Trends in Food Science & Technology 55 (2016) 84–97

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: http://www.journals.elsevier.com/trends-in-food-science-and-technology

Review

Opinion on the use of ohmic heating for the treatment of foods

Henry Jaeger [a], [*], Angelika Roth [b], Stefan Toepfl [c], Thomas Holzhauser [d], Karl-Heinz Engel [e], Dietrich Knorr [f], Rudi F. Vogel [e], Niels Bandick [g], Sabine Kulling [h], Volker Heinz [c], Pablo Steinberg [b]

[a] University of Natural Resources and Life Sciences (BOKU) Vienna, Institute of Food Technology, Vienna, Austria
[b] University of Veterinary Medicine, Foundation, Institute for Food Toxicology and Analytical Chemistry, Hannover, Germany
[c] German Institute of Food Technologies (DIL) e.V., Quakenbrück, Germany
[d] Paul-Ehrlich-Institut, Federal Institute for Vaccines and Biomedicines, Division of Allergology, Langen, Germany
[e] Technische Universität München, Chair of General Food Technology, Munich, Germany
[f] Technische Universität Berlin, Department of Food Biotechnology and Food Process Engineering, Berlin, Germany
[g] Federal Institute for Risk Assessment, Berlin, Germany
[h] Max Rubner-Institut, Federal Research Institute of Nutrition and Food, Department of Safety and Quality of Fruit and Vegetables, Karlsruhe, Germany

ARTICLE INFO

Article history:
Received 21 March 2016
Received in revised form
23 May 2016
Accepted 12 July 2016
Available online 15 July 2016

Keywords:
Food microbiology
Food safety
Food technology
Ohmic heating
Safety assessment

ABSTRACT

Background: The working group “Food Technology and Safety” of the DFG Senate Commission on Food Safety (SKLM) deals with new technologies which are being developed or used to treat foods. Ohmic heating is a new process for heating food by means of direct application of current to the food. Compared to conventional heating methods, this process can achieve shorter heating times while avoiding hot surfaces and can reduce temperature gradients. The electrical, thermophysical and rheological properties of the products play an important role in achieving uniform heating. In addition to the product parameters, process parameters such as the current frequency used, the electrode material and the geometry of the treatment chamber are also relevant.

Scope and approach: On June 22nd 2015, the SKLM issued an assessment of the process for Ohmic heating of food in German. The English version was issued on December 14th, 2015. The objective of this statement was to describe the state of the research, to draw attention to critical points in the application and science-based further development of the process, and to define the need for research.

Key findings and conclusions: As with conventional heating, the effectiveness of ohmic heating as a preservation process depends on reaching and maintaining a certain temperature at each point of the food for a sufficient period of time to inactivate microorganisms. The physicochemical product properties are extremely important for achieving heating conditions that are as uniform as possible. Because the electric field strengths applied are low, mainly thermal effects come into play. However, some studies discuss potential additional synergistic or non-thermal inactivation effects of the electric field. As with other processing methods, the structure and concentration of ingredients and contaminants in foods may be altered during ohmic heating. Besides the thermal effects of ohmic heating, it is also necessary to pay attention to potential electrochemical reactions at the contact surface between electrodes and food as well as potential non-thermal effects of the electric field, depending on the process conditions. Therefore, process control becomes particularly important to prevent such effects, which are sometimes undesirable.

Compared to conventional heating methods, the primary requirement in evaluating ohmic heating is a standardised means of acquiring the process control parameters. This includes, first and foremost, a space- and time-resolved temperature measurement that takes into account the product and electric field properties. It is absolutely necessary to carry out systematic studies while paying attention to the comparability with respect to product and process parameters as well as the system design. Consequently, the existing gaps in the data records are in part due to the insufficient comparability of the available studies.

---

[*] Corresponding author.
E-mail address: henry.jaeger@boku.ac.at (H. Jaeger).

http://dx.doi.org/10.1016/j.tifs.2016.07.007

Moreover, it is necessary to analyze thermal and non-thermal as well as additional process-induced changes in the food and its ingredients. This applies particularly to the effect on the potential allergenicity of the food components.
Thermal and non-thermal effects can be studied in a differentiated manner in simulation models. This is regarded as a promising approach for providing a model-like description of combination processes and for optimising process conditions as well.

1. Introduction

Conventional thermal methods for pasteurising and sterilising food are based on heat transfer, whereby the heat transfer and thermal conductivity are limiting factors for the quick heating of the product. Particularly in the case of viscous and particulate food, this results in a lengthening of the heating times with a possible overprocessing of individual product fractions and an associated loss of quality. Additionally, in the case of indirect heating methods, heat transfer via hot surfaces can lead to unwanted temperature peaks in the product (Goullieux & Pain, 2005). There is growing interest in alternative thermal methods of pasteurising and sterilising which avoid long heating times, overprocessing and unwanted temperature peaks; the use of ohmic heating in particular is among these methods (Goullieux & Pain, 2005; Ruan, Ye, Chen, Doona, & Taub, 2001; Yildiz-Turp, Sengun, Kendirci, & Icier, 2013; Zareifard, Ramaswamy, Trigui, & Marcotte, 2003).

Research on the preservation of food through the direct application of electric current began as early as at the end of the 19th century, when electricity became commercially available (Jones, 1897). The first industrial applications of ohmic heating for thermal treatment began in 1920 with the 'Electropure' process (Anderson & Finkelstein, 1919; Fellows, 2000; Toepfl, Heinz, & Knorr, 2007). This involved heating milk in a continuous process while using carbon electrodes and an alternating current of 220 V with a frequency of 60 Hz. This process was approved for pasteurising milk in six US states, and by 1950 it was used in 50 plants that supplied milk for approximately 50,000 consumers. At an early stage, additional methods of ohmic heating were patented, such as one for the direct electric heating of sausages (Kohn, 1933; McConnell & Oisson, 1938), and in the mid-20th century a method for blanching vegetables (Schade, 1951). Increasing costs for electricity and the development of alternative thermal processes for preservation, such as UHT-treatment, later led to the reduced usage of ohmic heating (Kessler, 1996). As a result, ohmic heating was essentially further developed for the sole purpose of thawing food (Naveh, Kopelman, & Mizrahi, 1983).

In the 1980s in Europe, interest in ohmic heating for the preservation of food was renewed, and industrial systems came into use (Skudder, 1988). Currently, ohmic heating is used as a thermal method to preheat, to blanch and to pasteurise and sterilise vegetable products, fruit preparations and meat products (Knirsch, dos Santos, Vicente, & Pennaa, 2010; Marcotte, Ramaswamy, & Sastry, 2014). The process is based on using the electrical resistance of the food being treated. Dissipation of the electrical energy when an electric current flows through food causes heat to be released (Joule effect). The amount of dissipated heat is directly related to the applied voltage and the electrical conductivity of the product or of individual product fractions (Ohm's law) (Kessler, 1996; Varghese, Pandey, Radhakrishna, & Bawa, 2014).

In earlier applications, the use of low alternating current frequencies in the range of 50–60 Hz was found to be disadvantageous, as this led to increased electrochemical reactions and electrode erosion, particularly in conjunction with metallic electrodes (Ruan et al., 2001). Direct contact of the food with the electrodes is regarded as a critical aspect of the application. The subsequent technical improvements of the process with respect to the electrode materials being used (such as titanium) and optimised alternating current frequencies in the kilohertz range led to a wider distribution of the technology (Pataro et al., 2014; Samaranayake & Sastry, 2005; Samaranayake, Sastry, & Zhang, 2005).

The advantages of ohmic heating lie in the heating of the product volume, which, ideally, should be uniform (Ruan et al., 2001). Depending on the conductivity of individual product fractions, the configuration of the treatment chamber and the flow characteristics of the food, it could be heated at relatively low temperature gradients. Since heating times are substantially shortened, the cooking load of food (C value), along with the process-dependent change in quality, is reduced while maintaining the same sterilisation effect (Fo value) (Baysal & Icier, 2010; Leizerson & Shimoni, 2005b).

