and others 2013), pear (Saeeduddin and others 2015), and twist spine prickly pear juices (Moussa-Ayoub and others 2011).

Similarly, other drawbacks related to quality attributes include (1) the detrimental effect on color in carrot/melon/orange/papaya smoothie (Andrés and others 2016b), coconut/nannari blended beverage (Kathiravan and others 2014a), grapefruit (Uckoo and others 2013), litchi (Guo and others 2011), spinach and sweet lime (Khandpur and Gogate 2015) juices, mango nectar (Tribst and others 2011), as well as in a longan/pennywort-based beverage added with rice (Worametrachanon and others 2014); (2) the losses in physicochemical properties in cactus (Deboni and others 2014), litchi (Guo and others 2011), longan (Zhang and others 2010), mango (Santhirasegaram and others 2015), and watermelon (Liu and others 2012) juices, as well as in blueberry nectar (Šimunek

Table 3–Conventional thermal processing: high temperature-short time (HTST)

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Amla, bael	Juice blend	80 to 90 °C/25 s	Juice treated at 90 °C showed best results for the nutritional quality of product	Rathod and others (2014)
Apple	Juice	90 °C/30 s	Complete inactivation of *L. brevis* and *S. cerevisiae*. 95.3% and 90.9% inactivation of PME and PPO	Aguilar-Rosas and others (2013)
Apple	Concentrated juice	100 °C/30 s	Reduction of *A. acidoterrestris* spores; the complete inactivation was not achieved	Djas and others (2011)
Apple	Smoothie added with carboxymethyl cellulose	85 °C/15 s	Negative effects were not reported	Sun-Waterhouse and others (2014)
Apricot	Nectar	110 °C/8.6 s	Complete inactivation of PPO, POD, and PME	Huang and others (2013)
Blackberry	Juice	92 °C/10 s	High levels of total phenolics, (−)-epicatechin, ferulic acid, and *p*-coumaric acid Retention of biological properties related to inhibition of peroxidation and its capacity to scavenge intracellular radicals	Azofeifa and others (2015)
Blackcurrant	Juice	103 °C/30 s	Significant loss in anthocyanin content (approximately 22%)	Woodward and others (2011)
Black mulberry	Juice	90 °C/30 s	Reduction of the antioxidant activity	Jiang and others (2015)
Blueberry	Juice	90 °C/15 s	No changes for reducing sugars, total acid, phenol contents, and soluble solids. Low stability of ascorbic acid	Chen and others (2014)
Carrot	Juice	98 °C/21 s	Higher viscosity and low stability of particles dispersion during the refrigerated storage	Chen and others (2012)
Carrot	Reduced-calorie juice	90 °C/15 s	Low β-carotene content	Sinchaipanit and others (2013)
Carrot, celery, green pepper, lemon, olive, onion, tomato	Blended beverage	90 and 98 °C/15 and 21 s	Decrease of ascorbic acid	Barba and others (2010)
Chinese bayberry	Juice	120 °C/3 s	Moderate flavor changes	Xu and others (2014)
Cucumber	Juice	85 °C/15 s	Yeasts and molds were completely inactivated, and their levels were below the detection limit for 50 d	Zhao and others (2013)
Grape	Juice	90 °C/30 s	Increase of 65% and 116.6% in total phenolic content and radical scavenging activity value, respectively	He and others (2016)
Grapefruit	Juice	80 °C/11 s	Significant decrease in citric and ascorbic acids	Igual and others (2010)
Guava	Nectar	90 °C/3.1 and 12.5 s	Treatments for 3.1 and 12.5 s retained, respectively, 92% and 90% of the initial ascorbic acid content after 12 d of refrigerated storage	Salazar-González and others (2014)
Lemon	Juice	90 °C/15 s	Increase of total phenolic content. Decrease of total carotenoid content	Uçan and others (2016)
Lemon, maqui berry	Isotonic drink	80 and 85 °C/6 s	Heat treatments did not affect anthocyanins. However, 80 °C/heat treatment with storage at 7°C controlled microbial growth	Gironés-Vilaplana and others (2016)
Lemon, pomegranate	Juice blend	90 °C/5 s	Complete inactivation of naturally occurring microorganisms. High increase in the color hue. Marked effect on ascorbic acid degradation	Mena and others (2013a)
Mandarin	Juice	82 and 92 °C/12 s	POD activity ranging from 0.11 to 0.23 (units/g of juice) at 82 and 92 °C, respectively	Hirsch and others (2011)
Mango	Nectar	110 °C/8.6 s	Significant inactivation of naturally occurring microorganisms. The activity of acid invertase was reduced by 91.4%. Significant increase of viscosity	Liu and others (2014)
Mulberry	Juice	110 °C/8.6 s	Total aerobic bacteria, yeasts, and molds were not detected for 28 d at 4 °C and 25 °C	Zou and others (2016)
Orange	Juice	90 °C/20 s	PME activity increased during storage (4 °C, 180 d)	Agcam and others (2014)
Orange	Juice mixed with milk	90 °C/15 s	5-log reduction of *L. plantarum* (CECT 220). Significant increase of HMF content	Zulueta and others (2013)
Orange	Fermented juice	85 °C/30 s	Partial amino acid degradation; however, the total amino acid content was higher	Cerrillo and others (2015)
Orange, sweet pepper	Juice blend	110 °C/8.6 s	About 4 log reduction of total aerobic bacteria, yeasts, and molds	Xu and others (2015b)
Papaya	Beverage	110 °C/8.6 s	Total aerobic bacteria, yeasts, and molds were below the limit of detection	Chen and others (2015a)
Papaya	Nectar	80 to 135 °C/1 to 3 s	β-Carotene was significantly reduced at 80 and 110 °C (22.5%) and increased at 135 °C, with an overall 6.26% increase	Swada and others (2016)
Persimmon	Juice	95 °C/30 s	Formation of phenylalanine-hexoside and tryptophan-hexoside	Jiménez-Sánchez and others (2015)
Pomegranate	Juice	110 °C/8.6 s	pH, total soluble solids, and titratable acidity did not show significant changes	Chen and others (2013a)
Prickly pear	Juice	131 °C/2 s	High loss in phenols	Jiménez-Aguilar and others (2015)
Pummelo	Juice	110 °C/8.6 s	PME and POD were inactivated. Decrease of total phenols (7.7%) and ascorbic acid (27.9%)	Gao and others (2015)

(*Continued*)

Table 3–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Purple sweet potato	Nectar	110 °C/8.6 s	Inactivation of yeasts and molds to a level below the detection limit, and the count of yeasts and molds in juice was kept lower than the detection limit during 12 wk of storage at 4 and 25 °C	Wang and others (2012)
Red-fleshed apple	Juice	115 °C/5 s	0.06 and 0.20 for PPO and POD residual enzyme activity, respectively	Katiyo and others (2014)
Strawberry	Nectar	80 to 135 °C/1 to 3 s	Antioxidant capacity was constant at 80 °C, significantly increased at 110 °C, and remained relatively constant thereafter, with an overall 9.82% increase.	Swada and others (2016)
Tomato	Juice	92 °C/5 s	Complete inactivation of total plate count. Slight increase of acidity	Giner and others (2013)
Watermelon	Juice	90 °C/30 s	Low viscosity values over the subsequent refrigerated storage	Aguiló-Aguayo and others (2010)

PME, pectin methyl esterase; PPO, polyphenol oxidase; POD, peroxidase.

and others 2014); and (3) the negative effects on flavor compounds in longan juice (Zhang and others 2010).

However, HTLT could affect in a positive way some bioactive compounds. Remarkable examples include the enhancement of: (1) total phenolic, total flavonoid, and monomeric anthocyanin contents, as well as total antioxidant capacity in black mulberry juice (Tomas and others 2015); (2) total phenolic and hydroxycinnamic acids amount in carrot juice (Dereli and others 2015); (3) anthocyanins and phenolic acids content in sour cherry juice (Elez Garofulić and others 2015); and (4) aromatic compounds in apple juice (Šimunek and others 2013).

