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INVITED REVIEW

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Thermal and non-thermal processing technologies on intrinsic and extrinsic quality factors of tomato products: A review

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Abstract

Tomato and tomato-based products play a vital role in human diet due to the presence of bioactive compounds. The conventional heat treatment is designed as a current practice in tomato products industry to ensure food safety but it can lead to undesirable changes both in the nutritional and in the sensory properties of the products. In order to avoid these unfavorable changes during the heat treatment, novel thermal, and non-thermal processing technologies have been receiving much attention with the aim of improving and replacing conventionally processed products. Among them, some of the most promising technologies of high pressure processing, pulsed electric fields, and power ultrasound in comparison to conventional thermal processing technologies are highlighted in this article. This review presents recent scientific information on impact of these technologies on physico-chemical, organoleptic, and microbial properties of tomato-based products. Furthermore, it analyses and discusses the opportunities and drawbacks in commercial applications.

Practical applications

The preservation of tomato and tomato products is of primary interest for the food industry. Several novel thermal and non-thermal technologies—discussed in this review—could be utilized for the production of high quality tomato-based products. These technologies are increasingly attracting the attention of food processors as they efficiently provide products with extended shelf life and higher quantities of labile bioactive compounds when compared to conventionally processed products.

1 | INTRODUCTION

Tomato (*Lycopersicon esculentum*) is the second most important vegetable crop with a global production around 170 million tons (FAOSTAT, 2017). Fresh tomato is consumed in large quantities, not only due to its pleasant taste and versatile use in culinary practices worldwide but also due to its high nutritional value and functional properties. Both in vitro and in vivo studies have elucidated the potential of tomato and its products consumption on reduced risk of various maladies like obesity, hyperglycemic and hypercholesterolemic attributes, cardiovascular disorders, and cancer insurgences (Perveen et al., 2015). Despite of this staggering production numbers and health benefits, tomato is a highly problematic agricultural commodity in terms of short postharvest life, due to high perishability (94% moisture). To overcome this issue, one thirds of the total world production of tomatoes is processed into less perishable products, such as juice, puree, paste, ketchup, sauce, whole canned tomatoes, and powder (Etebu & Enaregha, 2013).

Thermal processing techniques, such as pasteurization, sterilization, and aseptic processing are commonly used in tomato processing industry. These processing techniques, however, often causes detrimental effects on the total quality and stability of tomato products

(Jayathunge, Grant, Linton, Patterson, & Koidis, 2015). There is a growing demand for efficient novel non-thermal processing technologies to overcome undesirable changes in organoleptic properties and retain higher quantities of bioactive compounds, while maintaining the microbial stability of the product for the desired storage period (Jan, Sood, Sofi, & Norzom, 2017). In the past decade, novel non-thermal technologies, such as high pressure (HP), ultrasonic (US) and high intensity pulsed electric field technologies (HIPEF) have become established in the food industry; however, there are still many challenges to be tackled. Moreover, review papers related to impact of novel thermal (microwave, radio frequency, ohmic heating, etc.) and non-thermal processing technologies (high pressure processing [HPP], ultrasonication, pulsed electric field [PEF], etc.) on various aspects of food commodities have been extensively published (Coskun & Pazir, 2013; Morris, Brody, & Wicker, 2007; Pereira & Vicente, 2010; Rawson et al., 2011; Sorour, Tanaka, & Uchino, 2014). Among the latest publications, Peng et al. (2017) and Roobab, Aadil, Madni, and Bekhit (2018) have reviewed on the impact of thermal pasteurization of ready to eat foods and vegetables focusing on process design and effects on quality, and impact of non-thermal technologies on the microbial quality of juices, respectively. However, up to date no paper has been published in addressing the impact of novel thermal and non-thermal processing technologies merely on the quality of tomato products. Hence, this review provides a comprehensive summary of recently published literature on thermal and non-thermal processing technologies on physico-chemical, nutritional, and microbiological qualities of tomato-based products.

2 | QUALITY PARAMETERS

2.1 | Physical Properties

Besides microbiological safety, the organoleptic properties, appearance, color, flavor, consistency, and texture are the basic factors that determine the consumer acceptability of the tomato-based products. All these organoleptic properties depend on the agronomic conditions during the growth of the tomatoes and the processing conditions during the manufacturing of the different tomato-based products (Hayes, Smith, & Morris, 1998).

An attractive red color is one of the main characteristics of tomato products playing an important role in appearance and overall acceptability by consumers (Rawal et al., 2016). Color in the tomato is due to the presence of carotenoids, mainly lycopene, which comprises more than 60% of the total carotenoids present followed by β-carotene (3–7%). Maintaining the bright red color in processed and stored products has been a major challenge in tomato processing (Shi & Le Maguer, 2000). Hence, identification of indicators to express the color changes after and during processing is crucial in terms of quality (Jayathunge, Grant, & Koidis, 2017).

Viscosity is also one of the main attributes that should be considered to determine the overall quality and consumer acceptability of tomato products. Furthermore, desirable viscosity is important in optimizing some of unit operations like mixing, pumping, and filling during manufacturing of different tomato products (Heidarinasab & Nansa, 2010). Consistency of tomato products refers to their viscosity and the ability of their solid portion to remain in suspension throughout the shelf-life of the product. The consistency of tomato products is strongly affected by the content of pectin, a cell wall polysaccharide. Controlling the breakdown or retention of the pectin, and the enzymes (pectin methylesterase [PME] and polygalacturonase [PG]) that lead to changes in the pectin, is thus, of great importance during processing. Flavor is one of the most important quality attributes of fresh tomatoes together with color and texture. Volatiles in fresh tomatoes are formed from lipids, carotenoids, amino acids, terpenoids (C10 and C15), lignin, and other sources and include different aldehydes, ketones, alcohols, furans, and terpenes (Viljanen, Lille, Heinio, & Buchert, 2011). Native lipoxygenase (LOX) and hydroperoxidelyase enzymes are primarily responsible for the formation of lipid-derived volatile compounds. More than 400 volatile compounds have been identified in tomato fruit; Buttery (1993) listed 30 important volatiles according to odor threshold studies while Baldwin et al. (1998) identified 15–20 volatiles according to the impact on human perception. Results of several studies concluded that a mixture of Z-3 hexanal, Z-3 hexanol, hexanal, 1-penten-3-one, 3-methylbutanal, E-2-hexenal, 6-methylbutanal, E-2-hexanal, 6-methyl-5-heptan-2-one, methyl salicylate, 2-isobutylthiazole, and β-ionone has an aroma very similar to that of sliced fresh tomato (Baldwin et al., 1998).

