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Nutritional impact of ohmic heating on fruits and vegetables—A review

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Abstract: Ohmic heating, also called electrical resistance heating, joule heating, or electro-conductive heating, is an advanced thermal food processing technique where heat is internally generated in a sample due to electrical resistance when electric current is passed through it. It is a novel technique which provides rapid and uniform heating, resulting in less thermal damage to the food product. According to the recent literature, plant products are most suitable and often used for ohmic heat processing. Beyond heating of fruits and vegetables, the applied electric field under ohmic heating causes various changes in quality and nutritional parameters which include inactivation of enzymes and micro-organisms, degradation of heat-sensitive compounds, changes in cell membranes, viscosity, pH, color, and rheology. Ohmic heating rate depends on the electrical field strength and electrical conductivity of product. This review focuses on various factors affecting the electrical conductivity of fruits and vegetables and the effect of ohmic heating on their quality and nutritional properties.

1. Introduction

Heat treatment is often used for the processing and preservation of food products. Conventional heating is the most common method in the heating of foodstuffs. During conventional thermal processing in cans or aseptic processing systems for particulate foods, significant product quality damage occurs due to slow conduction or convection heat transfer (Zell, Lyng, Cronin, & Morgan, 2009). Innovative technologies such as microwave heating, inductive heating, ohmic heating, and many more have evolved as alternatives to traditional thermal processing. The main difference between ohmic heating and other electrical methods is that electrical energy is directly dissipated into the product.

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PUBLIC INTEREST STATEMENT

Innovative technologies have evolved as alternatives to traditional thermal processing. Ohmic heating is an advanced thermal food processing technique based on the passage of an alternating current through a sample which responds by generating heat internally. This review aims to study the effect of ohmic heating on the nutritional properties and quality attributes of various fruits and vegetables. It will help researchers and industries develop and use ohmic heating for various food systems.

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Ohmic heating, also called electrical resistance heating, joule heating, electro-conductive heating, is an advanced thermal food processing technique based on the passage of an alternating current through a sample which responds by generating heat internally due to its inherent resistance (Fryer, de Alwis, Koury, Stapley, & Zhang, 1993; Palaniappan & Sastry, 1991a). The energy generation is proportional to the square of the electric field strength and the electrical conductivity (EC) of the product (Goullieux & Pain, 2005; Ruan, Ye, Chen, & Doona, 2001). Since heat generation depends on EC, it is a key parameter to be quantified (Halden, De Alwis, & Fryer, 1990). The main advantage of ohmic heating is the rapid and uniform heating process. A large number of actual and potential applications exist for ohmic heating which include blanching, evaporation, dehydration, fermentation, sterilization, pasteurization, and heating of foods to serving temperature (USA-FDA, 2000). Other advantages over conventional heating include maintaining the color and nutritional value of food, shorter processing times, and higher yields (Castro, Teixeira, Salengke, Sastry, & Vicente, 2004a; Leizerson & Shimoni, 2005; Vikram, Ramesh, & Prapulla, 2005; Wang & Sastry, 2002). Ohmic heating has high energetic efficiency, low investment costs, and is considered technically simple (Kim et al., 1996; Qihua, Jindal, & van Winden, 1993; Ruan et al., 2001; Skudder, 1988).

Generally, fruits and vegetables exhibit sufficient conductivity to reach the required temperatures in less than 1 min at comparatively low electric field strengths (E < 100 V/cm) (Palaniappan & Sastry, 1991a; Sarang, Sastry, & Knipe, 2008; Wang & Sastry, 1997). According to the recent literatures, plant products are most suitable and most often used for ohmic heat processing (Leadley, 2008). Recent studies have deepened the knowledge on the ohmic heating process, applying this technology to different fruits and vegetables and their products, such as apples (Amiali, Ngadi, Raghavan, & Nguyen, 2006; Lima, 1996; Lima & Sastry, 1999; Mitchell & de Alwis, 1989; Wang, 1995; Wang & Sastry, 2000), strawberry (Castro, Teixeira, Salengke, Sastry, & Vicente, 2003; Moreno et al., 2012), turnip (Lima, Heskitt, & Shastry, 1999), various purees (Icier & Ilicali, 2005a; Icier, Yildiz, & Baysal, 2006), and juices (Icier & Ilicali, 2004; Icier, Yildiz, & Baysal, 2008; Jakób et al., 2010; Lima & Sastry, 1999; Lima, Heskitt, Burianek, Nokes, & Sastry, 1999; Palaniappan & Sastry, 1991b), among others.

2. Studies on ohmic heating for various fruits and vegetables

2.1. Acerola
Mercali, Jaeschke, Tessaro, and Marczak (2012) studied the vitamin C degradation in acerola pulp during ohmic and conventional heat treatment. EC as a function of temperature for acerola pulp was evaluated during construction and operation of an ohmic heating apparatus by Sarkis, Mercali, Tessaro, and Marczak (2013). The effect of the electric field frequency on ascorbic acid degradation and color changes in acerola pulp during ohmic heating was evaluated by Mercali, Schwartz, Marczak, Tessaro, and Sastry (2014).