High temperature-short time (HTST)

In order to avoid the drawbacks of the traditional thermal technologies, ensure product safety, and maintain the desired bioactive compounds, HTST thermal pasteurization (temperature $\geq$80 °C and holding times $\leq$30 s) has been proposed and tested (Table 3), because temperature dependency is more significant for microorganism destruction than for nutrient degradation (Achir and others 2016).

A broad range of studies mainly focused on microbiological quality of products. HTST treatments can: (1) control the growth of *Lactobacillus plantarum* CECT 220 in orange juice added with milk (Zulueta and others 2013), or the native microorganisms in orange/sweet pepper juice blend (Xu and others 2015b) and mango nectar (Liu and others 2014); (2) inactivate *Lactobacillus brevis* and *Saccharomyces cerevisiae* in apple juice (Aguilar-Rosas and others 2013), as well as the native microorganisms in purple sweet potato nectar (Wang and others 2012), tomato (Giner and others 2013) and cucumber juices (Zhao and others 2013), and lemon/pomegranate juice blend (Mena and others 2013a); and (3) ensure microbial stability during the storage of mulberry juice (Zou and others 2016) and purple sweet potato nectar (Wang and others 2012).

The effects of HTST treatment on different enzymes were also studied; it could: (1) reduce PME (95.3%) and PPO (90.9%) in apple juice (Aguilar-Rosas and others 2013); and (2) ensure the complete inactivation of PPO, POD, and PME in apricot nectar (Huang and others 2013), and PME and POD in pummelo juice (Gao and others 2015), respectively.

Interestingly, the application of HTST heat treatment is reported to increase: (1) total phenolics, (−)-epicatechin, ferulic acid, and *p*-coumaric acid content in apricot nectar (Huang and others 2013); (2) color hue in lemon/pomegranate juice blend (Mena and others 2013a); (3) nutritional value in fermented orange juice (Cerrillo and others 2015); and (4) viscosity in carrot juice (Chen and others 2012) and mango nectar (Liu and others 2014). Nevertheless, the exposure to high temperatures, even for short periods, can result in sensorial changes of appearance, texture, color, and flavor (Miller and Silva 2012). For example, HTST heat treatment can decrease: (1) the content of citric and ascorbic acids in grapefruit juice (Igual and others 2010); (2) the amount of ascorbic acid in lemon/pomegranate juice blend (Mena and others 2013a); and (3) total phenolic content in prickly pear juice (Jiménez-Aguilar and others 2015).

Mild temperature-long time (MTLT)

Over the last years, some researchers studied MTLT heat treatments (temperature <80 °C and holding times >30 s) to improve the shelf life of minimally processed products (Table 4). MTLT can provide: (1) the increase of total phenolic content in black jamun juice (Saikia and others 2015); (2) a good preservation of color in cucumber juice (Wang and others 2013); (3) high retention of ascorbic acid and other phenolic compounds in pineapple juice (Saeeduddin and others 2015); (4) an increase of color stability and viscosity in prickly pear juice (Cruz-Cansino and others 2015); (5) high retention of β-carotene content in reduced-calorie carrot juice (Sinchaipanit and others 2013); and (6) a good retention of ascorbic acid and anthocyanin (58.3% and 85.1%, respectively) in Chinese bayberry juice (Wang and others 2015).

Moreover, MTLT can ensure: (1) ca. 4.39 log reduction of aerobic plate count in pomegranate juice (Mena and others 2013b); (2) the complete inactivation of total plate count in maoberry juice (Chaikham 2015); and (3) the microbial stability of up to 2 y storage in grape juice (Mert and others 2013). However, Gouma and others (2015) reported only 2.9-log reduction of potential pathogen *Escherichia coli* (STCC 4201) population in apple juice (Gouma and others 2015). On the other hand, Kaya and others (2015) reported >6 log reduction of *E. coli* K12 (ATCC 25253) in lemon/melon juice blend (Kaya and others 2015), which is likely the result of using different *E. coli* strains, as well as a different acidic food-matrix. Pathogens can survive in juice because of acid adaptation and develop adaptive mechanisms by undergoing genetic and physiologic changes that allow cells to stay viable. Acid adaption of pathogens shows cross-protection against thermal processing (Song and others 2015). When microorganisms develop resistance to commonly used preservation methods, juice quality and safety may be affected, and therefore understanding of stress adaptive mechanisms plays a key role in designing safe food processing conditions (Guevara and others 2015).

Regarding the enzymatic activities, MTLT heat treatments were efficient to: (1) reduce significantly PPO, POD, and PME in pear juice (Saeeduddin and others 2015); and (2) completely inactivate PPO in maoberry juice (Chaikham 2015) and

Table 4–Conventional thermal processing: mild temperature-long time (MTLT)

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Amla	Juice	70 °C/10 min	Initial reduction and increase of the naturally occurring microbiota within the storage. The critical threshold was never attained	Sangeeta and others (2013)
Apple	Juice	55 °C/3.58 min	2.9-log reduction of *E. coli* (STCC 4201)	Gouma and others (2015)
Apple, banana, orange, strawberry	Smoothie	70 °C/10 min	Reduction of the total antioxidant capacity, total phenols, anthocyanins and color. Total inactivation of PPO	Keenan and others (2012)
Apple, orange	Juice blend	70 °C/60 and 90 s	A thermal treatment for 60 s did not have effect on the growth of *S. cerevisiae* SPA. Indeed, only a 0.49 log CFU/mL reduction was observed in samples, subjected to a thermal treatment for 90 s, after 8 d at room temperature	Tyagi and others (2014b)
Banana	Juice	45 to 60 °C/30 min	At a temperature below 50 °C, PPO activity only decreased by 9.1% at 55 °C and 20.5% at 60 °C	Yu and others (2013b)
Baobab	Drink	60 and 70 °C/0 to 180 min	83.37% and 91.71% ascorbic acid degradation after 180 min at 60 and 70 °C, respectively	Abioye and others (2013)
Blackberry	Juice	70 °C/0 to 300 min	The antioxidant capacity is highly related with anthocyanin degradation over time	Zhang and others (2012)
Black jamun	Juice	Approximately 75 °C/3 min	Increase in total phenolic content and ferric reducing antioxidant property	Saikia and others (2015)
Bottle gourd	Juice	63 °C/30 min and 75 °C/10 min	Higher decrease in ascorbic acid (35.27%) was observed at 63 °C. Increase in pasteurization temperature lead to significant increase in total phenolics	Bhat and others (2016)
Carrot	Reduced-calorie juice	65 °C/30 min	High retention of β-carotene content. Production of an unacceptable cooked flavor	Sinchaipanit and others (2013)
Carrot	Juice	20 to 70 °C/1 to 60 min	Juices processed at low temperatures of 20 °C showed an enhancement on both falcarinol and falcarindiol-3-acetate contents with increasing the processing times up to 10 min compared to untreated juices. In contrast, longer processing times of 30 and 60 min did not affect the polyacetylene levels of the samples	Aguiló-Aguayo and others (2014)
Carrot, celery, beetroot	Juice blend	70 °C/3 min	High losses of ascorbic acid, as well as low increase of acidity throughout the subsequent storage for 2 wk at 4 °C	Profir and Vizireanu (2013)
Carrot, orange, pumpkin-carrot, grapefruit, pumpkin celery, orange, pumpkin	Juice blend	70 °C/10 min	Negative influence on flavor and flavonoids during the refrigerated storage for 14 d	Dima and others (2015)
Carambola	Juice	Approximately 75 °C/3 min	Increase in ferric reducing antioxidant property	Saikia and others (2015)
Chinese bayberry	Juice	55 °C/8 min	58.3% and 85.1% of ascorbic acid and anthocyanin retention	Wang and others (2015)
Coconut, lemon, litchi	Beverage blend	40 to 70 °C/0 to 20 min	A minimum thermal inactivation of PPO up to 7.5 % was achieved at 40 °C/5 min, and a maximum level of inactivation to the tune of 50 % was attained at 70 °C/20 min	Jayachandran and others (2016)
Cucumber	Juice	60 °C/2 min	Good preservation of color	Wang and others (2013)
Grape	Juice	65 °C/30 min	No microbial growth up to 2 y storage. Detection of HMF	Mert and others (2013)
Guava	Whey drink-based beverage	60 to 70 °C/15 to 25 min	The beverage pasteurized at 65 °C/25 min was more acceptable compared to the other combinations for shelf life, microbiological safety, color, taste, aroma, and overall acceptability	Singh and others (2014)
Jaboticaba	Juice	15 to 90 min/60 and 70	A high stability of the monomeric anthocyanins was observed at 60 °C (degradation of 1% to 2% after 60 min)	Mercali and others (2015)
Litchi	Juice	Approximately 75 °C/3 min	Decrease in total phenolic content and ferric reducing antioxidant property	Saikia and others (2015)
Lemon, melon	Juice blend	72 °C/1.11 min	Reduction of *E. coli* K12 (ATCC 25253) population by >6 log	Kaya and others (2015)
Mandarin	Juice	65 °C/15 to 35 min and 75 °C/10 to 30 min	Juice processed at 65 °C for 15 min maintained better qualitative characteristics like total soluble solids, acidity, ascorbic acid, sugars, and nonenzymatic browning during 6 mo refrigerated storage	Pareek and others (2011)
Pear	Juice	65 °C/10 min	High retention of ascorbic acid and other phenols. Significant reduction in PPO, POD, and PME, and complete microbial inactivation	Saeeduddin and others (2015)
Pineapple	Juice	Approximately 75 °C/3 min	Decrease in total flavonoid content	Saikia and others (2015)
Pitahaya	Juice	65 to 75 °C/10 to 30 min	High preservation of betacyanin content at 65 °C. No effect of different heating times	Wong and Siow (2015)
Pomegranate	Juice	65 °C/1 min	4.39 log reduction of aerobic plate count. The anthocyanin content was enhanced	Mena and others (2013b)