2.2 | Bioactive compounds

Tomato is an excellent source of antioxidants contributing to the daily intake of a significant amount of these compounds. The antioxidant capacity is related to the amount, composition, and synergistic interaction of bioactive compounds, including carotenoids, vitamins, ascorbic acid and tocopherols, and phenolic compounds, such as flavonoids and hydroxyl cinnamic acid derivatives (Borguini & Torres, 2009; Kotkov, Lachman, Hejtmnkov, & Hejtmnkov, 2011). Regular consumption of tomato and tomato-based products could reduce the risks of developing cardiovascular diseases and cancer (Campbell et al., 2004), due to the ability of these bioactive compounds to prevent cell damage through free-radical scavenging, metal chelation, inhibition of cellular proliferation, modulation of enzymatic activity, and signal transduction pathways (Lobo, Patil, Phatak, & Chandra, 2010). Lycopene is a lipid soluble carotenoid that can be synthesized by plants and microorganisms, but not by the human body (Roldan-Gutierrez & Luque de Castro, 2007). The major cause of lycopene loss is the oxidation of its highly unsaturated structure by photo-oxidation or by auto-oxidation. These oxidative reactions may result in bleaching or lightening the red color, which forms colorless end products (Odriozola-Serrano, Solivia-Fortuny, Hernandez-Jover, & Martin-Belloso, 2009).

Vitamin C occurs in two forms; L-ascorbic acid (reduced form) and dehydro-L-ascorbic acid (oxidized form). Although, L-ascorbic acid is the predominant form of vitamin C in nature, both forms are biologically active (Iqbal, Khan, & Khattak, 2004). Tomato contains considerable amount of vitamin C (varying from 15 to 30 mg/100 g) and it is relatively stable because of the acidic conditions found in the fresh tomato tissues (Sahlin, Savage, & Lister, 2004). In addition to the antioxidant properties, vitamin C is an essential micronutrient, which prevents scurvy disease and is involved in numerous metabolic functions of the human body. Significant losses of vitamin C can occur during postharvest storage and processing, partly due to degradation and leaching into the cooking water. Better retention could be expected at lower temperatures and milder treatment conditions (Davey et al., 2002).

Phenolic compounds are one of the main groups of dietary phyto-chemicals found in fruits, vegetables, and grains. These are considered secondary metabolites synthesized by plants during normal development and also in response to stress conditions, such as wounding, UV radiation, heat, drought, and salinity (Naczka & Shahidi, 2004). Phenolic compounds, also known as polyphenols, constitute an essential part of the human diet. Total phenolic content in tomato fruits vary from 9.8 to 23.0 mg/100 g (Brat et al., 2006) with chlorogenic acid, caffeic acid, and rutin being the ones found in higher quantities. Great losses of total phenolic compounds are expected during tomato processing due to breakdown or leaching out (George et al., 2011).

2.3 | Microbiological load

Microbial spoilage of tomato products may lead to development of off-flavors, odors, turbidity, and gas production. A limited range of yeasts, molds, and acidic bacteria are able to grow in low pH foods ranging from pH 3.3 to 4.0 like tomato-based products (Bracket, 1997). Yeasts and molds are the major spoilage microorganisms in tomato juice due to their survival and ability to grow at low pH environments (Mosqueda-Melgar, Raybaudi-Massilia, & Martín-Belloso, 2012). Other than yeast and mold, spoilage microoganisms like lactobacilli, *Bacillus coagulans*, and *Clostridium pasteurianum* and *Neosartorya fisheri*, are frequently isolated from spoiled canned tomato juices, pulps, and sauces. Spores of *B. coagulans* are pressure-resistant and relatively heat-resistant at acidic pH, and are able to germinate and grow at pH values between 3.7 and 4.5 (Pacheco & Massaguer, 2004). Pasteurization destroys non-spore forming spoilage microorganisms, such as Lactobacilli, but has little effect on the heat-resistant spores of *Bacillus coagulans*, especially when the pH is 4.35 or higher. Spoilage of tomato juice may also be caused by the heat-resistant spores of *Clostridium pasteurianum* (Gould, 1992).

3 | CONVENTIONAL THERMAL PROCESSING AS CURRENT PRACTICE

Conventional food processing methods have relied on high temperatures as a way to ensure prolonged shelf-life and food safety. Through thermal processing, microorganisms, and enzymes, such as PME, PG, and LOX are inactivated. However, thermal processing is also used for product concentration. First thermal step in the tomato processing industry is blanching by means of a hot or cold break. In hot break process, tomatoes are rapidly heated to 80–100°C for a short period of time (5–10 min) inactivating pectic enzymes but also enzymes responsible for flavor (like LOX) due to application of high temperatures. However, following a cold break process (temperatures below 65°C) none of these enzymes are fully inactivated resulting in a loss of viscosity but an improvement in flavor (Vercet, Sanchez, Burgos, Montanes, & Lopez-Buesa, 2002) due to application of low temperature. Next thermal treatment applied is during the concentration of the pulp using evaporators. The length and type of this process depends on the final product but normally involves mechanical vapor recompression evaporation (63–79°C) and a high drying evaporation (79°C) (Koh, Charoenprasert, & Mitchell, 2012). Once the product is under the desired concentration the final thermal processing is the pasteurization (temperatures less than 100°C) and this process varies depending on the final product (Wu & Shen, 2011). A flow chart for a typical thermal processing technique for tomato is given in Figure 1.