2.2. Apple
EC of red and golden apple was determined over 25–140°C temperature range by Sarang et al. (2008). Ohmic heating was found to enhance the extraction of apple juice from red delicious apples (Wang, 1995). Lima and Sastry (1999) evaluated the effect of ohmic heating frequency on apple juice yield and hot-air drying rate. Lima and Sastry (1999) and Wang and Sastry (2000) determined the extraction rates of ohmically treated apple tissue with respect to non-treated sample and also measured the effect of frequency on extraction yield. Icier and Ilicali (2004) reported the effect of concentration on the ohmic heating rates of apple juices. The effect of ohmic heating on juice yield from apple tissues was determined by Praporscic, Lebovka, Ghnimi, and Vorobiev (2006). Viscosity and EC of apple juice was measured over temperature range (25–70°C) during ohmic heating by Singh, Singh, and PS (2008). Jakób et al. (2010) carried out the inactivation kinetics of pectin methylesterase (PME) during ohmic heating of fresh apple juice. The effect of temperature on ascorbic acid degradation of ground cashew apples during ohmic heating was evaluated by Lima, Elizondo, and Bohuon (2010).

2.3. Apricot

Pataro, Donsì, and Ferrari (2011) studied the effect of ohmic heating processing on the quality and shelf life of apricots in syrup using a continuous pilot scale ohmic unit while Icier and Ilicali (2005b) evaluated the EC of apricot puree during ohmic heating. Both the studies have successfully reported enhanced shelf life and quality of apricots.

2.4. Blueberry

EC as a function of temperature for blueberry pulp was evaluated during construction and operation of an ohmic heating apparatus by Sarkis et al. (2013). Marczak, Tessaro, Jaeschke, and Sarkis (2013) evaluated the anthocyanin degradation in blueberry pulp after thermal treatment using ohmic and conventional heating. Brownmiller, Howard, and Prior (2008); Lee, Durst, and Wrolstad (2002); Skrede, Wrolstad, and Durst (2000) carried out experiments to determine the anthocyanin degradation levels in blueberries.

2.5. Grape and guava

The effects of voltage gradient, temperature, and holding time on the polyphenoloxidase activity were investigated for grape juice ohmic heating (Icier et al., 2008). Srikalong, Makrudin, Sampavamontri, and Kovitthaya (2011) studied the effects of ohmic heating application on mechanical extraction and sensory characteristics of guava juice.

2.6. Orange

Viscosity and EC of orange juice was measured over temperature range (25–70°C) during ohmic heating by Singh et al. (2008). Palaniappan and Sastry (1991a) investigated the role of particle concentration in orange juices on the overall EC of a two-phase system during ohmic heating. Similarly, orange juice containing *Bacillus subtilis* spores were examined using continuous alternating current electric field (Uemura & Isobe, 2003). Vikram et al. (2005) studied the kinetics of ascorbic acid degradation during ohmic heating of orange juice by applying electric field strength of 42 V/cm. Lima (1996) used ohmic heating to heat orange juice for 30 min at 90°C with an electric field of 18.2 V/cm and studied ascorbic acid degradation kinetics. Leizerson and Shimoni (2005) evaluated the effect of ultrahigh temperature continuous ohmic heating treatment on fresh orange juice in comparison to the conventional pasteurization.

2.7. Peach and pear

Icier and Ilicali (2005b) evaluated the EC of peach puree during ohmic heating. The ohmic heating rate of peaches was evaluated at fixed electric field strength of 60 V/cm, and frequencies varying within 50 Hz–1 MHz. EC of peach and pear was determined over 25–140°C temperature range by Sarang et al. (2008). Moreno, Simpson, Estrada, Lorenzen, Moraga, and Almonacid (2011) investigated the effect of ohmic heating on the osmotic dehydration kinetics and microstructure of pears.

2.8. Pineapple and pomegranate

EC of pineapple was determined over 25–140°C temperature range by Sarang et al. (2008). Viscosity and EC of pineapple juice was measured over temperature range (25–70°C) during ohmic heating by Singh et al. (2008). The effect of ohmic heating technique on EC, heating rate, system performance, and pH of pomegranate juice was investigated (Darvishi, Khostaghaza, & Najafi, 2013).

2.9. Quince and sour cherry

Bozkurt and Icier (2009) examined the rheological characteristics of quince nectar during ohmic heating. Icier and Ilicali (2004) reported the effect of concentration on ohmic heating rates of sour cherry juice. The effect of solid content on anthocyanin degradation during ohmic heating was observed in studies involving sour cherries (Cemeroglu, Velioglu, & Isik, 1994; Garzon & Wrolstad, 2002).