(*Continued*)

Table 4–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Prickly pear	Juice	70 °C/30 min	Partial inactivation of mesophilic bacteria and enterobacteria. Higher total phenolic values	Cruz-Cansino and others (2015)
Rabbiteye blueberry	Juice	40 to 70 °C/0 to 3000 min	Half-life time values of 180.5, 42.3, 25.3, and 8.6 h for the degradation of anthocyanin at 40, 50, 60, and 70 °C, respectively	Kechinski and others (2010)
Sour orange	Juice	40 to 70 °C/5 to 25 min	Thermal treatments at low temperatures ($T < 60$ °C) did not reduce PME activity considerably. After 5 min of thermal treatment at 60 °C, the residual activity was 77.55%	Koshani and others (2014)
Watermelon	Juice	74 °C/45 s	*E. coli*, *L. innocua*, *L. plantarum*, and *S. cerevisiae* were inactivated below the detection limit. Alteration of the flavor profile	Aganovic and others (2016)

PME, pectin methyl esterase; PPO, polyphenol oxidase; POD, peroxidase.

apple/banana/orange/strawberry smoothie (Keenan and others 2012).

Some drawbacks related to MTLT include: (1) the reduction of total antioxidant capacity, total phenols, anthocyanin content, and instrumental color variables in smoothie (Keenan and others 2012); (2) high losses of ascorbic acid in carrot/celery/beetroot juice blend (Profir and Vizireanu 2013); (3) a decrease of total phenolic content and ferric reducing antioxidant property in litchi juice (Saikia and others 2015); (4) the reduction of total flavonoid content in pineapple juice (Saikia and others 2015); and (5) negative effects on color attributes of maoberry juice (Chaikham 2015).

Mild temperature-short time (MTST)

MTST heat processing uses temperatures <80 °C and holding times ≤30 s (Table 5). These treatments have a limited effect on product characteristics. Examples include: (1) the preservation of the sensory quality (appearance, sweetness, and acidity) in apple/cranberry juice blend (Caminiti and others 2011), as well as the biological properties related to inhibition of peroxidation and its capacity to scavenge intracellular radicals in blackberry juice (Azofeifa and others 2015); and (2) the enhancement of anthocyanin content in pomegranate juice (Mena and others 2013b), and total phenolic content in sweet cherry juice (Queirós and others 2015).

MTST heat treatments were reported to achieve: (1) a 6 to 7 log reduction of *Listeria innocua* (NCTC 11288) population in apple/mango/orange/pineapple smoothie (Palgan and others 2012); (2) a 3.5 to 3.7 log reduction of the native microorganisms in apple/banana/coconut/orange/pineapple smoothie (Walkling-Ribeiro and others 2010); (3) ca. 4.09 log reduction in pomegranate juice (Mena and others 2013b); (4) the total inactivation of microbiological load in sweet cherry juice (Queirós and others 2015); and (5) the control of the residual microorganisms (*L. innocua*, *E. coli*, *L. plantarum*, *S. cerevisiae*, and *Aspergillus niger*) in tomato juice for at least 21 d (Aganovic and others 2014), and the total plate count in apple juice for 48 d (Torkamani 2011).

However, MTST treatments can affect the physicochemical, sensory, and functional properties of beverages, namely: (1) color in apple juice (Torkamani 2011), as well as color and flavor in a carrot/orange juice blend (Caminiti and others 2012); (2) ascorbic acid content in lemon/pomegranate juice blend (Mena and others 2013a); and (3) unsaturated fatty acids in tomato juice (Aganovic and others 2014).

MWH

New thermal technologies have been studied as alternative methods to heat treatment (Mercali and others 2015). MWH is a promising way for some benefits, like the reduced processing time, high energy efficiency, a good process control, and space savings (Salazar-González and others 2014). An overview of the effects of MWH on fruit and vegetable beverages is shown in Table 6.

Generally, the effectiveness of MWH toward the conventional processing is confirmed by: (1) the increase of total phenolic content in carambola, watermelon, and pineapple juices (Saikia and others 2015); (2) the great retention of flavonoid compounds throughout 2 mo of frozen storage in grapefruit juice (Igual and others 2011); (3) the preservation of physicochemical properties in tomato juice (Stratakos and others 2016) and many juice-blends (Math and others 2014); (4) the increase of total flavonoid content in black jamun and litchi juices (Saikia and others 2015); (5) the significant retention of ascorbic acid and the preservation of color and rheological properties in guava nectar (Salazar-González and others 2014); and (6) the 2- to 3-fold increase of total soluble solids, acidity, sugars, polyphenols, anthocyanins, and antioxidant activity content in pomegranate juice (Dhumal and others 2013).

Overall, MWH systems have been considered to deliver reduced thermal exposure to inactivate microorganisms (Arjmandi and others 2016). However, some studies reported: (1) the inactivation of natural microorganisms in tomato juice (Stratakos and others 2016) and in pomegranate juice (Dhumal and others 2015); (2) a 3 log reduction of bacteria and fungi population in many juice blends (Math and others 2014); and (3) the microbial stability during storage of guava nectar (Salazar-González and others 2014) and orange juice (Demirdöven and Baysal 2015). Recently, MWH successfully eliminated vegetative bacteria in smoothies without compromising food quality. Interestingly, *L. monocytogenes* was not detected throughout the shelf life of product (Arjmandi and others 2016). Since increasing MWH power has an important effect on the reduction of heating time, a combination of high power and short time might be a solution for reducing the loss of quality, as well as destroy harmful pathogenic microorganisms (Arjmandi and others 2016).

Generally, MWH could not inactivate browning-related enzymes (Miller and Silva 2012), but there is not a general consensus on this topic. In fact, some studies stated that MWH ensures significant PME inactivation in guava nectar (Salazar-González and others 2014), and kava juice (Abdullah and others 2013), as well as its complete inactivation in carrot juice (Rayman and Baysal 2011). Some drawbacks related to MWH include: (1) the formation of colored decomposition products (that is, browning) in beetroot juice (Gonçalves and others 2013); and (2) the decrease of pH and color values in pomegranate juice (Dhumal and others 2015).