3.1 | Effect of thermal processing on physico-chemical properties

Quality of tomato and tomato products is affected by the use of heating during the industrial processing; color, viscosity and flavor are somewhat altered. Regarding the color, pigment degradation, and Maillard reactions can occur as well as ascorbic acid degradation (Stratakos, Delgado-Pando, Linton, Patterson, & Koidis, 2016). Shi, Dai, Kakuda, Mittal, and Xue (2008) reported significant loss in redness and color intensity of tomato puree after heating at 60–120°C for 1–6 hr. Hsu, Tan, and Chi (2008) also obtained brown colored (low a/b value) tomato juice due to breakdown of lycopene and formation of Maillard reaction products by intensive heat treatment (98°C/15 min). In contrast, heating also helps in preserving the color of tomato juice by inactivating enzymes responsible

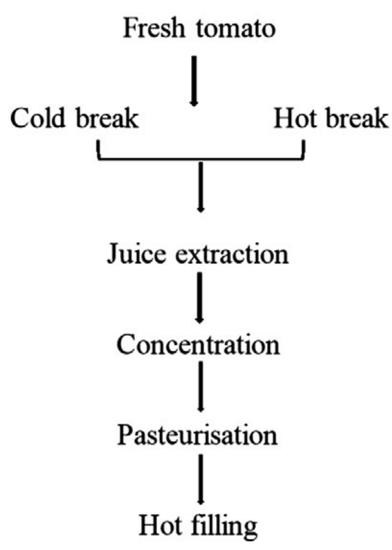

FIGURE 1 Flow diagram showing typical thermal processing of tomato

for enzymatic browning and also enhancing the color by improving the bioavailability of lycopene since it breaks down the cellulose structure of the plant cell (Jayathunge, Stratakos et al., 2017). Therefore, heating is an important pre-treatment to consider before applying non-thermal processing methods in order to enhance the color and bioaccessibility of lycopene in tomato products. Anese, Falcone, Fogliano, Nicoli, and Massini (2002) observed that application of thermal treatment was effective in maintaining the redness of tomato puree after processing at 90, 100, and 110°C. High Temperature Short Time processes (75°C for 23 s, 92°C for 5 s) have been applied to tomato juice to obtain a better color preservation (less browning) than conventional pasteurization (Giner, Hizarci, Marti, Saura, & Valero, 2013).

It is established that conventional pasteurization causes a large reduction of the viscosity of tomato puree compared to raw puree and homogenate (Krebbers et al., 2003; Sanchez-Moreno, Plaza, Ancos, & Cano, 2006a; Verlent, Hendrickx, Rovera, Moldnaers, & Van Loey, 2006). A low consistency tomato product may not retain its solid fraction in suspension, resulting in undesirable separation into pulp and serum (syneresis). To overcome this issue, the pectolytic enzymes are inactivated via a hot or cold break. The enzymes PME and PG in tomato juices could be completely inactivated at temperatures higher than 78°C for 40 s and 90°C for 5 min, respectively (Fachin et al., 2003). Even though a very hot break temperature increases the consistency of the tomato juice by pectolytic enzyme inactivation, some researchers have reported soluble pectin leaching out from cell walls and pectin denaturation and reduction of consistency due to prolonged heating (Goodman, Fawcett, & Barringer, 2002; Hayes et al., 1998). Giner et al. (2013) found that storage temperature and time affected total soluble solids (as Brix) and therefore viscosity in thermal treated tomato juice. As indicated by Lavelli, Harsha, Mariotti, Marinoni, and Cabassi (2015) heating treatments also increased the consistency of tomato puree measured as Bostwick consistency value.

Increasing temperature has an effect on tomato volatile odor compounds. Servilli, Selvaggini, Taticchi, Begliomini, and Monteroro (2000) reported that thermal treatment mainly modifies saturated and unsaturated C6 aldehydes, esters, ketones, and carotenoid derivatives, which are typical compounds of fresh tomatoes. The levels of 2-methyl-2-butenal and 1-hepten-3-one increased after tomato puree was subjected to heat treatment of 60°C, leading cooked tomato and tea-resembling odors (Viljanen et al., 2011). In contrast, the concentration of some important volatile compounds (hexanal, E-2-hexenal, Z-3 hexenal and 1-penten-3-one) decreased (Markovic, Vahcic, Ganic, & Banovic, 2007; Min & Zhang, 2003; Viljanen et al., 2011) and some volatiles (E-2-hexenal, 2-methyl butyric acid, 1-hexenol, Z-3-hexenol) were not detected after thermal processing (Markovic et al., 2007). Mirondo and Barringer (2015) found differences in the volatile profile of tomato juice from cold break and hot break, being at lower quantity in the latter. The same authors observed that after the concentration step the loss of volatiles followed the same pattern irrespective of the previous blanching process.

3.2 | Effect of thermal processing on bioactive compounds

Effects of thermal processing on the bioactive compounds of tomatoes and tomato products have been widely investigated. It is important to review these effects on different bioactive compounds in a separate manner, as their concentrations vary depending on the process and end product (Capanoglu, Beekwilder, Boyacioglu, De Vos, & Hall, 2010; Martinez-Hernandez et al., 2016).

There are conflicting data on carotenoid stability during thermal processing of tomatoes in the literature and the possible explanation for these contrasting results is not easy; Capanoglu et al. (2010) attributeed this issue to several factors such as differences in the tomato variety, ripeness state, agricultural treatments and also processing conditions. Perez-Conesa et al. (2009), George et al. (2011) and Gupta, Kopec, Schwartz, and Balasubramanium (2011) found that thermal treatments did not influence lycopene content. Moreover, Sharma and Le Maguer (1996) also observed that heating had no relationship with isomerization of lycopene and concluded that lycopene degradation was increased with the exposure of tomato solids to air, light, and high storage temperature. On the other hand, several authors (Anese et al., 2002; D'Evoli, Lombardi-Boccia, & Lucarni, 2013; Odriozola-Serrano, Solivia-Fortuny, & Martin-Belloso, 2008; Sahlin et al., 2004) have observed an increase in lycopene content in processed tomato products as compared to the raw tomatoes due to better extractability of carotenoids, as a result of thermal disintegration of chromoplasts and melting of carotenoid crystals. Similarly, Roldan-Gutierrz et al. (2007) observed higher concentration of cis isomers of lycopene content after thermal processing of tomatoes. It has also been observed that heating might result in an increase in carotenoid bioavailability and antioxidant activity (Chang, Lin, Chang, & Liu, 2006; Colle, Lemmes, Van Buggenhout, Van Loey, & Hendrickx, 2010). Kamiloglu et al. (2014) also reported that paste processing and drying significantly increased bioaccessible total lycopene content.