2.10. Strawberry

EC of strawberry was determined over 25–140°C temperature range by Sarang et al. (2008). Castro, Macedo, Teixeira, and Vicente (2004) investigated the effects of field strength and multiple thermal treatments on EC of strawberry products and also studied the ascorbic acid degradation kinetics. The effect of solid content on anthocyanin degradation during ohmic heating was observed in studies involving strawberries (Cemeroglu et al., 1994; Garzon & Wrolstad, 2002). Castro et al. (2003) discussed the effect of temperature and sugar content on EC values of strawberry-based products. The influence of ohmic heating on osmotic dehydration kinetics and microstructure of strawberries was studied by Moreno et al. (2012).

2.11. Vegetables

2.11.1. Beetroot and broccoli

Halden et al. (1990); Schreier, Reid, and Fryer (1993); Lima, Heskitt, and Sastry (2001) studied the diffusion of beet dye from beetroot into the solution using alternating electric field. Halden et al. (1990) investigated the effect of temperature on EC of beetroot when processed ohmically and conventionally. The leaching of soluble solids during blanching of beetroot by ohmic heating was examined by Mizrahi (1996). Similarly, the effect of ohmic and conventional heating process on textural properties of cylindrical pieces of red beet was investigated (Farahnaky, Azizi, & Gavahian, 2012). The effect of electrical processing on mass transfer in beetroot and model gels were reported by Fryer, Miri, and Parral (2012). Kulshrestha and Sastry (2003) also reported the effect of electric fields (as low as 10 Hz) on the permeability of beet cell membranes. Jakób et al. (2010) carried out the inactivation kinetics of peroxidase during ohmic heating of broccoli.

2.11.2. Carrot

Palaniappan and Sastry (1991a) studied the effects of insoluble solids and applied voltage on EC of pre-pasteurized carrot juices during ohmic heating. Jakób et al. (2010) carried out the inactivation kinetics of peroxidase during ohmic heating of carrot. Similarly, the effect of ohmic and conventional heating process on textural properties of cylindrical pieces of carrot and golden carrot were investigated (Farahnaky et al., 2012). Zareifard, Ramaswamy, Trigui, and Marcotte (2003) also studied the ohmic heating behavior and EC of two-phase (liquid phase and a solid phase containing carrot puree) food systems.

2.11.3. Cauliflower and cabbage

Processing and stabilization of cauliflower by ohmic heating technology was investigated by Goullieux, Zuber, and Godereaux (2001). Eliot, Goullieux, and Pain (1999a) studied the influence of precooking by ohmic heating on the firmness of cauliflower. Volden et al. (2008) studied ascorbic acid degradation kinetics of red cabbage at 95°C during ohmic heating.

2.11.4. Pea and potato

Peroxidase inactivation and color changes during ohmic blanching of pea puree were examined by Icier et al. (2006). Zhong and Lima (2003) examined the effect of ohmic heating on vacuum drying rate of sweet potato tissue. The effect of ohmic heating on cell membranes of potato was investigated by measurement of dielectric spectra from 100 Hz to 20 kHz. Sastry and Palaniappan (1992) studied the ohmic heating behavior of particle–liquid mixtures using potato cubes in sodium phosphate solutions. Jakób et al. (2010) also carried out the inactivation kinetics of peroxidase during ohmic heating of potato. Ohmic heating was found by Wang (1995) to enhance the drying rates of potato cylinders. The effect of ohmic heating on juice yield from potato tissues was determined by Praporscic et al. (2006).

2.11.5. Radish, tomato, and turnip

Imai, Uemura, Ishida, Yoshizaki, and Noguchi (1995) observed the effect of the electric field frequency on heating rate of Japanese white radish in the range of frequencies 50 Hz–10 kHz. Viscosity and EC of tomato juice was measured over temperature range (25–70°C) during ohmic heating by

Singh et al. (2008). Palaniappan and Sastry (1991b) studied the effects of insoluble solids and applied voltage on EC of pre-pasteurized tomato juices during ohmic heating. Palaniappan and Sastry (1991a) investigated the role of particle concentration in tomato juice on the overall EC of a two-phase system during ohmic heating. Lima, Heskitt, and Shastry (1999) studied the effect of temperature and EC of turnip tissue at 4 frequencies (4, 10, 25, and 60 Hz) under ohmic heating.

3. Quality and nutritional parameters affected by ohmic heating

3.1. Inactivation of Enzymes and micro-organisms

There has been limited research on the effect of ohmic heating on enzymes. The deactivation rate of different enzyme samples heated with ohmic or conventional heating was compared by Castro et al. (2004) and postulated that the electrical field applied during ohmic heating caused the faster deactivation than the conventional heating.

PME is an enzyme that has been found in essentially every plant tissue, several fungi, and bacteria. PME has no prosthetic group and catalyzes de-esterification of galactosyluronate methylesters of pectins, releasing protons and methanol into the media. The study conducted by Leizerson and Shimoni (2005) on orange juice showed that ohmic heating reduced PME activity by 98%. Similarly, Wilińska, de Figueiredo Rodrigues, Bryjak, and Polakovič (2008) compared the differences between the effect of conventional and ohmic heating on temperature dependences of inactivation rate constants for apple juice and cloudberry jams and has been found to follow first-order kinetics.