Table 5–Conventional thermal processing: mild temperature-short time (MTST)

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Amla	Juice blend	75 °C/25 s	Shelf life at 45 d (refrigeration)	Rathod and others (2014)
Apple	Juice	74.3 °C/25 s	Mesophilic bacteria below the detection limit for 48 d. Change in color	Torkamani (2011)
Apple	Cider	60 to 76 °C/1.3 s	A significant decrease in *E. coli* K12 (ATCC 23716) was found at 76 °C	Azhuvalappil and others (2010)
Apple, banana, coconut, orange, pineapple	Smoothie	72 °C/15 s	3.5 to 3.7 log reduction of naturally occurring microbiota. High structural degradation	Walkling-Ribeiro and others (2010)
Apple, orange	Juice blend	70 °C/30 s	The treatment did not have effect on the growth of *S. cerevisiae* SPA	Tyagi and others (2014b)
Apple, cranberry	Juice blend	72 °C/26 s	No significant loss in sensory quality	Caminiti and others (2011)
Apple, mango, orange, pineapple	Smoothie	72 °C/26 s	Microbial reduction of *L. innocua* (NCTC 11288) of about 6 to 7 log CFU/mL	Palgan and others (2012)
Blackberry	Juice	75 °C/15 s	Retention of the biological properties related to inhibition of peroxidation and to scavenge intracellular radicals	Azofeifa and others (2015)
Carrot, orange	Juice blend	72 °C/26 s	8% PME residual activity. Negative effects on color and flavor	Caminiti and others (2012)
Guava	Nectar	60 and 73 °C/0 to 20 s	Significant reduction in the heat resistance of cocktails of *E. coli* (NRRL 3704, ATCC 8739, ATCC 92522) and *S. enterica* serovars Typhimurium (NRRL B-4420), Typhi (NRRL B-573), and Enteritidis (Biotech 1963) when heating was increased from 60 to 73 °C	Gabriel and others (2015)
Lemon	Juice	42 to 72 °C/12 s	Any effect of temperature on final POD activity	Hirsch and others (2011)
Lemon, pomegranate	Juice blend	65 °C/30 s	Reduction of naturally occurring microbiota. Good preservation of color properties. Marked effect on ascorbic acid degradation	Mena and others (2013a)
Mandarin	Juice	42 to 72 °C/12 s	PME activity ranged from 0.07 to 0.88 (units/g of juice) at 72 and 42 °C, respectively	Hirsch and others (2011)
Orange	Juice	70 °C/7.2 s	No changes in pH, soluble solids, titratable acidity, and ascorbic acid content. 86.4% PME inactivation	Yuk and others (2014)
Pomegranate	Juice	65 °C/30 s	4.09 log reduction of natural microbiota. The anthocyanin content was enhanced	Mena and others (2013b)
Soursop	Nectar	60 and 73 °C/0 to 20 s	Significant reduction in the heat resistance of cocktails of *E. coli* (NRRL 3704, ATCC 8739, ATCC 92522) and *S. enterica* serovars Typhimurium (NRRL B-4420), Typhi (NRRL B-573), and Enteritidis (Biotech 1963) when heating was increased from 60 to 73 °C	Gabriel and others (2015)
Sweet cherry	Juice	70 °C/30 s	Reduction of natural microbiota below the detection limit. Increase of total phenolic content. No effect on anthocyanins	Queirós and others (2015)
Tomato	Juice	74 °C/30 s	Residual microorganisms (*L. innocua*, *E. coli*, *L. plantarum*, *S. cerevisiae*, and *A. niger*) were below the detection limit for at least 21 d. Enhancement oxidative breakdown of unsaturated fatty acids	Aganovic and others (2014)
Winter melon	Juice	71 °C/15 s	High acceptability in the sensory panel	Sun and others (2016)

PME, pectin methyl esterase.

Ohmic heating (OH)

OH is based on the passage of electrical current through a food product that provides electrical resistance (Baysal and Icier 2010). Since the electrical conductivity of most foods increases with temperature, OH is very effective in fruit juices, which contain water and ionic salts in abundance (Miller and Silva 2012). OH provides uniform and rapid heating of foods, with a beneficial effect on the nutritional and organoleptic properties of processed products (Mercali and others 2015). Additionally, OH offers better energy efficiency, lower capital cost, shorter treatment time, and is an environmentally friendly process (Lee and others 2015) since 90% of electrical energy is converted into heat (Srivastav and Roy 2014).

With regard to the applications of OH in the juice industry, a broad range of studies focused on its suitability for replacing traditional heating processes, studying in turn its effects on the nutrients in processed juices (Traffano-Schiffo and others 2014) (Table 7). Bhat and others (2016) confirmed this statement, suggesting that OH is a promising alternative to conventional thermal technologies with a maximum retention of functional components and the complete destruction of microorganisms in bottle gourd juice. Similarly, other studies reported: (1) the lack of the effect on the flavor of many juice blends during the refrigerated storage for 2 wk (Dima and others 2015); (2) the retention of the carotenoids in orange and grapefruit juices (Achir and others 2016); (3) a moderate loss of ascorbic acid in carrot/celery/beetroot juice blend (Profir and Vizireanu 2013); and (4) any effect on the overall quality of orange and pineapple juices (Tumpanuvatr and Jittanit 2012).

Electric field strength, which is applied in OH, is too weak to inactivate foodborne pathogens by electroporation alone. However, the lethal effect of cell electroporation is an important factor for inactivating foodborne pathogens when combined with heating (Park and Kang 2013). In apple juice, OH for 30 s at 58 °C accomplished 4.00-, 4.63-, and 1.11-log reductions in levels of *E. coli* O157:H7, *S. Typhimurium*, and *L. monocytogenes* organisms, respectively. Conventional heating under the same conditions resulted in 1.58-, 1.42-, and 0.41-log reductions, respectively, which were less than those obtained by OH for all 3 pathogens (Park and Kang 2013).

Table 6–Alternative thermal processing: microwave heating (MWH)