Another advantage is that the food does not come into contact with hot surfaces. It is also possible to largely prevent the formation of unwanted layers of biological, organic or inorganic composition (fouling) by suitably designing the electrode configuration (Ayadi, Benezech, Chopard, & Berthou, 2008; Goullieux & Pain, 2005).

The growing interest in the industrial use of ohmic heating makes it necessary to consider the critical aspects of the method to ensure that it is harmless to health. Although the effect of ohmic heating on the product is primarily classified as thermal, additional electrical effects, which also influence the quality and safety of the food being treated, can not be excluded.

Concepts for the application of ohmic heating to packaged food are in development (Ito, Fukuoka, & Hamada-Sato, 2014; Jun & Sastry, 2005; Somavat, Kamonpatana, Mohamed, & Sastry, 2012) but are not part of this statement.

2. Procedural principles and technical aspects

During ohmic heating there is a **conversion of electrical energy into thermal energy**. Food with an electrical conductivity in the range of 0.1–10 S/m can always be heated by means of ohmic heating. The products to be heated are subjected to an electric field within an arrangement of two or more electrodes. They are in direct contact with the electrodes or are coupled to them via an electrically conductive medium. The treatment can be performed as an intermittent batch process or in a continuous flow system. A current flow develops as a function of the field strength, electrode configuration and conductivity of the products. Based on Ohm's law, this current flow leads to energy input, which is characterised by nearly complete conversion of the electrical energy into heat, high energy density and short heating times. The voltages used lie between 400 and 4000 V. Field strengths in the range of 20–400 V/cm result when electrode gaps of 10–50 cm are used. The achieved **heating rates** depend on the output of the power supply, the design of the treatment equipment and the product properties (such as conductivity, viscosity and specific heat capacity). The required electrical output can be calculated from the mass flow, temperature increase and specific heat capacity based on the product and taking into consideration the product properties.

Ohmic heating can be achieved with direct or alternating current; however, alternating current is usually used to **prevent electrochemical and electrolytic effects** and the formation of unwanted reaction products. The current density (depending on the electrode geometry), frequency and electrode material (with specific tendency to oxidise) are particularly important regarding the magnitude of potential **electrochemical reactions on the electrodes**, which lead to electrolysis of the product and to erosion of the electrodes. Systems currently in use achieve current levels in the range of several hundred amperes. Current densities in the range of 0.5–20 A/cm^2 occur at the electrodes. These current densities facilitate unspecific, electrochemical reactions of the materials involved. To reduce oxidation reactions and metallic contamination of the product, alternating current is used at frequencies greater than 20 kHz. Electrochemical reactions occur less frequently when alternating current is used, due to the reversed field effect. At frequency values greater than 20 kHz, electrode erosion is reduced due to the inhibiting of Faraday reactions. Because of its low tendency to oxidise, the electrode material is usually stainless steel.

Another process with direct application of electric fields on the food is classified under the term “Pulsed Electric Field” (PEF) (Knorr et al., 2008; SKLM., 2007). Ohmic heating and PEF applications are differentiated by the process parameters used and defined by their **thermal and non-thermal (electric) effects** on the product. In the case of ohmic heating, the focus lies on generating thermal effects, while PEF treatment aims at generating electric effects and minimising thermal effects. Cell lysis occurs by using an electrical field to form pores in the microbial membrane (electroporation). Since, in contrast to PEF treatment, ohmic heating at 20–400 V/cm uses significantly lower field strengths than those required for electroporation of microbial cells (10 kV/cm) (Dimitrov, 1984; Teissie, Golzio, & Rols, 2005; Zimmermann & Neil, 1996; Zimmermann, Pilwat, Beckers, & Riemann, 1976), it can be assumed that ohmic heating inactivates microorganisms predominantly through heat. In the case of plant cells, however, electroporation can occur even at electric field strengths lower than 1 kV/cm (Angersbach, Heinz, & Knorr, 2000; S.; Kulshrestha & Sastry, 2003, 2010; S. A.; Lebovka, Bazhal, & Vorobiev, 2000; Sensoy & Sastry, 2004a; Wang & Sastry, 2000, 2002; Wegner et al., 2011). Here, cell lysis through ohmic heating can be the result of thermal permeabilisation of the plant cell membrane and, as in the case of PEF treatment, it can have an electrical cause (through electroporation of the cell membrane) (Gonzalez & Barrett, 2010).

Depending on the geometry of the treatment chamber, **local overprocessing and underprocessing** represent critical challenges to the process design, particularly for changing product properties. Overprocessing can lead to increased thermal loading and to the formation of thermally conditioned compounds with accompanying loss of quality; in addition to the quality, underprocessing also affects the shelf life of the product. To achieve the greatest possible **uniformity of heating**, the **electrode geometries** used are usually **adapted to the product properties**. This is important when using ohmic heating as a continuous flow method, since in such a case aspects of the **product flow** have to be taken into account. The design of the treatment chamber can be optimised with respect to the dwell time behaviour by simulating the flow profile based on the flow function. The uniformity of treatment can be increased in conjunction with a simulation of the electric field distribution and energy input as well as of the counter-effect on the viscosity and conductivity of the product.

Particularly in layers near a wall and on the electrode as well as on the insulator, a clear, local **overprocessing** can be observed because here the flow velocity of the product is lower and the longer dwell time results in a higher energy input. Depending on the product properties, these effects can be counteracted in part by using scrapers, higher flow velocities or electrode materials cooled through use.

When a continuous flow method is used, **underprocessing** often occurs in the central area of the treatment section parallel to the product flow because a high flow velocity with a low electric field strength is present there. The use of treatment sections connected in series can lead to increased uniformity of the temperature distribution. Ohmic heating is also used in combination with other volumetric heating methods, such as radio frequency heating, to improve uniformity of the heating.

In the case of conventional methods, there is **non-uniformity of heating** with the formation of **local high temperature peaks (called hot spots) and/or low temperatures (called cold spots)**, depending on the product geometry and process geometry as well as the heat transfer coefficients. In the case of ohmic heating, different electrical conductivities of individual product fractions or non-uniform distribution of the electric field will lead to inhomogeneities with hot spots and cold spots, regardless of the parameters of the product geometry. The cold spots are determined by the fraction with the lowest electrical conductivity in connection with the lowest electric field strength and a non-uniform electric field; hot spots are determined by the fraction with high electrical conductivity and a high electric field strength. **Disperse systems with aqueous, oil or particulate fractions** in particular show differences in conductivity, which lead to substantial differences in the temperature increase of the respective phase. Unlike conventional processes, when complex particulate food is subjected to ohmic heating, a cold spot may appear in the liquid phase, while the particles heat up significantly faster. During the ensuing holding time, heat dissipation results in reheating of the liquid phase (Salengke & Sastry, 2007b). However, if the liquid phase is the fraction with the highest electrical conductivity, this results in faster heating with subsequent heat dissipation towards the particulate fraction. Since the conductivity of aqueous media increases as a function of temperature when there is a temperature increase, it is possible to compensate for inhomogeneities during the heating or to increase them. Both the conductivity and the viscosity of the product can also be significantly altered during the process through likewise temperature-induced processes such as gelatinization of starch and proteins, denaturation of proteins or release of conductive components by destroying cell structures.

As with conventional heating, the effectiveness of ohmic heating as a **thermal process for inactivating microorganisms** depends on the temperature reached at each point of the food and the corresponding holding time (FDA., 2011). As a result, underprocessing (caused by the design of the treatment chamber) and cold spots (caused by the conductivity of the product fractions) pose a risk for the **microbiological safety** of the product (Marra, Zell, Lyng, Morgan, & Cronin, 2009; Shim, Lee, & Jun 2010).

Combined applications with conventional preheating and subsequent ohmic heating are increasingly attracting attention. Such combined methods offer advantages in terms of product safety. A more uniform temperature distribution and distribution of temperature-dependent conductivity is achieved through preheating. The subsequent jump in temperature through ohmic heating is smaller, and the homogeneity of the treatment is improved compared to the sole use of ohmic heating without preheating.