Peroxidases are known to be the most heat stable enzymes in vegetables, and their inactivation is usually used to indicate the adequacy of blanching (Akyol, Bayindirli, & Alpas, 2004). Ohmic blanching of pea puree at four different voltage gradients (20–50 V/cm) was performed by Icier et al. (2006). They observed that the inactivation time of peroxidase enzyme during ohmic blanching was less than water blanching by using 30 V/cm and above voltage gradient. As the voltage gradient increases the critical inactivation time decreases during ohmic blanching. Similar trends were reported by Icier and Ilicali (2004), while studying the ohmic heating rate of fruit concentrates. Cruz, Vieira, and Silva (2006) found that the application of thermosonication gave an increase in the peroxidase activity in watercress in the temperature range of 40–80°C.

Lipoxygenase and polyphenoloxidase inactivated at a faster rate due to electric fields, applied during ohmic heating than conventional heating (Castro et al., 2004). Similarly, the effects of voltage gradient, temperature, and holding time on the polyphenoloxidase activity were investigated for grape juice ohmic heating (Icier et al., 2008). There was an increase in ohmic heating rate with increase in voltage gradient. The critical deactivation temperature at higher voltage gradient was lower than at low voltage values because of the faster increase in EC at higher voltage gradients causing higher deactivation in polyphenol oxidase.

The deactivation of pepsin activity was reported for grape juice as a function of electric field strength, EC and pH (Yang, Li, & Zhang, 2004). They predicted that higher EC increased the deactivation of pepsin by pulsed electric field at the same temperature. Margot, Flaschel, and Renken (1997) reported similar results for the deactivation of trypsin for fruit juice at temperatures ranging from 55 to 70°C.

Garza, Piro, Vinas, and Sanchis (1994a) isolated and identified 172 micro-organisms from commercial peach puree consisting of bacteria, molds, and yeasts. An increase in OH frequency observed by (Canatella, Karr, Petros, & Prausnitz, 2001; Martín-Belloso et al., 1997) resulted in a decrease in the disintegration rate and final Z values during microbial inactivation. Orange juice was subjected to continuous alternating current electric field containing *Bacillus subtilis* spores to examine its inactivation. A pressurized electric sterilization system using a combination of high temperature and high electric field caused effective inactivation of spores in a shorter time, with a smaller loss of ascorbic acid and a less peculiar smell than the conventional heating treatment (Uemura & Isobe, 2003).

3.2. Changes in cell membranes/structures

The phenomenon of cell membrane electropermeabilization has been known for several decades and has recently received increasing attention because of its applicability to the manipulation of cells and tissues (Weaver & Chizmadzhev, 1996). Although the nature of the effects in plant tissues during ohmic heating is rather complex and is not completely understood, it was assumed that the electrical breakdown or electroporation mechanism is dominant (Wang & Sastry, 2002). Tissue damage during ohmic heating of different foods was observed (Kulshrestha & Sastry, 2010; Lebovka, Praporscic, Ghnimi, & Vorobiev, 2005). Electroporation process is more pronounced at low frequencies of plant tissue cell membranes (De Vito, Ferrari, Lebovka, Shynkaryk, & Vorobiev, 2008; Kulshrestha & Sastry, 2003; Mehrle, Naton, & Hampp, 1990). During low frequencies (<60) cell walls build up charges and form pores (electroporation) during ohmic heating (Imai et al., 1995; Sastry & Barach, 2000). Pores formed in the cell membranes upon electric field exposure cause a drop in resistance as ions are allowed to pass through the membrane (Coster, 1965). Furthermore, EC and electroporation rate both are affected by increase in product temperature (Lebovka, Shynkaryk, El-Belghiti, Benjelloun, & Vorobiev, 2007b; Wang & Sastry, 1997). Also, membrane rupture leads to a significant rise of tissue EC and may affect the process of ohmic heating (Sarang, Sastry, Gaines, Yang, & Dunne, 2007; Lebovka, Shynkaryk, & Vorobiev, 2007a, 2007b).

Studies conducted by Kulshrestha and Sastry (2003) showed that during ohmic heating, the permeability of plant cell membranes may alter below the temperature at which the membranes are permeabilized due to thermal effects. They reported an increase in permeation of beet cell membranes upon exposure to sinusoidal electric fields at frequencies as low as 10 Hz. The effect of ohmic heating on the membranes of cellular food material has been investigated by collecting dielectric spectra from 100 Hz to 20 kHz of cylinders of potato heated to various temperatures ranging from 30 to 70°C. Samples undergone ohmic heating had greater apparent membrane permeability than conventionally heated samples below 60°C. Praporscic et al. (2006) conducted ohmic heat treatment of apples and potatoes and concluded that at electric field strength less than 100 V/cm allows a high level of membrane destruction and mechanical softening of tissues even at a moderate temperature of T < 50°C. Structural changes in apples like cellular shape, reduction of cell size, decreased thickness of middle lamella, and cell rupturing were induced with combined effect of osmotic dehydration and ohmic heating (Moreno, Simpson, Estrada, Lorenzen, Moraga, & Almonacid, 2011). Electrical effect of the treatments was considered as the cause of these changes.