Fruit/vegetable source(s)	Product(s)	Processing conditions	Key finding(s)	Reference
Apple	Juice	1200 W/90 and 120 s	Microwave (MW) could effectively remove the moisture in apple juice without affecting the overall quality	Xinfeng (2014)
Apple	Concentrated juice	40 to 800 W/18 to 270 s/<97 °C	*A. acidoterrestris* spores could be inactivated by combining heat-treatment and MW	Djas and others (2011)
Beetroot	Juice	25 to 200 W/0.3 to 40 min/approximately 100 °C	Browning	Gonçalves and others (2013)
Banana, grape, papaya; Bittergourd, bottlegourd, cucumber; Bittergourd, black jamun; Carrot, pomegranate; Figs, watermelon; Grape, melon: Grape, papaya; Grape, mango	Juice blend	1800 W/0 to 400 s/<121 °C	3 log reduction bacteria and fungi. Enterobacteria below the detection limit	Math and others (2014)
Black jamun	Juice	600 and 900 W/30 s/approximately 75 to 80 °C	Increase of flavonoid content	Saikia and others (2015)
Black mulberry	Juice	300 W/<150 min	Good preservation of anthocyanins	Hojjatpanah and others (2011)
Blueberry	Juice	200 and 250 W	Good preservation of phenolic content	Elik and others (2016)
Blue-berried honeysuckle	Juice	90 to 135 °C/7 s	Only the portion of juice treated with the lowest temperature (80 °C) contained some contaminating bacteria	Piasek and others (2011)
Carambola	Juice	600 and 900 W/30 s/approximately 75 to 80 °C	Increase of total phenolic content, ferric reducing antioxidant property	Saikia and others (2015)
Carrot	Juice	540 to 900 W/4 min/<99 °C	Total inactivation of PME	Rayman and Baysal (2011)
Carrot, lemon, pumpkin, tomato	Smoothie	210 and 260 W or 1600 and 3600 W/approximately 90 °C/646 and 608 s or 206 and 93 s	Increase of the contents of total phenolic compounds and carotenoids. The highest power and the shortest time MWH treatments (3600 W for 93 s), resulted into better preservation of antioxidant capacity and vitamin C. No *L. monocytogenes* growth	Arjmandi and others (2016)
Chokeberry	Juice	90 to 135 °C/7 s	Total inactivation of contaminating bacteria from 90 to 135 °C	Piasek and others (2011)
Grapefruit	Juice	900 W/30 s/80 °C	Retention of flavonoids throughout 2 mo of frozen storage	Igual and others (2011)
Guava	Nectar	500 and 950 W/9 and 11 s/90 °C	Significant PME inactivation and ascorbic acid retention. Preservation of color and rheological properties. Microbial counts remained below detectable levels throughout storage	Salazar-González and others (2014)
Kava	Juice	1.8 kW	Significant PME inactivation (34% to 83%). Kavalactones were kept constant or increased	Abdullah and others (2013)
Litchi	Juice	600 and 900 W/30 s/approximately 75 to 80 °C	Increase of total flavonoid content	Saikia and others (2015)
Orange	Juice	540 to 900 W/1 min/<95 °C	95% PME inactivation. Preservation of the quality characteristics. Antimicrobial effect	Demirdöven and Baysal (2015)
Pineapple	Juice	600 and 900 W/30 s/approximately 75 to 80 °C	Increase in total phenolic content and radical scavenging activity	Saikia and others (2015)
Pomegranate	Juice	350 W/78 min	No microbial growth and absence of indicator organisms like *S. aureus*, *Pseudomonas* sp., *E. coli*, and *Salmonella* sp. Decrease in pH and effect on color, total soluble solids, acidity, sugars, polyphenols, anthocyanins, and antioxidant activity content	Dhumal and others (2015)
Tomato	Juice	18 kW/approximately 82 s/approximately 85 °C	Inactivation of naturally occurring microorganisms. Moderate effect on physicochemical and color characteristics	Stratakos and others (2016)
Watermelon	Juice	600 and 900 W/30 s/approximately 75 to 80 °C	Increase of total phenolic content	Saikia and others (2015)

PME, pectin methyl esterase.

Table 7–Alternative thermal processing: ohmic heating (OH)

Fruit/vegetable source(s)	Product	Processing conditions	Key finding(s)	Reference
Apple	Juice	60 V/cm/0 to 30 s/55 to 60 °C	Electric field-induced ohmic heating led to additional bacterial (*E. coli* O157:H7, *S. enterica* serovar Typhimurium, and *L. monocytogenes*) inactivation at sublethal temperatures	Park and Kang 2013
Black mulberry blueberry, coconut, guava, passion fruit, pummelo tamarind	Juice	50 Hz/10 and 33 V/cm/80 °C	Prediction of the temperature changes of the juice during OH was more accurate if the heat loss to the surroundings and evaporated moisture were included in the mathematical models	Tumpanuvatr and Jittanit (2012)
Bottle gourd	Juice	60 to 90 °C/0 to 105 s	No significant change in TS content at all temperature–time combinations but showed increase in TSS in temperature range of 60 to 90 °C. Maximum polyphenol content observed at 80 °C for 90 s; however, reverse trend was followed as temperature increased beyond 80 °C. Increase in temperature showed increase in carotenoids up to 80 °C, further increase in temperature led to degradation of these compounds	Bhat and others (2016)
Broccoli carrot	Juice	6 to 1500 min/58 to 78 °C	Destabilization of the labile isozyme fraction of POD	Jakób and others (2010)
Carrot, celery, beetroot	Juice blend	17.5 V/cm/3 to 4 min/70 °C	Low loss of ascorbic acid throughout the refrigerated storage for 2 wk	Profir and Vizireanu (2013)
Carrot, orange, pumpkin, carrot, grapefruit, pumpkin, celery, orange, pumpkin	Juice blend	17.5 V/cm/3 to 4 min/70 °C	No negative influence on flavor during the refrigerated storage for 2 wk	Dima and others (2015)
Cloudberry	Juice	6 to 1500 min/58 to 78 °C	A low destabilization of PME	Jakób and others (2010)
Grapefruit, orange	Juice	50 Hz/0.1 to 3 kV/m/50 and 150 min/95 °C	No negative effects on carotenoids	Achir and others (2016)
Jaboticaba	Juice	0 to 90 min/70 to 90 °C	Anthocyanins have similar degradation pathways during ohmic and conventional heating	Mercali and others (2015)
Lemon	Juice	20 to 74 °C/0 to 50 s	The electrical conductivity of lemon juice is strongly dependent on temperature	Darvishi and others (2011)
Orange, pineapple	Concentrated juice	50 Hz/10 and 33 V/cm/<500 s/80 °C	No additional effect on the juice quality	Tumpanuvatr and Jittanit (2012)
Pomegranate	Juice	20 to 85 °C/0 to 50 s	As the voltage gradient increased, time, system performance, and pH decreased	Darvishi and others (2013)
Potato	Juice	6 to 1500 min/58 to 78 °C	A significant destabilization of the labile isozyme fraction of POD	Jakób and others (2010)
Tomato	Juice	10 kHz and 60 Hz/<30 min/<110 °C	Accelerated inactivation of *B. coagulans* (ATCC 8038) spores	Somavat and others (2013)

PME, pectin methyl esterase; POD, peroxidase.

Bacillus coagulans is a nonpathogenic organism, but it can pose a safety hazard because of its ability to increase the pH of a high acid food, processed with a reduced treatment, to a level where surviving *Clostridium botulinum* spores can germinate (Somavat and others 2013). In this respect, OH at 60 Hz and 10 kHz resulted in accelerated inactivation of *B. coagulans* (ATCC 8038) spores in tomato juice compared to conventional treatment (Somavat and others 2013). According to the authors, these results could confirm the presence of the additional nonthermal effect of OH on bacterial spores.

Improving the Effectiveness of Thermal Processing Technologies

"Hurdle technology" is the term often applied when hurdles are deliberately combined to improve the microbial stability and quality of foods and their nutritional and economic properties (de Oliveira and others 2015). Different hurdles can have an additive or synergistic effect.

Examples of hurdle approaches used in thermal processing of fruit and vegetable juices and beverages include: (1) the evaluation of intrinsic hurdles such as pH and dissolved solids (°Brix), as well as (2) the combination with other preservation such as antimicrobials and bacteriocins. An overview of the different approaches currently used to improve the effectiveness of thermal processing is reported in Table 8 and 9.

When a thermal process is applied, the microbial heat resistance is influenced not only by temperature but also by several other factors, such as the physiological state of the microorganisms, pH, water activity, and the composition of raw material (Miller and Silva 2012). pH is generally considered the most important factor determining the heat resistance of bacterial spores (Peng and others 2012; Tola and Ramaswamy 2014).

The evaluation of solids content is also of concern, since it is extremely hard to kill pathogens in juice concentrate by thermal treatment (Song and others 2015). Song and others (2015) reported that 18 °Brix apple juice underwent a larger reduction of pathogens than 36 and 72 °Brix juice.