In contrast, other authors (Capanoglu, Beekwilder, Boyacioglu, Hall, & Vos, 2008; Seybold, Frohlich, Otto, & Bohm, 2004) found a decrease in the lycopene and carotenoid content after thermal processing. Goula, Adamopoulos, Chatzitakis, and Nikas (2006) claimed that lycopene degradation during thermal processing was dependent on the presence of oxygen and light, in addition to product temperature and moisture content. Moreover, recent study conducted by Yan et al. (2017) reported non-significant change in total lycopene and significant reduction in β-carotene content in thermally processed (90°C, 90 s) tomato juice. During heat treatment, lycopene content was decreased due to isomerization and degradation reactions but heat can also facilitate its extraction and solubilization. Exposure to higher temperatures for a long period increases the susceptibility of carotenoids to thermal isomerization (Perez-Conesa et al., 2009). Shi et al. (2008) observed both lycopene degradation and improved extraction at higher temperatures (100 and 120°C) and formation of cis isomers at lower temperatures (80°C).

Vitamin C (ascorbic acid) is very sensitive to light and oxygen and can be easily degraded by thermal treatment (Jayathunge et al., 2015). Hence, it is being considered as an indicator of the nutritional quality in fruit juices during processing. It is generally agreed that pasteurization treatment significantly decreases the vitamin C content in tomato puree (Dede, Alpas, & Bayindirli, 2007; Dewanto, Wu, Adom, & Liu, 2002; Gahler, Otto, & Bohm, 2003; Patras, Brunton, Pieve, Butler, & Downey, 2009; Perez-Conesa et al., 2009). Perez-Conesa et al. (2009) and George et al. (2011) found vitamin C degradation up to 90 and 80%, respectively, after pasteurization of tomato puree, while others have reported around 50% loss (Capanoglu et al., 2008; Jayathunge et al., 2015). The time and temperature of the heating process are the main factors in the oxidation of Vitamin C; and higher temperatures result in higher loses (Zanoni, Peri, Giovanelli, & Nani, 1999). Nonetheless, increase in the ascorbic acid content after thermal processing of tomato juice has been reported by Kips et al. (2017). The same contrasting behavior of vitamin C has also been reported in broccoli (Munyaka, Makule, Oey, Van Loey, & Hendrickx, 2010), carrots, apricots, and cherries (Leong & Oey, 2012).

Phenolic compounds are one of the main bioactive groups found in tomato products and considered as a rich source of natural antioxidants. Similar to vitamin C, there are also some discrepancies in the literature showing contrasting findings with regards to the level of total phenols in processed tomato. Total phenolic contents of tomato homogenate remain unchanged after thermal processing at 88°C for 2, 15, and 30 min (Dewanto et al., 2002). Similar behavior of tomato phenolic compounds was also reported by Jayathunge et al. (2015) in thermally processed (95°C/20 min) tomato juice. However, other studies reported changes of phenolic contents in heat processed tomato purees (Gahler et al., 2003; Lavelli & Glovanelli, 2003; Perez-Conesa et al., 2009). Gahler et al. (2003) observed an increase in total phenolics in tomato juice when processed thermally at 80°C for 20 min and suggested that it could be due to liberation of phenolics from the tomato matrix, while George et al. (2011) observed the decrease in phenolic content both in red (43%) and yellow (28%) tomatoes during puree manufacture.

3.3 | Effect of thermal processing on microbiological load

Heating of food is the most common and effective method for eliminating pathogenic microorganisms. Thermal pasteurization, was the most common method for the production of microbiologically safe food products. Apart from commercial pasteurization, thermal blanching treatment carried out as a pre-treatment is also beneficial in reducing microbial population of tomato-based products. Hsu et al. (2008) observed that hot break treatment (92°C/2 min) followed by pasteurization at 98°C for 15 min was required to reduce the microbial population of tomato juice below the detection limit (<1 log CFU/ml), while Dede et al. (2007) reported that heating at 80°C for 1 min was sufficient to achieve a similar reduction. Moreover, Jayathunge et al. (2015) also confirmed that thermal processing (95°C/20 min) was effective in reducing the total viable count to below the detection limit (<1 log CFU/ml). However, in order to reduce the spores of *Bacillus coagulans*, which are relatively heat resistant at acidic pH, to below 10 CFU/ml, heating of tomato juice at 100 and 105°C for 1.66 and 0.59 min, were required, respectively (Daryaei & Balasubramaniam, 2013). Hence, all these findings revealed that hot break (high temperature) treatment is effective in terms of obtaining microbiologically safe product in comparison to cold break (low temperature) treatment.

4 | NOVEL THERMAL PROCESSING TECHNIQUES

Although conventional thermal processing is the most frequently used strategy to inactivate enzymes and microorganisms in tomato products it can negatively affect the organoleptic characteristics and the nutrient content of foods (Igual, García-Martínez, Martín-Esparza, & Martínez Navarrete, 2011). Modern consumers demand products of high quality, which are nutritious and minimally processed with fresh like characteristics (Koidis, Rawson, Tuohy, & Brunton, 2012; Patane et al., 2018). In order to meet consumer demands, it is important to minimize thermal damage. Conventional heating systems are based on convection and conduction, which poses significant limitations. Therefore, novel thermal processing technologies that are able to improve the efficiency of heat delivery and temperature control are gaining importance.