The heating process causes membrane destruction and consequently the free water content increases (Bean, Rasor, & Porter, 1960; Halden et al., 1990; Sasson & Monselise, 1977).

3.3. Degradation of heat-sensitive compounds

The literature values for anthocyanin degradation in fruit products vary considerably. Studies demonstrated that its stability is influenced by the intrinsic properties of the product and the process characteristics causing these differences to occur. Anthocyanin degradation in blueberry pulp was evaluated after thermal treatment using ohmic and conventional heating Sarkis et al. (2013). Degradation increased with both increasing voltage and solids content. The comparison between ohmic and conventional heating showed that when lower voltage levels were used, the percentage of degradation was lower to those obtained during conventional heating. The pulp processed during ohmic heating exhibited higher anthocyanin degradation with high electric fields. Also, a higher level of degradation of vitamin C during ohmic heating using high voltages relative to conventional heating was shown by Assiry, Sastry, and Samaranayake (2003). They concluded that during ohmic heating, in addition to the degradation caused by heat, there is also electrochemical degradation due to number of reactions, including electrode reactions and electrolysis of the solution; in addition, reactions between the electrode materials and the electrolysis products may influence the degradation reaction mechanisms and the kinetic parameters. Brownmiller et al. (2008); Lee et al. (2002); Skrede et al. (2000) carried out experiments to determinate the anthocyanin degradation levels in blueberries using frequency of 60 Hz. In contrast, Volden et al. (2008) found a considerably higher level of anthocyanin degradation of 59% in red cabbage after 3 min of processing at 95°C. Moreover, in

studies in which anthocyanins were exposed to high temperatures for longer periods of time, the level of degradation reached 55% in blueberry jam (Queiroz, Oliveira, Pinho, & Ferreira, 2009). According to Patras, Brunton, O'Donnell, and Tiwari (2010), it is not possible to predict the exact effect of thermal treatment on anthocyanin retention, and it is necessary to evaluate each case individually until a consensus is reached. Studies involving strawberries and sour cherries reported increase in anthocyanin degradation with an increase in solid content (Cemeroglu et al., 1994; Garzon & Wrolstad, 2002).

Mercali et al. (2012) evaluated the effects of voltage and solid contents on vitamin C and ascorbic acid degradation in acerola pulp. A comparative study of the conventional and the ohmic heating processes showed that ohmic heating, when performed with low-voltage gradients, promoted degradation of both the ascorbic acid and the total vitamin C in a manner similar to conventional heating. However, high-voltage gradients induced greater ascorbic acid degradation because of electrochemical reactions. The effect of electric field frequency (10–10,000 Hz) on ascorbic acid degradation in acerola pulp during ohmic heating was evaluated and this technology was compared with the conventional heating process (Mercali et al., 2014). The use of low electric field frequency (10 Hz) led to greater ascorbic acid degradation and higher color changes probably due to occurrence of electrochemical reactions. Reactions were minimized above 100 Hz and both ohmic and conventional heating processes showed similar degradation rates of ascorbic acid and similar color changes. The use of high electric field frequency did not affect the degradation kinetics of ascorbic acid. Similar research on orange juice was conducted by Lima, Heskitt, Burianek, et al. (1999) and concluded that electric field had no significant effect on ascorbic acid degradation. They compared ohmic and conventional heating and found very similar kinetic parameters for both treatments. Vikram et al. (2005) studied the kinetics of ascorbic acid degradation during ohmic heating of orange juice by applying electric field strength of 42 V/cm, and found that after 3 min of heating at 90°C, degradation was approximately 35%. They further studied the effect of different heating methods (microwave, infrared, conventional, ohmic) on the vitamin and color degradation. Out of the four methods, ohmic heating resulted in maximum retention of vitamin C. Castro et al. (2004) studied the degradation of vitamin C in strawberry products subjected to ohmic and conventional heating. EC increased with temperature for all the products and conditions tested following linear relations. The obtained kinetics (first order) was identical for both heating processes which led to the conclusion that the presence of electric field did not affect the ascorbic acid degradation. Lima (1996) took similar conclusions for orange juice systems. Lima et al. (2010) found the temperature impact on ascorbic acid degradation in ground cashew apples. They observed that after heat treatment at 100°C for 120 min, ascorbic acid content was only 30% lower than the initial value. Leizerson and Shimoni (2005) evaluated the effect of ultrahigh temperature continuous ohmic heating treatment on fresh orange juice in comparison to the commercial pasteurization; the results showed similar ascorbic acid degradation for both technologies when the thermal histories were matched. Also, the reduction of vitamin C was maintained at 15% ($p > 0.05$) at temperatures of 90, 12, and 150°C for 1.13, 0.85, and 0.68 s.