3. Impact on food

As with other processing steps, during ohmic heating food may undergo changes which affect its consistency, taste and colour (Zell, Lyng, Cronin, & Morgan, 2010a, 2010b; Eliot, Goullieux, & Pain, 1999a, 1999b; Eliot & Goullieux, 2000; Mizrahi, 1996; Shirsat, Brunton, Lyng, McKenna, & Scannell, 2004; Yildiz, Bozkurt, & Icier, 2009; Yildiz, Icier, & Baysal, 2010).

Since food comes in direct contact with the electrodes during the process or is coupled with them via an electrically conductive medium, it is possible that under certain process conditions unwanted ions may get into the food through electrochemical reactions and corrosion of the electrodes may occur (Herting, Wallinder, & Leygraf, 2008; Wu, Kolbe, Flugstad, Park, & Yongsawatdigul, 1998; Zhao, Kolbe, & Flugstad, 1999).

The electrical conductivity is an important property of the food for ohmic heating because it is a prerequisite for the corresponding heat development (N. Shirsat, J. G. Lyng, N. P. Brunton, & B. M. Mckenna, 2004b; Wang & Sastry, 1993). Since the conductivity is temperature-dependent, it changes during the heating process. Cell structures that have been lysed as a result of heat release ions, which in turn lead to a significant change in the conductivity of the food and therefore affect the ohmic heating process (Castro, Teixeira, Salengke, Sastry, & Vicente, 2003; Darvishi, Khoshtaghaza, & Najafi, 2013; Icier & Ilicali, 2004, 2005a; Legrand et al., 2007; Wang & Sastry, 1997a, 1998).

3.1. Interactions with the food matrix

In addition to electrochemical reactions at the electrodes and the heat-related change in electrical conductivity of the treated food, ohmic heating has other ways of interacting with the treated food. Ingredients and additives have an impact on the structure and conductivity of the food. Thus, hydrocolloids such as starch, pectin or gelatine impact the ohmic heating depending on the proportion of these substances in the food and the hydration level. Starch solutions exhibited a rise in conductivity as the temperature increased; the conductivity decreased again as the level of gelatinization increased. This was most probably due to an altered structure or increased bonding of water (Wang & Sastry, 1997b). The amount of ovomucin in the egg white in chicken eggs affected its electrical conductivity and thermal conductivity (Imai, Uemura, & Noguchi, 1998; Imai, Uemura, Yoshizaki, & Noguchi, 1996). This was also found for surimi (crab meat imitation) after starch was added (Pongviratchai & Park, 2007). Ohmic heating increased the viscosity of surimi more than conventional heating at the same temperatures. This was due to a reduced decomposition of myosin and actin, which increased the continuous network structure and therefore also the gel quality (J. W. Park & Yongsawatdigul, 1998; J. W. Park, Yongsawatdigul, & Kolbe, 1998; Yongsawatdigul, Park, Kolbe, Abudagga, & Morrissey, 1995). The fat content and fibre density in meat and sausage likewise had an effect on the electrical conductivity and the thermal conductivity (Bozkurt & Icier, 2010a; N. Shirsat, J. G. Lyng, N. P. Brunton, & B. McKenna, 2004a).

When using ohmic heating for blanching of vegetables, it is generally possible to use larger pieces of vegetables than with conventional heating methods, for which the thermal conductivity is a limiting factor. Since larger pieces have a different surface to volume ratio when compared to smaller pieces, the loss of soluble substances is reduced (Mizrahi, 1996). In contrast, the amount of freely soluble components increased in white radish under certain low-frequency conditions, which was shown to be due to increased decomposition of cells and could also explain the faster initial heating at low frequencies (Imai, Uemura, Ishida, Yoshizaki, & Noguchi, 1995). In the case of peach pieces, at a low frequency there was a stronger lysis of the cell membranes with a resulting increase in electrical conductivity and texture degradation. Higher frequencies led to a reduction of these effects, but the time until the desired final temperature was reached increased (Shynkaryk, Ji, Alvarez, & Sastry, 2010). Cell lysis was also observed in potatoes and apples and increased at higher temperatures with a moderate electric field and an electric field strength lower than 100 V/cm (Lebovka, Praporscic, Ghnimi, & Vorobiev, 2005). Similar effects were observed when blanching mushrooms (Sensoy & Sastry, 2004b). Juice from quinces, a pectin-rich fruit, obtained through ohmic heating or through conventional heating exhibited no difference regarding its flow properties (Bozkurt & Icier, 2009). Ohmic heating was also investigated as a pretreatment method (50 °C) to increase the yield of extract from sugar beet cuts in combination with subsequent high-voltage pulse treatment (i.e. PEF). It was possible to substantially increase the juice extraction by thermal decomposition of the tissue matrix in combination with the electropermeabilisation of the cell membranes (Praporscic, Ghnimi, & Vorobiev, 2005).

3.2. Impact on food components

The stability of nutritional components in food depends on the process conditions. It has been reported that the flavouring substances decanal, octanal, limonene, pinene and myrcene decomposed to a smaller extent during ohmic heating than during conventional heating methods (Leizerson & Shimoni, 2005b). No difference in the kinetics of the decomposition of anthocyanins in acerola puree was found between the two methods (Mercali, Jaeschke, Tessaro, & Marczak, 2013), whereas the decomposition of vitamin C in acerola puree depended on the ohmic heating conditions and was enhanced by increasing the voltage. At low voltage gradients, the decomposition of vitamin C was comparable to that when using conventional heating methods (Mercali, Jaeschke, Tessaro, & Marczak, 2012). This dependence on the magnitude of the voltage used is also found when analyzing the degradation of anthocyanins (Sarkis, Jaeschke, Tessaro, & Marczak, 2013). The degradation of vitamin C and browning in baby food was less affected during ohmic heating than during sterilisation by means of direct steam injection (Courel et al., 2011).

Studies on the phenol oxidase activity in grape juice have shown that in the course of the temperature increase during ohmic heating the enzyme activity rose, until a critical temperature was reached, and thereafter sank. This temperature was dependent on voltage gradients (Icier, Yildiz, & Baysal, 2008). Based on these results, the authors concluded that there is a difference between conventional and ohmic heating regarding the inactivation of phenol oxidases.

In the case of orange juice, it was reported that both conventional and ohmic heating led to a comparable inactivation of pectin esterases (by 90–98%) (Leizerson & Shimoni, 2005b). Another study on orange juice showed that ohmic heating inhibited the pectin esterase (pectin methylesterase) to a greater extent than conventional heating (Demirdoven & Baysal, 2014).

A study with pea puree indicated that under certain conditions the activity of peroxidases during ohmic heating at shorter processing times was reduced if compared to conventional heating (Icier, Yildiz, & Baysal, 2006). No difference was found between the heating methods for the inactivation of peroxidases in carrot pieces (Lemmens et al., 2009). For many of the foods that were investigated, the data records are contradictory (Table 1). However, the majority of studies lacked exact temperature-time profiles allowing a comparison of the treatment conditions.

Table 1
Applications and parameters of ohmic heating with the corresponding impact on the quality of the differently treated products (OH – Ohmic Heating, PEF – Pulsed Electric Field).