4.1 | Microwave heating

Microwave heating can be used as an alternative in order to preserve or enhance tomato juice shelf life, quality and nutrient content of tomato juice. Microwave heating is able to generate heat from within the food matrix, which is not possible with any of the conventional heating methods (Fu, 2004). Processing with microwaves has proven to be faster and capable of better retaining quality and nutritional characteristics (e.g., vitamin retention) compared to conventional heating technologies (Chandrasekaran, Ramanathan, & Basak, 2013). Kaur, Khurdiya, Pal, and Kapoor (1999) has shown that microwave processed tomato juice had a higher retention of ascorbic acid, total carotenoids, and lycopene contents compared to conventionally processed juice. One of the most important concerns of microwave heating is the non-uniform temperature distribution, which can have implications in terms of safety as well as quality (Chandrasekaran et al., 2013). Volumetric and continuous microwave systems are now available and utilize a unique delivery method of microwave energy to achieve a much greater penetration depth during processing (AMT, 2014). Stratakos et al. (2016) investigated the effect of an industrial continuous flow microwave volumetric heating system in comparison to conventional pasteurization for the processing of tomato juice. They found that microwave processing produced a physicochemically and microbiologically stable product with higher antioxidant capacity, in reduced processing time compared to conventional heat pasteurization. The study also showed that microwave heating resulted in higher antioxidant bioaccessibility. Recently, Orikasa et al. (2017) evaluated the use of microwave in the concentration step of the tomato puree processing and found improvements in lycopene concentration and energy consumption. From the microbiological point of view, microwave pasteurization or sterilization have been used to assess its effect on certain pathogens. Lu, Turley, Dong, and Wu (2011) found a reduction of *Salmonella enterica serovars* on tomato grapes after microwaving. In the same study, when microwaving time was less than 40 s, the losses of ascorbic acid, lycopene, and the effect on texture were negligible. Arjmandi et al. (2017) analyzed the heating effect of microwave on tomato puree compared with conventional pasteurization. The authors found that microwave decreased the residual activity of enzymes, such as POD, PME, and PG.

4.2 | Radio-frequency heating

Radio-frequency radiation has also been used as an alternative to conventional heat pasteurization of tomato puree. The capacity for deeper penetration in comparison to microwaves within the food in combination with the more uniform field patterns make the radio-frequency heating more efficient (Marra, Zhang, & Lyng, 2009). However, researches on radio-frequency processing of tomato products are very limited. Felke, Pfeiffer, Eisner, and Schweiggert (2011) compared radio-frequency heating to conventional heating and found that radio-frequency heating had a higher retention of the L-ascorbic acid and was able to preserve color characteristics of tomato puree. Additionally, 5-hydroxymethylfurfural was produced only at small amounts after radio-frequency heating suggesting a milder pasteurization process. Although, to the best of our knowledge, no studies on the effects of radio-frequency heating seem to have been conducted on the microbiological safety of tomato products, research on other types of food has shown that this technology is able to efficiently inactivate pathogenic vegetative bacteria and spores in different food products (Guo, Piyasena, Mittal, Si, & Gong, 2006; Laycock, Piyasena, & Mittal, 2003; Uemura, Takahashi, & Kobayashi, 2010). Radio-frequency has also proven very effective in inactivating of polyphenoloxidase and LOX in model food systems (Manzocco, Anese, & Nicoli, 2008). The advantages of radio-frequency heating, other than the increased penetration capacity, include low investment costs, energy savings due to high energy efficiency and compatibility with automated batch and continuous production lines (Zhao, Flugstad, Kolbe, Park, & Wells, 2000). Therefore, more research is needed on the effects of this processing technology on the inactivation of endogenous enzymes, spoilage and pathogenic bacteria in order to fully elucidate the potential benefits derived from its use.

4.3 | Ohmic heating

Ohmic heating has been used to process different fruits and vegetables with promising results (Nayak, Liu, & Tang, 2015); however, the studies on tomato products are very limited. The working principle of ohmic heating is the passage of an electrical current directly through a food that serves as an electrical resistance and heat is produced immediately within the food. Hence, in ohmic heating, microbes are thought to be thermally inactivated or killed (Icier & Ilicali, 2005). Spigno, Moncalvo, Dallavalle, and Casana. (2014) showed that ohmic heated tomato pulp had almost twice as high antioxidant capacity as compared to conventionally treated one. Lee, Ryu, and Kang (2013) investigated the efficiency of continuous ohmic heating (25–40 V/cm) for the inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium and *Listeria monocytogenes* in tomato juice. Results showed that higher electric field strength or longer treatment time resulted in a greater reduction of the pathogenic microorganisms. Treatment of tomato juice with 25 V/cm for 30 s was sufficient to achieve a 5-log reduction in *E. coli* O157:H7, with similar results obtained for *S.* Typhimurium and *L. monocytogenes* (Lee, Sagong, Ryu, & Kang, 2012). Also, the vitamin C content was determined and found to be significantly higher in the ohmically heated juice compared to conventionally heated one. Ohmic heating has also been found effective against spores. Ohmic heating (10 and 60 kHz) was able to cause accelerated inactivation of *Bacillus coagulans* spores in tomato juice, an important spoilage microorganism in tomato products, as compared to conventional heating (Somavat, Mohamed, & Sastry, 2013). Ohmic heating has also been used to produce tomato paste. Boldaji, Borghei, Beheshti, and Hosseini (2015) found that ohmic heating at 14 V/cm was able to produce tomato paste without negatively affecting color parameters. Makroo Rastogi, and Srivastav (2017) investigated the effects of ohmic heat treatment on the enzyme inactivation in tomato juice and characteristics of the paste prepared from the treated juice and observed that PG and PME enzyme inactivation achieved in 1 min of ohmic heating at 90°C was similar to that of conventional hot water heating of 5 min at the same temperature. Moreover, they reported that paste produced with ohmic heating was more viscous and redder than conventionally heated products. However, lycopene and ascorbic acid content of paste were found similar in both types of paste.

Overall, these novel thermal technologies appear to be viable alternatives to conventional pasteurization since they show great potential in reducing thermal load damage during processing and improving nutrient content without compromising safety.

5 | NON-THERMAL PROCESSING TECHNOLOGIES

A wide range of non-thermal processing techniques have gained popularity in the recent times as a potential tool for the substitution or replacement of traditional thermal processing methods of foods. Additionally, non-thermal processes offer several advantages over thermal processes, such as low processing temperatures, efficient energy utilization, keeping the quality of food like color, flavor, taste & nutrient retention, and inactivation of quality deteriorative enzymes & spoilage causing microorganisms (Siemer, Aganovic, Toepfl, & Heinz, 2015).