Several studies reported the synergistic effect of heat treatments and antimicrobial compounds or bacteriocins to extend the shelf-life of fruit and vegetable juices and beverages and/or inhibit pathogens. On the other hand, the pressure from consumers for minimally processed products free from traditional preservatives has induced manufacturers to consider new strategies for juice stabilization including natural antimicrobials (Belletti and others 2007). Overall, supplementation of these additives together with heating might result in more acceptable thermal process schedules, possessing the desired lethalities without

Table 8–Improving the effectiveness of thermal treatments. Approach 1: evaluation of intrinsic hurdles

Fruit/vegetable source(s)	Product	Processing conditions	Intrinsic hurdle	Key finding(s)	Reference
HTLT					
Carrot	Juice	87 °C/0 to 24 min or 92 °C/0 to 16 min or 97 °C/0 to 8 min	pH 4.5 to 6.2	Enhancement of the lethality at acidic pH	Tola and Ramaswamy (2014)
Carrot, basil, celery, cucumber, lemon, olive, onion, pepper, tomato	Blended beverage	50 to 65 °C/0 to 75	pH (4.25 to 5.20)	A reduction of 5 log CFU/mL of *L. innocua* (CECT 910) at 65 °C could be achieved after 1 or 2 min, depending on the pH (4.25 to 4.75 or 5.20, respectively)	Vega and others (2016)
Tomato	Juice	100 °C/2 to 10 min	pH 3.8 to 4.3	Lethality toward *B. coagulans* (ATCC 8038) enhanced by pH	Peng and others (2012)
MTLT					
Apple	Juice	25 to 55 °C/1 min	Soluble solids 18 to -72 °Brix	An increase of soluble solids caused an increase of the lethality of the treatment	Song and others (2015)
Pitahaya	Juice	65 °C/30 min	pH 3.0 to 7.0	High preservation of betacyanin content at pH 4	Wong and Siow (2015)
OHMIC HEATING					
Grape	Juice	10 to 15 V/cm/25 to 80 °C	Soluble solids 10.5 to 14.5 °Brix	Electrical conductivity increased as concentration and temperature increased	Assawarachan (2010)
Carrot	Juice	4 kHz/87 °C/0 to 24 min or 92 °C/0 to 16 min or 97 °C/0 to 8 min	pH 4.5 to 6.2	Lethal effect of electricity on *Bacillus licheniformis* spores could be enhanced at higher pH and temperature	Tola and Ramaswamy (2014)
Orange	Juice	16 V/cm/20 kHz/0 to 60 s/50 to 60 °C	pH 2.5 to 4.5	The lethality of the thermal treatment towards *E. coli* O157:H7, *S.* Typhimurium and *L. monocytogenes* was enhanced by high temperatures and acidic pH	Lee and others (2015)

negatively affecting product qualities (Gabriel and Estilo 2015).

In apple juice, HTLT thermal treatment alone (80 °C/6 min) was not able to reduce *Alicyclobacillus acidoterrestris* (DSMZ 2498 and c8 cocktail) spore number, while citrus and lemon extract combined with thermal treatments reduced alicyclobacilli after 16 d by 1 or 1.50 log CFU/mL (Bevilacqua and others 2013). When combined with heat (51 °C/approximately 60 min), propolis reduced time and temperature required to achieve a 5 log reduction of *E. coli* O157:H7 (Sakai stx 1A− /stx 2A−) by 75% and 3 °C, respectively (Luis-Villaroya and others 2015). Using a MTLT treatment (54 °C/10 min), essential oils decreased the time to inactivate *E. coli* O157:H7 VTEC − (Phage type 34) cells by 3.5 to 5.7 times (Ait-Ouazzou and others 2012).

In coconut liquid endosperm, heat treatment (55 °C/120 min) combined with malic acid attained a 3-fold reduction of *E. coli* O157:H7 (Gabriel and Estilo 2015). In mango juice, the time to inactivate by 5 log cycles *E. coli* O157:H7 decreased by 75% when heat treatment (54 and 60 °C/10 min) was combined with carvacrol (Ait-Ouazzou and others 2013). In orange juice, a reduction of 2.34 log CFU/mL for *A. acidoterrestris* (CCT 49028) spores was observed in the first 24 h of incubation after heat treatment (99 °C/1 min) + saponin (Alberice and others 2012). The addition of 200 ppm of (+)-limonene or citrus essential oil to orange juice reduced the heating time to achieve a 5 log reduction of *E. coli* O157:H7 (VTEC − Phage type 34) by 3.8 or 2.5 times, respectively (Espina and others 2014). In pineapple juice, the use of 15 ppm of essential oil during pasteurization of pineapple juice at 60 °C reduced the time required for a 4-log reduction in *Listeria monocytogenes* (56 LY) by 74.9% (Ngang and others 2014).

Overall, these compounds control microbial growth by lowering the pH levels and disrupting cellular membrane functionality as well as by acting on enzymes and genetic material (Gabriel and Estilo 2015). Cell membrane alterations caused by these compounds are able to induce sublethal injury. As sublethal injury is supposed to be related to the higher sensitivity of survivors to stress conditions after treatment, the success of a combined treatment should be correlated with the degree of sublethal injury caused by the hurdles in the bacterial population. Moreover, under suitable conditions, sublethal injured cells might be repaired, which is a very important aspect to be taken into account regarding food safety (Guevara and others 2015).

The antimicrobial compounds can have a positive effect on the quality parameters. Combined with thermal treatment, stevia increased the stability of color and some polyphenols, such as quercetin, gallic acid, and rosmarinic acid, during the storage of roselle beverage. In addition, stevia decreased the loss of scavenging activity and α-amylase inhibitory capacity (Pérez-Ramírez and others 2015). Other compounds combined with thermal treatments include ascorbic acid (Wong and Siow 2015), SO_2 (Cui and others 2012), *Scapania nemorea* methanolic extract (Bukvicki and others 2014), and nanocomposite packaging containing nano-ZnO particles (Emamifar and others 2012).

Among antimicrobial compounds, bacteriocins have received special attention due to their natural origin but also because they are associated with a large number of fermentations (Martín-Belloso and Sobrino-López 2011). For example, nisin with thermal pasteurization had a synergistic effect on the inactivation of total aerobic bacteria (1.18 log reduction) in cucumber juice (Zhao and others 2013). In litchi juice, heat treatment combined with nisin reduced the aerobic bacteria by 4.19 log CFU/mL (Li and others 2012). In carrot juice, at the lowest nisin concentration tested (0.13 μM), growth rate was significantly reduced; at higher concentrations (0.39 μM), the growth of *L. monocytogenes* (CECT 4031) was completely inhibited for at least 15 d (Esteban and Palop 2011). Heat treatment (55 °C/120 min) combined with nisin caused a 3-fold reduction of the heat resistance of *E. coli* O157:H7 in coconut liquid endosperm (Gabriel and Estilo

Table 9–Improving the effectiveness of thermal treatments. Approach 2: combination with antimicrobials and bacteriocins