Product and process objective (1) Heating/thawing (2) Blanching (3) Pasteurisation (4) Sterilisation (5) Cell disintegration	Conditions of ohmic heating	Effects	References
Vegetables			
Japanese white radish(1)	40 V/cm, 50 Hz-10 kHz	Release of liquid components after quick heating at a low frequency due to electroporation of the tissue, reduction of the electrical resistance	(Imai et al., 1995)
Beets in salt water(2)	Electrodes not in direct contact with beets: conduction via a salt solution, alternating current at 300 V, boiling point reached in less than 30 s.	It was possible to heat larger beet pieces in less time, and the loss of soluble substances was reduced by a factor of 10	(Mizrahi, 1996)
Potato cubes in salt water(4)	60 min of precooking at 55–60 °C, followed by OH	Structure retention was improved	(Eliot & Goullieux, 2000)
Potato cubes in salt water(4)	Blanching at 90–95 °C for 1–4 min, followed by OH at 135 °C for 2–4 min.	Blanching pretreatment shortened the holding time of the OH and increased the firmness of the potato cubes	(Eliot et al., 1999a)
Cauliflower in salt water(4)	30 min of precooking at 40–50 °C, followed by OH for 30 s. at 135 °C	Structure retention was improved	(Eliot, Goullieux, & Pain, 1999b)
Cauliflower(4)	Continuous system, 10 kW, 130 kg/h, pretreatment at 50–60 °C, 20–30 min, OH treatment 130–131 °C, for about 22 s, discharge temperature 36–40 °C	Precooking at low temperatures, a fast flow rate and sufficient electrical conductivity retain the stability and structure of the cauliflower	(Eliot-Godereaux, Zuber, & Goullieux, 2001)
Sweet potato cubes(1,5)	50-90 V/cm, 30–90 °C	Reduction of the time for vacuum drying	(Zhong & Lima, 2003)
Mushrooms(2)	Blanching, 212 V; 7.3 cm electrode spacing; 15–180 s, 70 °C	Mushrooms with 50% solid mushroom substance in water, heating to 70 °C within 40 s (compared to conventional blanching, usually with less than 25% solid mushroom substance), indications of non-thermal permeabilisation	(Sensoy & Sastry, 2004b)
Sugar beets(1,5)	60 V/cm, 50 Hz, 30–70 °C, 10–30 min.	Combination of PEF and OH, 85–87% juice extraction, indication of electropermeabilisation and thermal softening of the sugar beet tissue	(Praporscic et al., 2005)
Pea puree(2)	20-50 V/cm, 100 °C	Faster peroxidase inactivation than with conventional heating, better colour retention	(Icier et al., 2006)
Red beans as a ready-to-eat meal in tomato sauce(3)	250 V, 20 cm electrode spacing, 30 A, 50 Hz, 20–80 °C, continuous OH process	Electrical conductivity depends on temperature and particle concentration; both the overheating of the liquid phase and the heterogeneity of the suspension lead to instability of the electrical parameters	(Legrand et al., 2007)
Potato slices(1)	35 V/cm, up to 75 °C	Potato pieces, which underwent an OH pretreatment by using direct electrode contact without liquid, absorbed less oil during subsequent frying than those that underwent an OH pretreatment in a salt solution	(Salengke & Sastry, 2007a)
Carrot pieces(2)	50 Hz, 60–90 °C, 1–40 min.	Compared to the microwave and conventional heating, no significant differences in the peroxidase and pectin methylesterase activity, in the level of methoxylation and in the content of β-carotene	(Lemmens et al., 2009)
Artichoke, extraction of by-products(2)	25 and 40 V/cm, 85 °C, 5 min.	Ohmic blanching as a pretreatment before air drying, same peroxidase inactivation as when blanching with water at 100 °C in the same time, higher vitamin C content and overall content of phenolic compounds (polyphenols)	(Icier, 2010)
Spinach puree(1)	Heating at 30 to 60, 70, 80 or 90 °C, 4 different voltage gradients between 10 and 40 V/cm	Voltage gradients did not affect the chlorophyll content, carotene content and colour values, retention of colour properties was better than with conventional heating, time for heating from 30 to 70 °C at 20 V/cm was the same as in the case of conventional heating, twice as fast at 30 V/cm, more browning through OH in the same temperature range	(Yildiz et al., 2010)

Table 1 (*continued*)

Product and process objective $^{(1)}$ Heating/thawing $^{(2)}$ Blanching $^{(3)}$ Pasteurisation $^{(4)}$ Sterilisation $^{(5)}$ Cell disintegration	Conditions of ohmic heating	Effects	References
Red beets, carrots$^{(1)}$	220 and 380 V, 51 cm electrode spacing, 50 Hz; 1.5–19 min.	Become soft faster with OH, softer structure at the end	(Farahnaky, Azizi, & Gavahian, 2012)
Fruit juice/fruits			
Orange juice$^{(3)}$	18.2 V/cm; 65–90 °C	Same temperature profile as for conventional heating, same decomposition of vitamin C	(Lima, Heskitt, Burianek, Nokes, & Sastry, 1999)
Apple juice$^{(5)}$	20-70 V/cm, 4 Hz and 60 Hz	OH pretreatment for juice extraction, at 4 Hz there was improved juice extraction, higher electrical conductivity, faster heating and a shorter pretreatment time than at higher frequencies	(Lima & Sastry, 1999)
Apple juice, sour cherry juice, orange juice$^{(3)}$	20-60 V/cm	Electrical conductivity changes with the temperature of the juice, voltage gradients and concentration	(Icier & Ilicali, 2004, 2005a)
Orange juice$^{(3)}$	90, 120 and 150 °C; 0.68–1.13 s; 50 Hz; maximum voltage of 8 kV; electrode spacing of 20 cm	Reduction of the pectin esterase activity by 98% and of the vitamin C content by 15%, no difference in taste compared to fresh orange juice	(Leizerson & Shimoni, 2005a, 2005b)
Grape juice$^{(3)}$	20, 30 and 40 V/cm, 60–90 °C	Optimisation of polyphenol oxidase inactivation	(Icier et al., 2008)
Pomegranate juice$^{(3)}$	10-40 V/cm 90 °C for 3–12 min.	During the warming-up phase there was a change in rheological properties, colour and phenol content comparable to conventional heating; no other changes during the holding phase at 90 °C; conclusion: no electrical effects	(Yildiz et al., 2009)
Quince juice$^{(3)}$	10-40 V/cm, 0, 10, 15, 20 and 30 min, 65–75 °C	No difference in the rheological analyses, same pseudoplastic (shear-thinning) behaviour; conclusion from this: no electrochemical reactions during OH	(Bozkurt & Icier, 2009)
Pomegranate juice$^{(3)}$	30-55 V/cm, 60 Hz, 20–85 °C	The OH rate and the pH value decreased as the voltage gradient increased, electrical conductivity increased as the temperature increased	(Darvishi et al., 2013)
Strawberry products$^{(3)}$	25-100 V/cm, 100 °C	Field strength did not affect the electrical conductivity of the product except for strawberry pulp (field strength increased by 40%, electrical conductivity increased by 30%), conventional or ohmic preheating led to a different electrical conductivity, low electric field strengths did not lead to reduced decomposition of vitamin C, decomposition was similar during conventional heating and OH	(Castro et al., 2003)
Apricot puree, peach puree$^{(3)}$	20-70 V/cm, 50 Hz, 70°	Electrical conductivity was dependent on the temperature, ion concentration and pulp percentage	(Icier & Ilicali, 2005b)
Peach pieces$^{(3)}$	60 V/cm, 200 kHz, 65 °C	Reduction of electroporation above 100 kHz	(Shynkaryk et al., 2010)
Apricot pieces in syrup$^{(3)}$	90 °C, 113 s, continuous ohmic heater (30 kW)	Storage for one year at 25 °C, microbiologically stable, retention of the quality attributes	(Pataro, Donsì, & Ferrari, 2011)
Fruit dessert consisting of apple puree and peach pieces$^{(5)}$	OH: Pasteurisation at 105 °C before packaging in bags, conventional heating: in the container at 121 °C	Formation of 5-hydroxymethylfurfural (5-HMF), furfural (F), 3-hydroxy-2-pyrone and 2-furoic acid during conventional heating and OH was comparable, 5-HMF and F formation was dependent on the intensity and duration of the heating	(Louarme & Billaud, 2012)
Pears$^{(3)}$	13 V/cm, 50/60 Hz, 100 V, combined with vacuum impregnation for conditional preservation	OH used after vacuum impregnation, permeability of the cells increased	(Moreno et al., 2011)
Strawberries$^{(1,5)}$	9.7–17 V/cm; 70–130 V; combined with vacuum impregnation for conditional preservation	Combination of vacuum impregnation and OH at 13 V/cm yielded the best dehydration of strawberries	(Moreno, Simpson, Baeza, et al., 2012; Moreno, Simpson, Pizarro, et al., 2012)
Acerola$^{(3)}$	120-200 V, electrode spacing not specified	Decomposition of vitamin C during OH treatment with a low voltage gradient comparable to conventional	(Mercali et al., 2012, 2013)