5.1 | High pressure processing

HPP is a technology that uses water as a medium to transmit pressures between 100 and 900 MPa to inactivate vegetative microorganisms and quality-related enzymes to preserve food. It has been demonstrated that HPP improved color properties of tomato products in comparison with their conventional heat processed and unprocessed counterparts (Jayathunge et al., 2015).

It has already been found that the application of pressure above 300 MPa can cause irreversible protein denaturation at room temperature, while lower pressure results in largely reversible changes in protein structure (Knorr, Heinz, & Buckow, 2006). Denaturation of the enzyme with the accompanying conformational changes can alter the functionality of the enzyme resulting in increase or loss of biological activity and changes in substrate specificity (Hendrickx, Ludikhuyze, Broeck, & Weemaes, 1998). Hence, HP may cause inactivation or activation of enzymes depending on the applied pressure and the type of enzyme (Terefe, Buckow, & Versteeg, 2014), which can directly effects on the viscosity of the product. Porretta, Birzi, Ghizzoni, and Vicini (1995) also confirmed that viscosity of tomato juice was strongly dependent on the pressure applied but independent of treatment time. Viscosity enhancement in tomato juice after treatment with HPP (400–600 MPa) compared to thermally treated juice (Hsu, 2008; Hsu et al., 2008; Krebbers et al., 2003; Sanchez-Moreno, Plaza, Ancos, & Cano, 2006b). Recently, Yan et al. (2017) also reported an increase in tomato juice viscosity after HP homogenization (246 MPa, 99°C, <1 s). On the other hand, viscosity loss during HP (700 MPa/80 or 90°C) and low pressure (100–300 MPa/4°C and 25°C) conditions also have been observed (Hsu, 2008; Verlent et al., 2006).

The effect of HPP on nutritional and sensory properties of tomato products has been widely investigated and proved useful for preserving the nutritional, antioxidant and flavor properties of foods since it can be applied without heating (Oey, Lille, Van Loey, & Hendrickx, 2008; Yan et al., 2017). Porretta et al. (1995) reported improvement in sensory attributes of pressurized tomato juice due to the remarkable presence of n-hexanal as compared with conventionally treated products. Significantly higher vitamin C content was observed in HP processed tomato puree as compared to thermally processed (Dede et al., 2007; Patras et al., 2009). Regarding the carotenoids retention after HPP, a slight, but significant, decrease in carotenoid content was reported by Patras et al. (2009) when tomato puree was processed at 400 MPa. On the other hand, they observed 172% increase in the samples processed at 600 MPa in comparison to the unprocessed tomato puree samples. HPP at 100–600 MPa has been shown to increase in lycopene extractability from tomato juice and puree (Hsu et al., 2008; Krebbers et al., 2003; Qiu, Jiang, Wang, & Gao, 2006; Sanchez-Moreno et al., 2006b). HPP has the ability to inactivate many types of vegetative cells, but spores are resistant to pressurization up to 1,200 MPa (Lechowich, 1993). A moderate pressure treatment (500 MPa/3 min) at ambient temperature (25°C) is usually sufficient to produce a stable refrigerated tomato juice product (Porretta et al., 1995). Zimmermann, Schaffner, and Aragao (2013) studied the inactivation *B. coagulans* spores in tomato pulp, using pressure assisted thermal sterilization (PATS) (300–600 MPa, 50–60°C for 15 min) and observed an increase in spore reduction up to 5.7 log reduction with both pressure and temperature increases, showing the PATS efficiency to destroy *B. coagulans*spores in tomato pulp.

5.2 | Ultrasonic processing

US is a form of energy generated by sound waves of frequencies that are >16 kHz, the threshold of human hearing (Jayasooriya, Bhandari, Torley, & D'Arcy, 2004). The mechanism of microbial inactivation by high power US is through physical (cavitation, mechanical effects, and micro-mechanical shocks) and/or chemical (formation of free radicals due to sono-chemical reaction) principles (Piyasena, Mohareb, & McKeller, 2003) The technology is considered as a promising novel non-thermal technology with a wide range of benefits such as higher product yields, shorter processing times, reduced operating and maintenance costs, improved tastes, texture, flavor, and color, and the reduction of pathogens at lower temperatures (Patist & Bates, 2008). Adekunte, Tiwari, Scannell, and O'Donnell, (2010) reported decreases in L (lightness), a (redness) and b (yellowness) values and increases in total color difference (ΔE—color change during processing) in tomato juice, indicating visual color changes after sonication (34.4–61.0 μm, 2–10 min, 32–45°C). US processing of tomato juice has been reported to enhance the rheological properties of sonicated tomato juice by reducing particle size and inactivating PME and PG enzymes (Raviyan, Zhang, & Feng, 2005; Terefe et al., 2009; Wu, Gamage, Vilkhu, Simons, & Mawson, 2008). Moreover, US has also been shown effective to maintain the juice cloud of tomato (Wu et al., 2008). On the other hand, 3–40% degradation of ascorbic acid were observed in tomato juice subjected to US treatment (20 kHz, pulse duration of 5 s on and 5 s off/30–40°C for 2–10 min; Adekunte et al., 2010).

Limited information is available on the effects of US on the nutritional and sensorial quality of tomato products. It is possible that the free radicals generated during cavitation may cause oxidation of nutrients and other food components leading to quality degradation. However, there is no evidence in literature to show that sonication (together with heat or pressure) causes higher quality degradation than an equivalent thermal process (Terefe, Buckow, & Versteeg, 2015). In general, when US is applied at suitable power density, it has great potential in inhibiting decay, maintaining flavor and nutritional quality of tomato products. US is reported to have a minimal effect on the quality of tomato juice and at the same time is able to achieve the desired 5 log reduction in a key spoilage yeast, *Pichia fermentas* during tomato juice processing (Wu et al., 2008). The mechanism of microbial killing during US processing is mainly due to breakdown of cell walls, disruption and thinning of cell membranes, and DNA damage via free radicals production and localized heating (Chemat, Zill-e-Huma, & Khan, 2011).