3.4. Viscosity and pH

Singh et al. (2008) measured viscosity and EC, critical parameters affecting ohmic heating (OH). Viscosity of apple, pineapple, orange, and tomato juices have been measured in the temperature range 25–70°C using an Ostwald viscometer. The results showed that viscosity decreased with increase in temperature for four juices. This could be due to decrease in cohesive force between molecules at higher temperature. Processing and stabilization of a soup containing potato particles (cubes: 12–16 mm) by ohmic heating technology showed that this process resulted in a final product of pleasant texture and high viscosity, with a high content of particles >10 mm (Zuber, Schietequatte, & Da Silva, 2000).

The effect of ohmic heating technique on EC, heating rate, system performance, and pH of pomegranate juice was investigated by Darvishi et al. (2013). The voltage gradient had significant effect on the pH change of pomegranate juice samples. As the voltage gradient increased, time and pH decreased.

3.5. Rheological characteristics

Bozkurt and Icier (2009) studied the rheological characteristics of quince nectar during ohmic heating. Ohmic heating was applied to quince nectar by changing the voltage gradient (10–40 V/cm) at 50 Hz. The rheological behavior of quince nectars was examined by application of different mathematical models. Herschel–Bulkley model fitted the experimental data best, for all temperatures. Non-Newtonian shear thinning behavior was obtained for quince nectar at the pasteurization conditions (temperature range of 65–70°C, and holding time of 0–30 min). They also reported that ohmic heating did not cause different effect on the rheological properties of quince nectar compared to conventional heating. Krokida, Maroulis, and Saravacos (2001) also performed similar study comparing the available data in literature of fruit pulps (guava, raspberry, pineapple, apricot, apple, mango, tamarind, black currant) and found that these fruit pulps showed shear thinning behavior. Pelegrine, Silva, and Gasparetto (2002) determined that pineapple and mango pulps were shear-thinning fluids, as their apparent viscosity decreased with an increase in shear rate. Branco and Gasparetto (2003) also studied the rheological behavior of ternary mixtures of mango pulp, and juices of carrot and orange, where the ternary mixtures presented the non-Newtonian fluid behavior.

3.6. Color changes

Sant'Anna, Gurak, Marczak, and Tessaro (2013) summarized that several studies in the last years have focused on evaluating color instrumentation as an alternative to control the presence of bioactive compounds with antioxidant activities, such as carotenoids (Meléndez-Martínez, Britton, Vicario, & Heredia, 2007; Spada, Noreña, Marczak, & Tessaro, 2012), anthocyanins and other polyphenols (Jiménez-Aguilar et al., 2011; Larrauri, Rupérez, & Saura-Calixto, 1997), betalain (Esquivel, Stintzing, & Carle, 2007), and chlorophyll (Koca, Karadeniz, & Burdurlu, 2006). Color can be used as a quality indicator to evaluate the extent of deterioration due to thermal processing (Avila & Silva, 1999).

Ascorbic acid degradation and color changes in acerola pulp during ohmic heating was investigated by Mercali et al. (2014). Acerola has a good amount of anthocyanins and carotenoid pigments, their gradual degradation results in color changes in the final product. Color parameters L*, a*, b* decreased over time for all treatments, which indicates color changes during the heating treatment. At low electric field frequency (10 Hz), higher color change was probably due to occurrence of electrochemical reactions. Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods was examined by Vikram et al. (2005). The study included a comparative evaluation of kinetics of vitamin degradation and changes in visual color as an index of carotenoids. The degradation of visual color as expressed by the combination (a*b) values followed first-order kinetics for all methods of heating. The R^2 values were greater than 0.992 in all cases. The highest values for activation energy were for ohmic heating which implies that a smaller temperature change is needed to degrade color more rapidly. Peroxidase inactivation and color changes during ohmic blanching of pea puree were studied (Icier et al., 2006) and it was observed that first-order kinetics described the changes in color values during ohmic blanching. Hue angle is the most appropriate combination (R^2 = 0.954), which described closely the reaction kinetics of total color changes of pea puree for ohmic blanching at 20 V/cm.

Several researchers (Ahmed, Kaur, & Shivhare, 2002a; Ahmed & Shivhare, 2001; Ahmed, Shivhare, & Raghavan, 2000; Ahmed, Shivhare, & Sandhu, 2002b; Ibarz, Pagan, & Garza, 2000; Shin & Bhowmik, 1995) have also reported that color degradation kinetics follows a first-order reaction kinetics. Garza, Ibarz, Pagán, and Giner (1999) applied first-order reaction kinetics for non-enzymatic color changes of peach puree during thermal treatment and found the reaction rate constant for color parameter at 98°C water bath. Similarly, the first-order reaction constant of "L" value of pear puree processed at 98°C water was reported by Ibarz, Pagán, and Garza (1999).