(*continued on next page*)

Table 1 (*continued*)

Product and process objective (1) Heating/thawing (2) Blanching (3) Pasteurisation (4) Sterilisation (5) Cell disintegration	Conditions of ohmic heating	Effects	References
		heating, indication of electrochemical reactions	
Blueberry pulp(3)	Up to 240 V, electrode spacing not specified, up to 90 °C	Decomposition of anthocyanins during OH treatment with a low voltage gradient was the same as or lower than during conventional heating, increased at higher voltage gradients, and was also higher with an increasing content of solid material during OH treatment	(Sarkis et al., 2013)
Meat/fish			
Sausage meat(1)	230 V; 50 Hz; 3.5–7 V/cm	Higher salt content required, higher fat content reduced the electrical conductivity compared to steam cooking: no difference in texture, less elasticity, different colour, no difference in taste, microscopically: Cell damage was stronger	(Shirsat, Brunton, Lyng, & McKenna, 2004; Shirsat, Brunton, Lyng, McKenna, et al., 2004; Shirsat, Lyng, Brunton, & Mckenna, 2004b)
Pork cuts(1)	5-7 V/cm	No difference in texture, slight difference in elasticity and colour determination, no difference in the sensory test	(Shirsat, Lyng, Brunton, & McKenna, 2004a)
Hamburger patties(1)	Constant 50 V and up to 13 A, electrode spacing not specified	In combination with conventional heating, no loss of various quality attributes, significantly shorter cooking time than when using only conventional heating	(Ozkan, Ho, & Farid, 2004)
Beef(1)	10, 20 and 30 V/cm, 25 °C	Ohmic thawing, fewer histological and structural changes than through conventional warming	(Icier, Izzetoglu, Bozkurt, & Ober, 2010)
Beef(1)	Up to 250 V, 50 Hz, 15 A, 9 cm electrode spacing	Brighter surface colour, no significant change in texture	(Zell, Lyng, Cronin, & Morgan, 2009; Zell et al., 2010a)
Turkey meat(1)	8.33 V/cm; 100 V a) Low temperature long time (LTLT) 72 °C 4 min, 80° 3 min. b) High temperature short time (HTST) 95 °C 5 min.	Heating was faster than with conventional heating, higher quality with LTLT, better flavour development with HTST	(Zell, Lyng, Cronin, & Morgan, 2010b)
Minced beef with varying fat content(1)	20, 30 and 40 V/cm, 50 Hz, 80 °C	Initial fat content and temperature, but not the voltage gradient, affected the electrical conductivity	(Bozkurt & Icier, 2010a)
Beef(1)	20, 30 and 40 V/cm	Heating was faster, samples were firmer, fat loss was similar	(Bozkurt & Icier, 2010b)
Surimi(1)	Higher than 13.3 V/cm; 55 °C; up to 5 min.	Reduced decomposition of myosin and actin, structure retained	(Yongsawatdigul, Park, & Kolbe, 1995; Yongsawatdigul, Park, Kolbe, et al., 1995)
Surimi(1)	6.7–16.7 V/cm; 90 °C; 40–180 s(1)	Higher water retention, better colour preservation, higher concentration of sulfanyl compounds	(Tadpitchayangkoon, Park, & Yongsawatdigul, 2012)
Miscellaneous items			
Solutions of wheat starch, potato starch and cereal starch(1)	20 V/cm, 60 Hz, up to 90 °C	Electrical conductivity rose with the temperature and sank with the level of gelatinization, conditioned by structural changes and the increase in bound water	(Wang & Sastry, 1997b)
Solutions made of wheat starch and mung bean starch(1)	100 V; 3.5 cm electrode spacing; 50 Hz; up to 90 °C	Conductivity sank, presumably due to reduced motion of charged particles due to the swelling of the starch granules	(Li, Li, Li, & Tatsumi, 2004)
Rice bran(1,5)	100 V/cm, 1–60 Hz	Non-thermal effects on the lipase activity through OH treatment, yield of lipids up to 98%, reduction of the frequency leads to higher yield of oils, indication of electroporation	(Lakkakula, Lima, & Walker, 2004)
Milk(3)	50 Hz-10 kHz	Surface heat less than with conventional heating, the higher the frequency, the lower the corrosion and fouling	(Bansal & Chen, 2006)
Milk(3)	2083-3030 A/m^2, 65–75 °C	Electrodes were particularly important, no corrosion with graphite and stainless steel electrodes	(Stancl & Zitny, 2010)
Whey solution(3)	20-40 V/cm, 30–80 °C	Electrical conductivity was dependent on temperature and concentration	(Icier, 2009)

Table 1 (*continued*)

Product and process objective (1) Heating/thawing (2) Blanching (3) Pasteurisation (4) Sterilisation (5) Cell disintegration	Conditions of ohmic heating	Effects	References
		of the solution, less sensitive to temperature and temperature changes	
Liquid baby food(4)	No information	Compared to conventional heating, no difference with respect to soluble proteins, FAST index and other markers such as furosine, carboxymethyllysine and colour	(Roux et al., 2011)
Liquid baby food(4)	No information	No difference compared to conventional heating: Lower content of soluble proteins, furosine and carboxymethyllysine, as well as of fluorescent Maillard reaction products, vitamin C decomposition and browning	(Courel et al., 2011)
Vegetable puree with and without portions of chicken meat (baby food)	No information	There was 3–7 times less furan with OH than after autoclaving in the packaging; in the case of OH, with a rising Fo value there was no rise in furan; when sugar and vitamin C were added, there was a rise in the furfural, hydroxymethylfurfural and furan content, but in the case of OH it was lower; both methods led to a complete decomposition of the natural vitamin C content (very low due to the recipe); in the case of OH, there was a higher retention of carotenoids and polyphenols	(Prometheus, 2014)
Liquid whole egg(1)	20 V/cm 20–60 °C	Flow properties are the same, no significant difference in the apparent viscosity, no significant difference in the activation energy and the apparent viscosity in the various rheological models, but there were differences in the activation energy in the case of OH	(Bozkurt & Icier, 2012)
Egg albumin solution(1) Fresh egg white	10 V/cm, 50 Hz-10 kHz	Albumin solution: Transition to a gel at 75 °C, at this temperature the heating speed increased independently of the frequency, no gel formation at concentrations of albumin less than 2 w/v% fresh egg white: no increase in the heating speed up to 90 °C; indicates that gelatinous components of the egg white prevented heat transfer	(Imai et al., 1998; Imai et al., 1996)
Thyme oils through water distillation(1)	220 V, electrode spacing not specified, 50 Hz, 4 h as with conventional water distillation	Energy savings based on shorter extraction times	(Gavahian, Farahnaky, Javidnia, & Majzoobi, 2012)
Enzymes from apple juice, cloudberry jam, vegetable puree made of carrots, broccoli and potatoes, milk(2,3)	50 Hz, up to 70 °C	Analysis of alkaline phosphatase, pectin methyl esterase and peroxidase: The same inactivation mechanisms, the kinetic parameters of the enzymes were differently affected, indication that the tertiary structure of the enzymes was not altered by the electric field, but that the environment of the enzyme molecules was altered by the rise in ion concentration and differing distribution of ions	(Jakob et al., 2010)

3.3. *Formation of process contaminants*

Compared to the established steam-injection method, the sterilisation of infant formula using continuous ohmic heating showed no differences in the content of soluble proteins, furosine and carboxymethyllysine as well as in the content of fluorescent Maillard reaction products (Courel et al., 2011). The EU research project “Prometheus” analyzed the formation of furan in pureed baby food after sterilisation by means of ohmic heating in comparison with conventional autoclave technology (Prometheus, 2014). Products, which were sterilised using ohmic heating, contained 3 to 7 times less furan than those which were heated in the packaging in autoclaves. However, the volatility of furan and the effect of the packaging on the loss of furan were not taken into account. A dependency of the furan content on the Fo value was only observed in the case of the autoclaved samples.