Fruit/vegetable source(s)	Product	Processing conditions	Additional hurdle(s)	Key finding(s)	Reference
HTLT+ANTIMICROBIALS					
Apple	Juice	80 °C/6 min	**Citrus extract or lemon extract** (80 ppm)	The combination of citrus or lemon extract with the thermal treatment reduced *A. acidoterrestris* (DSMZ 2498 and c8 cocktail) spores by 1 or 1.50 log CFU/mL	Bevilacqua and others (2013)
Apple, orange	Juice blend	80 °C/60 and 90 s	**Lemon grass oil** (0.28 to 1.13 mg/mL)	The combination of thermal treatment for 90 s enhanced the log reduction of *S. cerevisiae* SPA by 1 log as compared to lemon grass alone	Tyagi and others (2014b)
Apple, orange	Juice blend	80 °C/60 and 90 s	**Mentha oil** (0.28 to 1.13 mg/mL)	The combination of thermal treatment for 90 s enhanced the log reduction of *S. cerevisiae* SPA by 1.03 log as compared to only mentha treated samples	Tyagi and others (2013)
Grape	Wine	80 °C/15 min	**SO_2** (40 mg/L)	99.91% lethality toward *S. cerevisiae* (QA23)	Cui and others (2012)
Guava	Juice	85 °C/1 min	**Sodium metabisulphite** (0.04 g/L), or **potassium sorbate** (0.8 g/L), or **sodium benzoate** (0.5 g/L), or **sodium metabisulfite** (0.02 g/L) + **sodium benzoate** (0.25 g/L), or **sodium metabisulphite** (0.02 g/L) + **potassium sorbate** (0.4 g/L)	The preservatives used were effective in inhibiting microorganisms during storage at room temperature. Formulations with the isolated metabisulphite and associated with potassium sorbate showed the highest sensory acceptance	da Silva and others (2016)
Mango	Juice	121 °C/15 min	**Zinc oxide nanoparticles** (5 and 8 mM) containing citric acid (0.3%)	Zinc oxide nanoparticles reduced the counts of *L. monocytogenes* (PTCC1163), *E. coli* (PTCC1394), *S. aureus* (PTCC1431), and *B. cereus* (PTCC1015) strains in juice	Firouzabadi and others (2014)
Orange	Juice	99 °C/1 min	**Saponin** (100 to 500 mg/L)	Reduction of 2.34 log CFU/mL for *A. acidoterrestris* (CCT 49028) spores in the first 24 h	Alberice and others (2012)
Papaya	Spiced beverage blend	80 to 90 °C/15 min	**Citric acid** (0.1%)	Microbiota below the detection limit (5 mo at approximately 28 °C)	Ramachandran and Nagarajan (2014)
Prickly pear	Juice	121 °C/15 min	**Sodium benzoate** (300 ppm) + **potassium sorbate** (100 ppm) + **fumaric** (0.17% w/v), citric (0.4% w/v) and **tartaric** (0.5% w/v) *acids*	After 4 d of storage, the use of acids caused a reduction of *E. coli* (ATCC 11229) (3- to 6-log CFU/mL) and *S. cerevisiae* (ATCC 26109) (2 log CFU/mL)	García-García and others (2015)
Roselle	Beverage	95 °C/15 min	**Sodium benzoate** (0.7 g/L), **stevia** (14 to 15 g/L), **citric acid** (0.2 and 0.3 g/L)	Stevia increased the stability of color and some polyphenols, such as quercetin, gallic acid, and rosmarinic acid, during storage. In addition, stevia decreased the loss of scavenging activity and α-amylase inhibitory capacity, whereas the incorporation of citric acid showed no effect	Pérez-Ramírez and others (2015)
HTST+ANTIMICROBIALS					
Acerola, cashew apple, guava, papaya, passion fruit	Blended nectar added with caffeine	90 °C/30 s	**Sodium metabisulfite** (60 mg/L) + **sodium benzoate** (500 mg/L)	The product was microbiologically stable during 6 mo of storage at room temperature (approximately 25 °C). The ascorbic acid content decreased significantly throughout time.	de Sousa and others (2010)
Apple, orange	Juice blend	80 °C/30s	**Lemon grass essential oil** (0.28 to 1.13 mg/mL)	Inhibition of *S. cerevisiae* SPA after 2 d of storage at room temperature. No growth for 7 d	Tyagi and others (2014b)
Apple, orange	Juice blend	80 °C/30 s	**Mentha essential oil** (0.28 to 1.13 mg/mL)	Complete growth inhibition of *S. cerevisiae* SPA using 1.13 mg/mL of mentha oil. No effect on odor and color	Tyagi and others (2013)
Prickly pear	Juice	131 °C/2 s	**Sodium benzoate** (0.3 g/L), **sodium sorbate** (0.15 g/L), **fumaric acid** (1.4 g/L), **tartaric acid** (0.4 g/L) and **sodium citrate** (0.3 g/L)	Loss of ascorbic acid (46% to 76%), total phenolic (27% to 52%), flavonoids (0% to 52%), betalains (7% to 45%), and antioxidant activity (16% to 45%) when compared to untreated beverages	Jiménez-Aguilar and others (2015)
MTLT+ANTIMICROBIALS					
Apple	Juice	54 °C/0 to 35 min	**Citrus lemon essential oil** (200 μL/L)	6.2-fold increase in the lethality on *E. coli* O157:H7. No effect on the sensory attributes	Espina and others (2012)

(*Continued*)

Table 9–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Additional hurdle(s)	Key finding(s)	Reference
Apple	Juice	54 °C/10 min	**(+)-limonene** (0.2 μL/mL)	The combination increased the lethality *Leuconostoc fallax* 74 by 1.5 log CFU/mL	Chueca and others (2016)
Apple	Juice	54 °C/8 min	**Citral** (18 and 200 ppm)	The addition of 18 and 200 ppm of citral to the juice acted synergistically with heat to inactivate 4.5 and 7.4 log *E. coli* O157:H7 cells, respectively	Espina and others (2010)
Apple	Juice	51 °C/approximately 60 min	**Propolis** (0.1 and 0.2 mg/mL)	The time to achieve a 5 log reduction of *E. coli* O157:H7 was reduced by 75% and the temperature by 3 °C	Luis-Villaroya and others (2015)
Apple	Juice	54 °C/10 min	**Essential oils** (0.2 μL/mL)	When combined with heat, *Mentha pulegium* or *Thymus algeriensis* accused, respectively, a 3.5- and a 5.7-fold decrease of the time to achieve a 5 log reduction of *E. coli* O157:H7 (VTEC - Phage type 34)	Ait-Ouazzou and others (2012)
Apple	Juice	54 and 60 °C/10 min	**Carvacrol** (1.3 mM)	The time to achieve a 5 log reduction of *E. coli* O157:H7 was reduced by 75%	Ait-Ouazzou and others (2013)
Apple	Juice	55 °C/0 to 3.58 min	**Dimethyl dicarbonate** (25 to 75 mg/L)	*E. coli* (STCC 4201) reduced by 4.4 log CFU/mL. The addition of dimethyl decarbonate (>25 mg/L) increased the lethality of heat	Gouma and others (2015)
Apple, orange	Juice blend	70 °C/60 and 90 s	**Eucalyptus essential oil** (0 to 4.5 mg/mL)	2.25 mg/mL of eucalyptus oil + 90 s thermal treatment reduced *S. cerevisiae* SPA below the detection limit	Tyagi and others (2014a)
Citron	Soft drink	55 °C/15 min	**Citral** (0 to 120 μL/L) or **linalool** (0 to 60 μL/L) or **β-pinene** (0 to 60 μL/L)	Additive/synergistic effect of the compounds	Belletti and others (2010)
Carrot	Juice	45 and 50 °C/5 to 15 min	**Caprylic acid** (5.0 mM) and/or **citric acid** (2.5 or 5.0 mM)	Combined treatment with caprylic acid + citric acid (2.5 mM) at 50 °C for >5 min or with caprylic acid + citric acid (both at 5.0 mM) at either 45 °C or 50 °C for >5 min completely inactivated the natural occurring bacteria. Combined treatment also increased the redness of the juice	Kim and Rhee (2015)
Carrot	Juice	55 °C/5 and 10 min or 63 °C/1 min	**Citral** (50 mg/L), or **carvacrol** (30 mg/L), or **(E)-2-hexenal** (65 mg/L)	Accelerated death kinetics of *L. monocytogenes* (56LY) in the presence of the aroma compounds	Sado Kamdem and others (2010)
Coconut	Liquid endosperm	55 °C/120 min	**Malic acid** (800 to 1500 ppm)	3-fold reduction of the heat resistance of the *E. coli* O157:H7	Gabriel and Estilo (2015)
Mango	Juice	54 and 60 °C/10 min	**Carvacrol** (1.3 mM)	The time to achieve a 5 log reduction of *E. coli* O157:H7 decreased by a 75%	Ait-Ouazzou and others (2013)
Orange	Juice	52 to 61 °C/0 to 12 min	**Vanillin** (900 to 1.100 ppm) and/or **citral** (25 to 75 ppm)	The addition of 900 ppm vanillin and 25 ppm citral enhanced the lethality of the thermal treatment towards *L. innocua* (ATCC 33090)	Char and others (2010)
Orange	Juice	54 to 60 °C/0 to 250 min	**(+)-limonen** (50, 100, and 200 ppm) or **citrus essential oil** (50 to 200 ppm)	The addition of 200 ppm of (+)-limonene or citrus essential oil reduced the time to achieve a 5-log inactivation of *E. coli* O157:H7	Espina and others (2014)
Orange	Juice	54 and 60 °C/10 min	**Carvacrol** (1.3 mM)	The time to achieve a 5 log reduction of *E. coli* O157:H7 decreased by 84%	Ait-Ouazzou and others (2013)
Orange	Concentrated juice	45 °C/28 d	**Sodium benzoate** (50 and 100 mg/L), **commercial benzoic acid** (50 and 100 mg /L), and **micronized benzoic acid** (25 and 50 mg/L)	A continuous bactericidal effect against 2 *Alicyclobacillus* strains for 28 d period using micronized benzoic acid (50 mg/L)	Kawase and others (2013)
Pineapple	Juice	55 to 65 °C/0 to 15 min	***Eryngium foetidum* essential oil** (0 to 60 ppm)	The use of 15 ppm of essential oil during pasteurization of pineapple juice at 60 °C reduced the time required for a 4-log reduction in *L. monocytogenes* (strain 56 LY) by 74.9%	Ngang and others (2014)
Pitahaya	Juice	65 °C/30 min	**Ascorbic acid** (0.25 to 1.50% w/w)	Juice added with 0.25% ascorbic acid gave the highest betacyanin content	Wong and Siow (2015)
Soursop	Juice	60 °C/60 min	**Sodium benzoate** (0.05%)	Significant decrease in microbial load throughout the period of storage (30 to 31 °C; 2 wk) compared to nonpasteurized juice. Decrease in titratable acidity from 23.62 to 18.10	Nwachukwu and Ezeigbo (2013)
Tomato	Juice	54 and 60 °C/10 min	**Carvacrol** (1.3 mM)	The time to achieve a 5 log reduction of *E. coli* O157:H7 decreased by 75%	Ait-Ouazzou and others (2013)