5.3 | Pulsed electric field processing

PEF technology involves the delivery of short high power electrical pulses (ms or μs) to a product placed in a treatment chamber confined between electrodes. These electrodes have a specific gap between them which is known as treatment gap of the chamber. During PEF processing, high voltage is applied that results in the inactivation of microorganisms present in the food sample while imposing minimal detrimental influence on food quality (Syed, Ishaq, Rahman, Aslam, & Shukat, 2017). A typical system for treatment of pumpable fluids consists of a PEF generation unit, which is in turn composed a high voltage generator and a pulse generator, a treatment chamber, a suitable product handling system and a set of monitoring and controlling devices (Soliva-Fortuny, Balasa, Knorr, & Martin-Belloso, 2009). Both moderate (mild) and HIPEF treatments are used in food industry and among them HIPEF technology (1–10 μs short pulses at 20–80 kV/cm) has been extensively studied as an alternative to traditional thermal treatment (Mosqueda-Melgar, Raybaudi-Massilia, & Martín-Belloso, 2008). The application is gaining interest due to inactivation of microorganisms and enzymes while maintaining the nutritional quality, antioxidant content, and freshness of liquid foods (Martin-Belloso & Elez-Martinez, 2005). Studies have been reported that HIPEF treatment (40 kV/cm, 57 μs) was effective to preserve the color (Aguilo-Aguayo, Solivia-Fortuny, & Martin-Belloso, 2008; Min & Zhang, 2003; Odriozola-Serrano et al., 2009) and flavor (Min & Zhang, 2003) of tomato juice in comparison to heat treated samples by controlling the enzymatic activities. The effectiveness of HIPEF in inactivating more than 80% of PME activity in tomato juice (Espachs-Barroso, Loey, Hendrickx, & Martin-Belloso, 2006; Giner et al., 2000) with significant viscosity enhancement (Aguilo-Aguayo et al., 2008; Giner et al., 2000) also has been reported. Regarding the microbiological safety, Min, Jin, and Zhang (2003) reported that use of HIPEF was effective in reducing numbers of microorganisms, including yeasts and molds, by 6 log in tomato juice, a similar reduction to those achieved by heat pasteurization. However, the lethal effect of PEF on microorganisms in tomato juice is related to electric field strength, number of pulses applied, and temperature (Nguyen & Mittal, 2007; Raso, Calderon, Gongora, Barbosa-Canovas, & Swanson, 1998).

Apart from HIPEF technology, moderate intensity puled electric field (MIPEF) technology also is becoming interested in the food industry. In MIPEF, mild levels (less tan 2 kV) of voltage is being used comparison to the HIPEF treatment. Valliverdu-Queralt et al. (2013) found that MIPEF treatment (1 kV/cm, 16 mono polar pulses of 4 μs) of tomatoes increased the content of carotenoid compounds in tomato juices produced from the treated tomatoes. Specifically, they were very high in lutein, α- and β-carotene and *trans*-lycopene, 9- and 15-*cis*-lycopene, which they attributed to a MIPEF-induced stress response enhancing the production of metabolites. Table 1 summarizes information on the effects of novel thermal processing on a variety of tomato products.

6 | FUTURE STRATEGIES

The novel thermal and non-thermal technologies may become the trend of developing food processing techniques in the future. This review provides information on these processing technologies as alternatives to conventional heat processing to overcome persistent problems in tomato product processing. Though there are many advantages of utilizing these technologies, there are also limitations involved. Among other potential technology-specific issues, non-uniformity of the treatment due to limited penetration of microwave and ohmic heating is commonly encountered. This challenge is often already an issue at laboratory scale, and it can become progressively worse when scaling up to pilot plants and, subsequently, to commercial equipment. Therefore, the temperature control system designs via mathematical modeling should be approached to improve the heating uniformity of processing equipments. These controlled systems may realize the dynamic regulation of processing conditions, minimize the energy consumption and quality deterioration. Moreover, the lack of process validation of innovative processes are also a limitation for industrial uptake (Barbosa-Canovas, Albaali, Juliano, & Knoerzer, 2011).

Furthermore, unfavorable consumer perception for some of novel technologies like microwave heating also has been reported, leading to misunderstanding and rejection by consumers of treated food products. They relate these technologies to harmful events, toxicity and most likely will assume higher pricing for products treated with such technologies. Proper consumer education to increase awareness on applications of novel technologies are important and must be carried out to promote consumer acceptance and further diversify options for food processing manufacturers to produce safe, fresh-like, and quality products. Therefore, it is of the utmost importance to plan effective public awareness and education programs to highlight the added-value, such as quality and environmental benefits of these technologies.

In recent past, literature has proved the effectiveness in applying hurdle technology in preservation of food products. It is the combined use of several shelf-preservation methods to make a product shelf-stable, to improve quality and to provide additional safety. Hence, in future using the thermal and non-thermal processing technologies as a hurdle technology, might offer new ways of enhancing the quality and shelf-life of tomato-based products, rather than investigating one specific processing technique. For an example, a recent study reported a positive impact of osmotic pre-treatment and HP on extending the shelf-life of fresh cut tomatoes instead of having one thermal treatment (Dermesonlouoglou et al., 2017).

Tomato product color is one of the main quality parameters, which drive consumer purchasing decision. Hence, manufactures aim to preserve and enhance the color without degradation during processing. Avoiding detrimental changes in the color of tomato products is an

TABLE 1 Array of studies on impact of novel non-thermal processing on quality of tomato-based products