Table 1 provides an overview of the foods subjected to ohmic heating and summarizes the process parameters which were used and the effects which were observed.

The wide variety of investigated foods processed using ohmic heating and the description of the process parameters used as well as the process effects achieved illustrate the wide range of applications and the complex interactions between process and product matrix. At the same time, wide ranges of parameters within the studies but also between different studies and the lack of systematic experiments with precise specification of the process conditions limit the possibility of comparing and validating the results obtained with different techniques.

4. Inactivation of microorganisms through ohmic heating

As with conventional heating methods, in the case of ohmic heating, microorganisms in food are killed off by raising the temperature.

The inactivation of microorganisms through ohmic heating compared to conventional heating is shown in Table 2. It was attributed primarily to thermal effects. Experiments with the yeast *Zygosaccharomyces bailii* showed no differences between ohmic and conventional heating regarding their inactivation, which suggests that the effects are purely thermal (Palaniappan, Sastry, & Richter, 1992). Experiments with the gram-negative bacterium *Escherichia coli* under special conditions (Palaniappan et al., 1992) as well as with spores of the Gram-positive bacteria *Bacillus subtilis* (Cho, Yousef, & Sastry, 1999) and *Bacillus licheniformis* (Pereira, Martins, Mateus, Teixeira, & Vicente, 2007) showed that it is possible to achieve a stronger inactivation through ohmic heating compared to conventional heating under the same temperature conditions. Under the chosen conditions of the experiment, the observed effects could not be further differentiated. A comparison of the temperature-time profiles of both heating methods based on the available data was not possible.

In addition to the improved inactivation through ohmic heating, experiments with *Alicyclobacillus acidoterrestris* spores found a temperature-independent correlation between the voltage used and the achieved degree of inactivation (Baysal & Icier, 2010). A similar dependency on parameters of the electric field were shown for the electric field strength (Lee, Sagong, Ryu, & Kang, 2012; Sagong, Park, Choi, Ryu, & Kang, 2011) and for the frequency (Lee, Ryu, & Kang, 2013) during ohmic heating.

In experiments with *Escherichia coli* O157:H7 and *Salmonella typhimurium*, both Gram-negative bacteria, and *Listeria monocytogenes*, a Gram-positive bacterium, the inactivation through

Table 2
Studies on the inactivation of microorganisms via ohmic heating and comparison with the degree of inactivation reached under conventional heating conditions (OH – Ohmic Heating; D and z values – see glossary).

Species	Matrix	Conditions of conventional heating	Conditions of ohmic heating	Effects	References
Zygosaccharo-myces bailii	Phosphate buffer solution	Heating through circulating water in the jacket of the OH chamber	No information	No difference	(Palaniappan et al., 1992)
Escherichia coli	Phosphate buffer solution		Electrical pretreatment	Higher killing rate	
Bacillus subtilis spores	0.1% NaCl solution, nutrient solution	Heating through circulating water in the jacket of the OH chamber	60 Hz; 88.0; 92.3; 95.5 and 99.1 °C; up to 35 min.	Survival rate lowered, D values raised, inactivation by a maximum of 4 log units	(Cho et al., 1999)
Alicyclobacillus acidoterrestris spores	Orange juice	No access to data	30 V/cm, 70, 80, and 90 °C, up to 30 min.	Faster inactivation, inactivation by 5 log units, at 70 °C depending on applied voltage	(Baysal & Icier, 2010)
Escherichia coli	Goat milk	Heating of aliquots of the bacteria solution or spore solution used for inoculation in Eppendorf tubes	20 to 54 V/cm, 55–65 °C, up to 10 min.	D values and z values lower	(Pereira et al., 2007)
Bacillus licheniformis spores	Cloudberry jam		20-54 V/cm 70 –80 °C, up to 50 min.	D values lower, no significant difference with z values	
Escherichia coli, Salmonella typhimurium, Listeria monocytogenes	Peptone water (pH 7.2), apple juice (pH 3.5)	Container in water bath with constant temperature	30 and 60 V/cm, 55 and 60 °C, 10 and 30 s.	Sronger inactivation compared to conventional heating, more pronounced at a low pH value	(I. K. Park & Kang, 2013)
Escherichia coli, Salmonella typhimurium, Listeria monocytogenes	Orange juice, tomato juice	Open container in oil bath with same temperature profile as for OH, stirring by hand	10-20 V/cm, 2 –9 min.	Inactivation by 5 log units, stronger inactivation in tomato juice than in orange juice, less inactivation of *E. coli* compared to *S. typhimurium* and *L. monocytogenes*	(Lee et al., 2012; Sagong et al., 2011)
Escherichia coli, Salmonella enterica	Salsa (chunky tomato-based, with onions, chilli, vinegar, pasteurised, overall pH value 4.16)	No comparison to conventional heating	25-40 V/cm, 1 –3 min.	With 25 V/cm and 30 s inactivation by 5 log units for *E. coli*	(Lee et al., 2013)
Bacillus amyloliquefaciens and *Geobacillus stearothermophilus* spores	0.1% NaCl solution, green pea puree, carrot puree, tomato juice	No comparison to conventional heating	Pressurised: 50 V/cm, 105 °C, 10–30 min, 600 MPa	In tomato juice inactivation by 3.1–4.8 log units after 10 min, in 0.1% NaCl solution by 4.6–5.6 log units after 30 min, pH value-dependent	(S. H. Park et al., 2013)
Saccharomyces cerevisiae	Phosphate buffer solution	Same temperature profile	10-20 V/cm	Faster release of cytoplasmic proteins than with conventional heating	(Yoon, Lee, Kim, & Lee, 2002)

ohmic heating was investigated at sublethal temperatures (see Table 2). Particularly in the case of acidic matrices, inactivation was traced back to an increase in cell permeability, but this effect was not further differentiated (I. K. Park & Kang, 2013). The effect of the food matrix, particularly the pH value, on inactivation through ohmic heating was also shown, for example, in the case of *Bacillus* and *Geobacillus* endospores (S. H. Park, Balasubramaniam, Sastry, & Lee, 2013).

Accelerated inactivation of spores was reported for *Geobacillus stearothermophilus* spores in the case of ohmic heating (Somavat, Mohamed, Chung, Yousef, & Sastry, 2012) and *Bacillus coagulans* spores (Somavat, Mohamed, & Sastry, 2013) in a model system using capillaries. The underlying mechanisms have yet to be elucidated.

The spectrum and variability of the data and process parameters summarised in Table 2 illustrate the limits of their validity and comparability. The individual studies used very different system designs, process parameters and test protocols, including the methods for acquiring data. In addition, there are only a few systematic investigations which deal with product and process factors and their impact on the inactivation process.

5. Aspects of allergenicity

Allergenicity describes the property of a substance to first sensitise the immune system against the compound (sensitising potential) and, upon repeated contact, to trigger an allergic reaction (allergy-elicitating potential). As regards foods as allergens, IgE-mediated immediate-type reactions are the primary focus of clinical and scientific studies (EAACI., 2014). Proteins contained in foods are primarily analyzed and evaluated here because they are the most important elicitors of food-mediated allergic reactions. In a recent review article of the European Food Safety Authority (EFSA) (EFSA., 2013) about the impact of processing on the allergenicity of foods, the double-blind, placebo-controlled oral food challenge (DBPCFC) of allergic study subjects was defined as the method of choice to evaluate allergenicity (allergy triggering). However, human challenge studies are very rarely conducted due to ethical concerns and economic constraints, so that human data regarding the impact of food processing on the potential to elicit an allergic reaction is available in a limited number of cases (EFSA., 2013; Thomas et al., 2007). Furthermore, human studies to analyze the impact of processing on the sensitising potential of allergens are forbidden for ethical reasons. Therefore, most data on the allergy eliciting or sensitising potential of compounds originate from animal studies (Dearman & Kimber, 2009; Thomas et al., 2007), *in vitro* models (Vogel, Holzhauser, & Vieths, 2006) or, even more frequently, from binding studies with human IgE antibodies. However, the further away the experimental models are from humans, the less predictive they are when wanting to evaluate allergenicity.