(*Continued*)

Table 9–Continued.

Fruit/vegetable source(s)	Product	Processing conditions	Additional hurdle(s)	Key finding(s)	Reference
MTST+ANTIMICROBIALS					
Apple, orange	Juice blend	70 °C/30 s	**Eucalyptus essential oil** (0 to 4.5 mg/mL)	A dose 2.25 mg/mL of eucalyptus oil combined with thermal treatment reduced the naturally occurring microbiota by 4.5 log CFU/mL	Tyagi and others (2014a)
Apple, orange	Juice blend	70 °C/30 s	***Scapania nemorea* methanolic extract** (0.05 to 0.2 mg/mL)	Partial inactivation of *S. cerevisiae* 635. Changes in color and flavor of the beverages were considered acceptable also after 1 wk of storage at 25 °C	Bukvicki and others (2014)
Orange	Juice	65 and 55 °C/16 s	**Ag** and **ZnO nanoparticles** (10% m/m of low-density polyethylene nanocomposite packaging)	Application of nanocomposite packaging-containing Ag decreased the pasteurization temperature of juice by 10 °C, resulting in a lower degradation of ascorbic acid	Emamifar and others (2012)
HTLT+ BACTERIOCINS					
Apple	Juice	90 °C/25 min	**Bificin C6165** (0 to 160 μg/mL)	The heat resistance of *A. acidoterrestris* (DSM3922 and CFD1) spores declined gradually as bificin C6165 concentration increased	Pei and others (2014)
HTST+ BACTERIOCINS					
Cucumber	Juice	85 °C/15 s	**Nisin** (100 IU/mL)	Nisin with thermal pasteurization had a synergistic effect on the inactivation of total aerobic bacteria	Zhao and others (2013)
MTLT+ BACTERIOCINS					
Carrot	Juice	55 °C/15 min	**Nisin** (0.13 to 0.39 μM)	The antimicrobial effect towards *L. monocytogenes* (CECT 4031) relied upon the concentration of nisin	Esteban and Palop (2011)
Coconut	Liquid endosperm	55 °C/120 min	**Nisin** (0 to 150 ppm)	The combined treatment caused a 3-fold reduction of the heat resistance of *E. coli* O157:H7	Gabriel and Estilo (2015)
Litchi	Juice	32 to 52 °C/5 to 30 min	**Nisin** (200 ppm)	Aerobic bacteria reduced by 4.19 log CFU/mL at 52 °C for 15 min	Li and others (2012)
Orange	Juice	72 °C/2 min	**Antilisterial Bacteriocin101 and 103** (40 ppm)	*L. monocytogenes* (MTCC 657) was controlled for 6 d at 4 °C	Backialakshmi and others (2015)
HTST+BACTERIOCINS + ANTIMICROBIALS					
Orange	Nectar	90 °C/15 s	**Nisin** (46.8 IU/mL) + cinnamaldehyde (0.39 μL/mL)	The combination of nisin and cinnamaldehyde showed a synergistic effect against *A. acidoterrestris* (ATCC 49025) and extend the shelf life of nectar to 33 d at 45 °C	Khallaf-Allah and others (2015)
MTLT+ BACTERIOCINS + ANTIMICROBIALS					
Carrot	Juice	55 °C/15 min	**Nisin** (0.13 μM) + **carvacrol** (0.11 and 0.22 mM)	The growth of *L. monocytogenes* (CECT 4031) was inhibited for at least 15 d even at the lowest concentration tested (0.13 μM nisin plus 0.11 μM carvacrol)	Esteban and Palop (2011)
Litchi	Juice	30 to 45 °C/0.5 to 6 h	**Nisin** (200 IU/mL) + **dimethyl dicarbonate** (250 mg/L)	Molds and yeasts, and bacteria were not detected in the juice supplemented with 200 IU/mL nisin and exposed to 250 mg/L dimethyl dicarbonate at 45 °C for 3 h	Yu and others (2013a)

2015). However, several studies have been able to demonstrate that nisin was only able to reduce the population of Gram-negative cells that have been previously exposed to sublethal injury after exposure to 55 °C; and that the bacteriocin had little or no effect on uninjured cells (Gabriel and Estilo 2015). In apple juice, the heat resistance of *A. acidoterrestris* (DSM3922 and CFD1) spores declined gradually as bificin C6165 concentration increased (Pei and others 2014).

Some authors evaluated the combination between bacteriocins + antimicrobials and heat treatment. For example, yeasts and molds, and bacteria were not detected in litchi juice supplemented with 200 IU/mL nisin and 250 mg/L dimethyl dicarbonate at 45 °C for 3 h (Yu and others 2013a). In another study, the growth of *L. monocytogenes* (CECT 4031) in carrot juice was inhibited for at least 15 d by 0.13 μM nisin + 0.11 μM carvacrol (Esteban and Palop 2011).

In this perspective, predictive microbiology is a useful tool to determine shelf life and stability of juices and beverages treated with combined stabilizing techniques (Belletti and others 2007).

Future Perspectives and Current Efforts

Fruit and vegetable consumption is a marker of higher-quality diets. The consumption of fruit juices, along with whole fruit, is one way to meet total fruit consumption goals (Francou and others 2015).

Recent analyses showed that whole fruit contributed fully 2/3 to total fruit consumption, with only 1/3 coming from juices. However, whereas whole fruit consumption was highest among older adults and among groups with higher education and incomes, no social gradient was observed for juices (Francou and others 2015). Hence, these products were more likely to meet total fruit and vegetable goals that are promoted by food and nutrition policy.

The benefits and the drawbacks of heat treatments in juices were extensively reported in many papers and hereby shortly addressed. In most cases, these effects are strongly dependent on the food matrix. Moreover, the efficacy of treatments can also be affected by the complexity of the product and microorganisms.

The use of nonconventional heat approaches or the combination with some antimicrobial compounds are promising ways, but the optimization of the combination time/temperature still remains the only effective way to design energy-saving and efficient methods. Thus, a better understanding of the mechanism of action of thermal processing technologies and their effects on bioaccessibility and bioavailability of beneficial compounds, would also contribute to an effective application in juice.

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