Tomato product	Non-thermal technology	Effect on quality/nutrient content	Effect on microbiota	Reference
Juice	HPP	Complete inactivation of PME & PG at 800 MPa during 20 min processing time	N/A	Crelier, Robert, Claude, and Juillerat (2001)
Juice	HPP	Combined pressure temperature processing increase the extractability of lycopene in comparison to thermally treated product	N/A	Gupta et al. (2011)
Juice	HPP	Increased red color, ascorbic acid, phenolic and carotenoid content comparison to pasteurized product	N/A	Hsu (2008)
Juice	HPP	Effective to maintain the initial viscosity of tomato juice for 28 days after storage at 4°C	–	Hsu et al. (2008)
Juice	HPP	Higher redness, total carotenoids content, lycopene contents after processing and short shelf life period (30 days) comparison to thermally processed products	–	Jayathunge et al. (2015)
Puree	HPP	Slight increase in viscosity during storage at 4°C for 8 weeks period	Effective in inactivating *B. Stearothermophilus* spores	Krebbers et al. (2003)
Juice	HPP	Improved viscosity and color properties in comparison to heat processed products	–	Porretta et al., 1995
Juice	HIPEF	Inactivation of more than 80% of PME activity, 100% POD activity and 12% PG activity. significant viscosity enhancement and higher *L* values and redness	N/A	Aguilo-Aguayo et al. (2008)
Juice	HIPEF	Lower color change and browning in comparison to thermal treatment	N/A	Aguilo-Aguayo, Solivia-Fortuny, and Martin-Belloso, 2009
Juice	HIPEF	Non-significantviscosity difference, 46% residual lipoxygenase activity and no significant change in vitamin C. Reduction of 50% vitanic C content during storage for 30 days at 4°C	Reduction in the levels of microorganisms, including yeasts and molds, by 6log similar to heat pasteurization.	Min et al. (2003)
Juice	HIPEF	Higher retention of the tomato volatiles, trans-3-hexenal, 2-isobutylthiazole and cis-3-hexanoland higher *L* values and *a*/*b* (redness) in comparison to thermally processed samples	N/A	Min and Zhang (2003)
Juice	HIPEF	PME and PG enzyme activity reduction (55%) after combined treatments of heating (<50°C), antimicrobial compounds (nisin) and HIPEF	–	Nguyen and Mittal (2007)
Juice	HIPEF	Effective in preserving color, carotenoids and phenolic contents during the storage of 56 days at 4°C	N/A	Odriozola-Serrano et al. (2009)
Juice	HIPEF	N/A	Higher inactivation of *B. fulva*after PEF processing (30 kV/cm at 23°C)	Raso et al. (1998)
Pulp	US	Reduction in lycopene bioacccessibility	N/A	Anese, Mirolo, Beraldo, and Lippe (2013)
Juice	US, HIPEF	Higher lycopene bioaccessibility and color retention comparison to thermally processed products	N/A	Jayathunge, Stratakos et al. (2017)

Note. HPP: high pressure processing; HIPEF: high intensity pulsed electric field; US: ultrasonic processing.

important consideration when assessing the suitability of novel processing technologies. Blanching is a pre-treatment conducted primarily to preserve the color while inactivating enzymes. Therefore, application of blanching treatment prior to non-thermal processing techniques might be effective to enhance the color of tomato products. Moreover, the industry may be better served by focusing on process optimization of existing thermal blanching, where considerable over-blanching might be taking place leading to color degradation during routine processing. Alternative novel technologies to blanching are now being studied as enzyme inactivation instruments. Khani, Shokri, and Khajeh (2017) studied the use of dielectric barrier discharge and gliding arc plasma reactors to inactivate the peroxidase enzyme in tomato extract, obtaining better efficiency, and reaching lower temperatures (40°C)—and thus higher nutrient retention—than conventional blanching.

Also, non-thermal novel technologies should be evaluated as potential ways of enhancing the generation of beneficial secondary plant metabolites in plant based foods. PEF has been shown to induce stress conditions in tomatoes, which is accompanied by an increase in reactive oxygen species (Galindo et al., 2009). Secondary metabolites play a major role in the adaptation of plants to the environment and in overcoming stress conditions. In the presence of reactive oxygen species synthesis of antioxidants will take place. Hence, novel processing technologies or combinations of them, under specific conditions, can potentially act as abiotic stressors leading in the accumulation of health-related secondary metabolites (e.g., carotenoids), and thus enable the industry to produce improved tomato products. For an example, Jayathunge, Stratakos et al. (2017) reported enhancement of lycopene bioaccessibility of processed tomato juice, derived from MIPEF treated fruits. Apart from the quality-related aspects, novel technologies are still struggling with limitations in terms of full industrial application due to high initial capital expenditure and lack of skilled labor.

7 | CONCLUSIONS AND FUTURE TRENDS

Existing and new views of novel thermal and non-thermal potential applications for the tomato industry were discussed in this review. Current knowledge has shown that in general conventional high temperature treatments can affect levels of quality parameters of tomato-based products negatively. Hence, a wide range of studies including novel thermal and non-thermal processing technologies conducted in at pilot scale, like microwave heating, ohmic heating, radio frequency heating, HPP, ultrasonication, and pulse electric field processing, have been performed to investigate nutritional, sensorial and microbial quality attributes and their behavior during storage. The thermal and non-thermal technologies discussed in this review have the potential to meet the mandatory 5 log microbial reduction in the pathogens of interest to ensure the safety of tomato-based products. Within the food industry, there is an increasing emphasis on and trend toward mild and short processing technologies in response to a growing consumer demand for minimally processed and high quality food products with superior functional properties. Novel processing technologies represent rapid, efficient, and reliable alternatives to improve the quality of food and also have the potential to develop new products. Although many innovative food processing techniques have shown potential for improving the nutritive quality of tomato products, a significant proportion of these have not been applied commercially yet. Reasons for delaying a wider implementation of these technologies at the industrial scale are related to high investment costs, lack of full control of variables associated with the process operation and lack of regulatory approval as well as consumer acceptance.

In the future, more studies on the effect of novel processing parameters on the bioactive compounds of treated foods should be conducted. In-depth research is needed to study the kinetics of the generation, retention, and degradation of health-related compounds as affected by thermal and non-thermal treatment conditions and to elucidate the mechanisms underlying the induced changes. The retention of these quality attributes during the product's shelf life until consumption is also of vital importance in terms of consumer requirements. Moreover, applications of these novel processing technologies should be further explored not only to stabilize the content of health-related phytochemicals but also their bioaccessibility, bioavailability and biological activity in humans. On the other hand, further research and development activities should be carried out to develop products using novel processing technologies at competitive low cost declaring clear benefits to enhance the consumer willingness to purchase. Moreover, the discussed technologies can potentially play an important role in product innovation, which is the response to the growing demand for value addition along with more sophisticated and diverse food products. Finally, it can be concluded that novel thermal and non-thermal processing technologies have the potential to improve food chain security and add value to food products with quality enhancement.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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