In the case of ohmic heating of food, thermal and electrical effects, which could have an impact on allergenicity, do occur. The potential allergenicity of a food treated with ohmic heating could be altered when compared to a food undergoing conventional, thermal processes. Therefore, food that has undergone ohmic heating can not automatically be compared to thermally treated food, and would have to be re-evaluated accordingly. Up to now, no studies regarding the direct impact of ohmic heating on the allergenicity (allergy sensitising or eliciting potential) of foods have been published. Since differences in the degree of decomposition and retention of some substances have been found between ohmic heating and conventional heating (see Chapter 3: e.g. references (Leizerson & Shimoni, 2005b; Yildiz et al., 2010; Yongsawatdigul, Park, Kolbe, et al., 1995)), it is conceivable that neoallergenic structures are formed or endogenously present allergens decompose differently. For example, myosin is described as an allergen in shellfish and could be less decomposed through ohmic heating when compared to conventional heating (Yongsawatdigul, Park, Kolbe, et al., 1995).

Thermal effects could result in a decrease or increase of allergenicity. Changes in allergenicity influenced by Maillard reactions must also be taken into account as a secondary effect of thermal reactionsand could result in the formation of neoallergenic structures. Electrically caused effects could lead to an increased release of allergens. The potential changes, which have been outlined here, are explained in greater detail in the following chapter.

5.1. *Heat-related changes*

It can be assumed that, in general, the same or similar heat-related effects occur during both conventional and ohmic heating; these effects then have a similar or different impact on the allergenicity of food depending on the magnitude of the total thermal load. A review by EFSA on the impact of processing on the allergenicity (eliciting potential) of food summarised and discussed various clinical trials with celery, cow's milk, hen's egg, tree nuts, wheat and peanuts (EFSA., 2013). The authors concluded that, on the one hand, heating reduces the allergenicity of eggs, milk, celery and hazelnuts. On the other hand, the reduction varied depending on the individual subjects and the studied food. Similar results were found in another review article on the impact of thermal processing on the allergenicity of tree nuts (Masthoff et al., 2013). Accordingly, the potential allergenicity of so-called pathogenesis-related proteins of the PR-10 family in hazelnuts and almonds, which can trigger pollen-related food allergies, decreased when evaluated in *in vitro* tests. In contrast, the potential allergenicity of non-specific lipid transfer proteins and storage proteins from various different nuts remained unaffected. The examples illustrate the differences in the thermal impact on the allergenicity depending on the allergenic food, the sensitisation profile of the individuals affected and the structure of the various allergenic proteins.

Regarding the heating process, it has been suggested that thermally accelerated, non-enzymatic browning reactions between decreasing sugars and proteins (the so-called Maillard reaction) could contribute to the formation of neoallergenic structures in pecans (Malanin, Lundberg, & Johansson, 1995), soybean hulls (Codina, Oehling, & Lockey, 1998) and peanuts (Maleki, Chung, Champagne, & Raufman, 2000). In addition, there are indications that certain Maillard reaction products also possess immunomodulatory properties (Toda, Heilmann, Ilchmann, & Vieths, 2014).

As a gentle process when compared to conventional heating processes, ohmic heating is associated with shortened heating times, which result in a lower total thermal food load (lower C value with the same Fo value). Presumably, this lower total thermal load would result, on the one hand, in a lower reduction of the allergenicity of existing allergenic structures and, on the other hand, in a reduced formation of neoallergenic structures if compared to conventional heating.

5.2. *Electrically caused changes*

Potential electroporation of the cell membranes could lead to the release of larger quantities of allergens or the formation of stress-inducible allergens. As mentioned in a previous statement of the SKLM on the plasma treatment of food with plant-based components, the defence system of the plant could trigger the formation of stress-inducible secondary metabolites and pathogenesis-related proteins, some of which possess a high allergenic potential (Schluter et al., 2013). The process control for ohmic heating should be designed in such a way that the neoformation of such substances is inhibited as far as possible.

6. Aspects of process control

The required **process control** can be achieved by determining a critical control parameter, preferably the **temperature measurement**. Here, it is necessary to take into account the potential formation of **hot or cold spots** and, in addition to determining a mean temperature, it is absolutely important to use spatially distributed measuring sensors. In addition to the technical design of the system, inhomogeneities in **conductivity** in particular are another cause of non-uniform temperature distribution in the product. Therefore, the conductivity of the product is of great relevance with respect to the **process homogeneity** during the process design phase. The conductivity of the individual components can be adapted using a corresponding product recipe.

The established concepts of thermal preservation can be used to **design and monitor the process**. This includes determining the **inactivation kinetics by using the D and z values** of unwanted, pathogenic microorganisms. This also applies to the inactivation of enzymes. To design the process while **ensuring the microbiological safety** of the product, an essential condition is to locate the cold spots through knowledge of the material properties and process properties. Techniques for verifying the inactivation of microorganisms and for modelling and simulating purposes can be used to validate the process (Kamonpatana et al., 2013b, 2013a;; Tumpanuvatr & Jittanit, 2011; Zareifard et al., 2003; Zhu, Zareifard, Chen, Marcotte, & Grabowski, 2010).

To enable a comparison of the **inactivation of microorganisms** or their D and z values by ohmic heating versus conventional thermal processes, an adequate **control of the temperature** and pH value as well as an **identical temperature profile** for both heating methods is absolutely necessary.

When wanting to **verify the non-thermal effects** of ohmic heating on microorganisms and food, it is difficult to find a systematic experimental setup which enables comparison of the results, because the fast, volumetric heating during ohmic heating cannot be adequately transferred to conventional heating. To make a comparison of the processes, the **temperature-time profiles** and the Fo and C values (see the glossary) determined from this profile must be specified to clearly name the differences and to identify non-thermal effects of ohmic heating.

In order to distinguish between thermal effects and **electric effects (electroporation)** that may occur, it is necessary to take into account the relevant electric field strength values which are critical for the corresponding plant cells or microorganisms; if these values are exceeded, the probability that non-thermal effects occur will increase. In this case, electrical effects must be taken into account because, in addition to the aspects of ohmic heating as a thermal process to be considered, these effects may be relevant for the process design and for a safety evaluation based on this design. Ohmic heating in a **capillary model system** enables control of the temperature-time profile and, therefore, the comparison with conventional heating and the option of differentiating between thermal and non-thermal effects (Somavat, Mohamed, et al., 2012).

In liquid, low-viscosity food, the **direct steam injection or infusion** processes are usually able to achieve heating rates similar to those reached with ohmic heating. Therefore, regarding the temperature-time profiles these processes are well suited for a comparison with ohmic heating. In contrast, conventional processes to sterilise high-viscosity products containing particles, such as autoclaving have significantly lower heating rates due to the packaging geometry, product properties and heat transfer limitations, which makes them suitable for a comparison only under certain conditions.

When specifying the treatment conditions and test results, it is necessary to use a protocol which is as standardised as possible to enable comparison of the **process conditions for ohmic heating**. This includes specification of system parameters (electrical power, field strength, alternating current characteristics, geometry and number of electrodes, flow speed and holding time), product parameters (phases, particle content, conductivity, density, viscosity and heat capacity) and the determined minimum and maximum temperature of the product. The treatment chamber should be optimised through **simulations** of the flow profile, electric field distribution and energy input, while taking into account the viscosity and electrical conductivity of the product.

Each process combination of ohmic heating with other processes requires that the corresponding process and product parameters relevant to the heating behaviour and temperature distribution are also taken into account; because of this, a reevaluation of the actual ohmic heating process based on the aforementioned aspects is also needed.