4. Factors affecting ohmic heating

The design of effective ohmic heaters depends on the EC of foods (Sarang et al., 2008). The ohmic heating rate is directly proportional to the square of the electric field strength and the EC (Sastry & Palaniappan, 1992). Since, heat generation depends on EC, it is a key parameter to be quantified. It

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depends on temperature, applied voltage gradient, frequency, particle size, concentration, moisture content, and concentration of electrolytes (Icier & Ilicali, 2005b; Ye, Ruan, Chen, & Doona, 2004). Various factors affecting EC were analyzed.

4.1. Temperature

It is important to quantify electrical conductivities not only at room temperature as many researchers found that EC increases with temperature (Fryer et al., 1993; Halden et al., 1990; Marcotte, Ramaswamy, & Piette, 1998; Roberts, Balaban, Zimmerman, & Luzuriaga, 1998; Wang & Sastry, 1997; Yongsawatdigul, Park, & Kolbe, 1995). The temperature dependency of the EC liquid products follows linear or quadratic relations, depending on the product type tested such as strawberry pulps (Castro et al., 2004); sour cherry juice (Icier & Ilicali, 2004); namely apple, orange, and pineapple juices (Amiali et al., 2006); pomegranate juice (Yildiz, Bozkurt, & Icier, 2008); orange juice (Icier & Ilicali, 2005a; Leizerson & Shimoni, 2005; Qihua et al., 1993); lemon juice (Cristina, Moura, & Vitali, 1999; Darvishi, Hosainpour, Nargesi, Khoshtaghza, & Torang, 2011), and grape juice (Icier et al., 2008). The heating behavior and EC of carrot–starch mixtures were studied (Zareifard et al., 2003) and observed a linear increase in EC values with increase in temperature. Similar trend was observed by Icier et al. (2008) while studying the polyphenoloxidase deactivation kinetics during ohmic heating of grape juice at three different voltage gradients (20, 30, 40 V/cm). This trend was also observed by Sarang et al. (2008) while studying the EC of fruits (red apple, golden apple, peach, pear, pineapple, and strawberry) at temperature range 25–140°C during ohmic heating. Similarly, Icier and Ilicali (2005b) also reported temperature-dependent electrical conductivities of fruit purees (apricot and peach) during ohmic heating. There was a linear increase in the EC of fruit purees with temperature rise. They postulated that the rate of change of temperature for the apricot puree was higher than the peach puree at all voltage gradients applied. Castro et al. (2003) also discussed the effect of temperature and sugar content on the EC values of strawberry-based products. EC increases with temperature (Amiali et al., 2006; Castro et al., 2004; Darvishi et al., 2011; Icier & Ilicali, 2004, 2005a; Icier et al., 2008; Kemp & Fryer, 2007; Kumar, Singh, & Tarsikka, 2011). Similarly, the effect of temperature on EC was measured by Castro et al. (2004) during ohmic heating of strawberry products. EC increased with temperature presenting a linear or second-order relation, depending on the product. Halden et al. (1990) also noted the increase in EC of beetroot with temperature was sharper when processed electrically than the smoother increase seen when processed conventionally.

4.2. Field strength

The increase in field strength results in increasing fluid motion through the capillaries, which is directly proportional to EC (Halden et al., 1990). The effect of field strength on EC was studied during ohmic heating of strawberry products (Castro et al., 2004). An increase in EC with field strength was observed for two strawberry pulps and strawberry filling but not for strawberry topping or strawberry apple sauce. Castro et al. (2003) also measured the EC of fresh strawberries at different field strengths from 25 to 70 V/cm, and found that the EC increased almost linearly with the field strength. The pea puree was blanched ohmically by using the voltage gradients of (20–50 V/cm) and by water blanching at 100°C (Icier et al., 2006). They observed as the voltage gradient increased, the time required to reach 100°C decreased because there is increased heat generation with time at higher voltage gradients. Similar effect was explained by Icier and Ilicali (2004) during ohmic heating of fruit concentrates. Also, the changes in EC of grape juice with temperature during ohmic heating at three different voltage gradients (20, 30, 40 V/cm) was studied by Icier et al. (2008) and it was observed that EC at 40 V/cm was slightly higher than at 20 or 30 V/cm, between 55 and 75°C. Similar effect was observed by Palaniappan and Sastry (1991b) during ohmic heating of pre-pasteurized carrot and tomato juices.

4.3. Applied frequency

Singh et al. (2008) conducted studies on viscosity and EC of fruit juices. They reported that EC was more at 10 kHz than at 1 kHz in all the juices indicating that heating rate increases with increasing frequency. The ohmic heating of turnip as a function of frequency (4, 10, 25, and 60 Hz) and wave shape of alternating current were investigated by Lima, Heskitt, and Sastry (1999) and it was shown

that heating rate increased with decreasing frequency. The lower the frequency, the faster the sample reached elevated temperatures. Similar effect was observed by Imai et al. (1995) during ohmic heating of Japanese white radish from 50 to 10,000 Hz.

4.4. Nature of food and ionic content effect

Stirling (1987) and Marcotte (1999) classified published data on EC values of solid and liquid foods. Generally, solid vegetable particles have lower EC than liquids. Zareifard et al. (2003) observed the heating behavior when there was no liquid phase in the ohmic heating cell during ohmic heating behavior of two-phase system. The OH cell was filled with carrot puree (100% carrot particles) and observed much longer time (twice as much) was required to raise the temperature from 20 to 80°C than when the solid concentration was less. Increase in the EC during heating of biological tissue occurs due to increase in the ionic mobility because of structural changes in the tissue like cell wall protopectin breakdown, expulsion of non-conductive gas bubbles, softening, and lowering in aqueous-phase viscosity (Bean et al., 1960; Sasson & Monselise, 1977). Greater the ionic concentration faster is the heating rate. de Alwis, Halden, and Fryer (1989) studied the effect of EC of strawberry as well as peach and concluded that greater EC may be attributed to the softer tissues and hence higher ionic mobility in comparison to the harder tissues of apples, pineapple, and pear. Halden et al. (1990) observed that higher the concentration of ionic constituents, the higher the conductivity of the product.

4.5. Particle size, concentration, and location

Zareifard et al. (2003) observed that EC values decreased as the particle size increased in carrot–starch mixture during ohmic heating behavior and EC of two-phase systems. They also observed that with the increase in particle size, the heating time to achieve the same temperature rise also increased. Benabderrahmane and Pain (2000) observed the same result, demonstrating less liquid heating efficiency as particle diameter increased.

Sastry (1991) noted that particle concentration is a critical factor in determining the heating rate of the two phases. Investigations by Palaniappan and Sastry (1991a) on the role of particle concentration in orange and tomato juices revealed that overall EC decreased as the percentage of solid constituents dispersed in the liquid phase increased. Solids of low conductivity relative to the fluid will heat slower than the fluid if they are in low concentration. During the study of ohmic heating behavior of two-phase food systems, it was found that as particle concentration increased, values of EC decreased uniformly (Zareifard et al., 2003). Sastry and Palaniappan (1992) studied the ohmic heating behavior of particle–liquid mixtures using potato cubes in sodium phosphate solutions. They concluded that solids having lower EC than the fluid would lag behind the fluid if they were in low concentration, but in high concentrations, the particles may heat faster than the fluid. Icier and Ilicali (2004) also discussed the effect of concentration on the ohmic heating rates of apple and sour cherry juices. They reported that the decrease in concentration of juices from 60 to 20% enhanced the ohmic heating rate of juices.

The position of the particle with respect to electric field can be significant in electric heating depending on relative EC of the solid and liquid (de Alwis et al., 1989). Davies, Kemp, and Fryer (1999) also demonstrated the effect of particle orientation with respect to one another. Zareifard et al. (2003) also studied the ohmic heating behavior of a mass of particles as affected by their location with respect to electrodes. It was observed that for the parallel condition, the liquid phase heated faster than the solid phase while in the series condition, reverse was observed. For the parallel condition, voltage was same. The liquid phase heated faster than the solid phase. Therefore, the current that passed through the liquid was greater than the current through the solid; hence more heat was generated in liquid phase. For series condition, the solid phase heated faster than the liquid phase. The amount of current passing through food system was same, while the voltage applied was different for each phase. Since the resistance of solid was greater than that of the liquid, the amount of heat generated in solid phase was greater.

5. Conclusion

Ohmic heating is an alternative heating process in which the food product is heated internally due to inherent resistance. Ohmic heating rate is dependent on the temperature, applied voltage gradient, frequency, particle size, concentration, and concentration of electrolytes. It linearly increases with increase in temperature, voltage gradient, and concentration of ionic constituents. With increase in particle size and frequency, heating rate gets decreased. During study of ohmic heating behavior of two-phase food systems, it was found that as particle concentration increased, values of EC decreased uniformly. The effect of ohmic heating on quality and nutritional parameters of fruits and vegetables is also studied. Electrical fields applied during ohmic heating leads to faster deactivation of enzymes and micro-organisms. The phenomenon of electroporation is dominant at low frequencies which lead to membrane rupture and ultimately a significant rise in tissue EC. The results showed that degradation of heat sensitive compounds (anthocyanins, ascorbic acid, and vitamin C) increases with both increasing voltage and solid contents. It has been observed that at low voltage levels, the percentage of degradation was lower to those obtained by conventional heating. A higher level of degradation was seen at high voltages, whereas the use of low electric field frequency led to greater degradation due to occurrence of electrochemical reactions. Above 100 Hz, these reactions were minimized and both ohmic and conventional heating processes show similar degradation rates. The properties such as viscosity, pH, rheology, and color were also examined. With increase in temperature, viscosity decreases leading to increase in ohmic heating rate. pH decreases with increase in voltage gradient. Similar effect was observed on rheological properties when juice was treated with both conventional and ohmic heating method. The studies reported that color degradation kinetics follow a first order reaction kinetics.

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