7. Research needs

The following aspects related to the use of ohmic heating for manufacturing safe food need to be investigated:

- Ensuring uniformity of the heating
- Inactivation kinetics of relevant microorganisms (indicator microorganisms)
- Differentiation of thermal and non-thermal effects
- Influence of physicochemical product properties
- Studies on process-induced chemical changes
- Studies on its impact on the allergenic potential of food
- Design of process and system models
- Development of simulation models
- Evaluation of combined methods
- Systematic studies taking into account the comparability

Inhomogeneities in temperature distribution were identified as a critical point with respect to the safety and quality of food. For this reason, **ensuring uniform heating** is particularly important. There is a need to develop product composition concepts adapted to the process. The suitability of the process for various product groups must be investigated. To reduce inhomogeneities in electrical conductivity, it is essential, among other aspects, to adapt relevant material characteristics of individual product fractions. It is necessary to develop methods for obtaining temperature-time profiles at various positions in the treatment cell, which in turn are able to detect cold and hot spots in the product and enable various processes to be compared.

The identification of cold spots is of crucial importance in ensuring **microbiological safety**. Furthermore, there is a need to investigate **inactivation kinetics** for individual fractions of a product. It is necessary to define limit ranges for the occurrence of non-thermal effects during microbial inactivation. Electrode reactions and electric field strengths that occur must be taken into account to identify the underlying mechanisms of inactivation. There is a need to distinguish between **thermal and non-thermal effects**. Here, it is necessary to investigate non-thermal effects during the inactivation of microorganisms by taking into account the occurrence of sublethal damage and the potential recovery of inactivated cells. Otherwise, there may be danger of underprocessing if the process is designed based on potential, non-thermal effects and using purely thermal requirements for the inactivation of microorganisms.

Comprehensive knowledge of **physicochemical properties of food** and food components is the basis for an adequate description of processes. It is also necessary to investigate the entire temperature range relevant to the process, particularly for temperatures above 100 °C, for which there are gaps in the data records. The impact of the product composition on the physicochemical properties of the product and their optimisation must also be studied.

In addition, **process-induced chemical changes** of the product, including changes in the allergenicity at the molecular level, must be investigated. Corresponding indicators must be developed to improve the data records. To prevent unwanted process effects, including electrode reactions that occur, it is necessary to define **process windows** and exclude certain ranges of the **process variables** (such as low frequencies). These process windows require suitable indicators as a basis for the development of validation concepts.

There are no data on the impact of ohmic heating on the **allergenic potential** of foods, so that there is a need for research in this case. It is necessary to investigate whether allergens form or are only insufficiently inactivated. Potential non-thermal effects on the formation or reduction of allergens must be investigated. It is also necessary to identify cold spots and underprocessing with respect to the heat-related reduction of allergens. Furthermore, shorter processing times during ohmic heating could mean that the heating effect does not last long enough. As with the inactivation of microorganisms, the temperature-time profiles have to be controlled.

The design of **process and system models** must be a primary objective. These models should define relevant influencing variables, such as the geometry and material of the treatment chamber, the composition of the product, including size and density of existing particles as well as the electrical conductivity of individual fractions.

It is necessary to develop and establish **simulation models for the evaluation** of the treatment chamber's geometry, the electric field distribution and flow conditions depending on the product properties; the purpose is to achieve corresponding process optimisations prior to an experimental process validation. By doing so, it is necessary to check whether the incomplete data available for specific products can be replaced by generic approaches to describe product and process parameters. Therefore, the structured development of model systems requires additional systematic work that takes into account various product and process conditions as well as differentiation of the process effects. This also applies to the application of thermal-thermal **combination methods** such as ohmic heating combined with radio frequency heating.

Data on microbiological safety, process-induced chemical changes and the impact on the allergenicity of foods are scarce. The gaps in data records are in part due to the insufficient comparability of the existing studies. **Systematic studies ensuring the comparability** of product and process parameters as well as system design should serve as the basis for a comparison of processes and for the further science-based development of ohmic heating.

References

Anderson, A. K., & Finkelstein, R. (1919). A study of the electro-pure process of treating milk. *Journal of Dairy Science, 2*, 374–406.

Angersbach, A., Heinz, V., & Knorr, D. (2000). Effects of pulsed electric fields on cell membranes in real food systems. *Innovative Food Science and Emerging Technologies, 1*, 135–149.

Ayadi, M. A., Benezech, T., Chopard, F., & Berthou, M. (2008). Thermal performance of a flat ohmic cell under non-fouling and whey protein fouling conditions. *Lwt-Food Science and Technology, 41*, 1073–1081.

Bansal, B., & Chen, X. D. (2006). Effect of temperature and power frequency on milk fouling in an ohmic heater. *Food and Bioproducts Processing, 84*, 286–291.

Baysal, A. H., & Icier, F. (2010). Inactivation kinetics of Alicyclobacillus acidoterrestris spores in orange juice by ohmic heating: Effects of voltage gradient and temperature on inactivation. *Journal of Food Protection, 73*, 299–304.

Bozkurt, H., & Icier, F. (2009). Rheological characteristics of quince nectar during ohmic heating. *International Journal of Food Properties, 12*, 844–859.

Bozkurt, H., & Icier, F. (2010a). Electrical conductivity changes of minced beef-fat blends during ohmic cooking. *Journal of Food Engineering, 96*, 86–92.

Bozkurt, H., & Icier, F. (2010b). Ohmic cooking of ground beef: Effects on quality. *Journal of Food Engineering, 96*, 481–490.

Bozkurt, H., & Icier, F. (2012). The change of apparent viscosity of liquid whole egg during ohmic and conventional heating. *Journal of Food Process Engineering, 35*, 120–133.

Castro, I., Teixeira, J. A., Salengke, S., Sastry, S. K., & Vicente, A. A. (2003). The influence of field strength, sugar and solid content on electrical conductivity of strawberry products. *Journal of Food Process Engineering, 26*, 17–29.

Cho, H. Y., Yousef, A. E., & Sastry, S. K. (1999). Kinetics of inactivation of Bacillus subtilis spores by continuous or intermittent ohmic and conventional heating. *Biotechnology and bioengineering, 62*, 368–372.

Codina, R., Oehling, A. G., Jr., & Lockey, R. F. (1998). Neoallergens in heated soybean hull. *International archives of allergy and immunology, 117*, 120–125.

Courel, M., Roux, S., Pain, J.-P., Birlouez-Aragon, I., Municino, F., & Massa, M. (2011). Comparison of continuous ohmic heating and steam injection for the sterilization of infant formula. In *IDF world dairs summit. Parma, Italy*.

Darvishi, H., Khoshtaghaza, M. H., & Najafi, G. (2013). Ohmic heating of pomegranate juice: Electrical conductivity and pH change. *Journal of the Saudi Society of Agricultural Sciences, 12*, 101–108.

Dearman, R. J., & Kimber, I. (2009). Animal models of protein allergenicity: Potential benefits, pitfalls and challenges. *Clinical & Experimental Allergy, 39*, 458–468.

Demirdoven, A., & Baysal, T. (2014). Optimization of ohmic heating applications for pectin methylesterase inactivation in orange juice. *Journal of food science and technology, 51*, 1817–1826.

Dimitrov, D. S. (1984). Electric field-induced breakdown of lipid bilayers and cell-membranes – A thin viscoelastic film model. *Journal of Membrane Biology, 78*, 53–60.

EAACI. (2014). European academy of allergy and clinical immunology. In *Food allergy and anaphylaxis guidelines* (p. 276). Zurich: A. Muraro and G. Roberts.

EFSA. (2013). European food safety authority. In *Literature searches and reviews related to the prevalence of food allergy in Europe* (Vol. EN-506, p. 343). University of Portsmouth. EFSA supporting publication.

Eliot-Godereaux, S. C., Zuber, F., & Goullieux, A. (2001). Processing and stabilisation of cauliflower by ohmic heating technology. *Innovative Food Science & Emerging Technologies, 2*, 279–287.

Eliot, S. C., & Goullieux, A. (2000). Application of the firming effect of low-temperature long-time pre-cooking to ohmic heating of potatoes. *Sciences Des Aliments, 20*, 265–280.

Eliot, S. C., Goullieux, A., & Pain, J. P. (1999a). Combined effects of blanching pre-treatments and ohmic heating on the texture of potato cubes. *Sciences Des Aliments, 19*, 111–117.

Eliot, S. C., Goullieux, A., & Pain, J. P. (1999b). Processing of cauliflower by ohmic heating: Influence of precooking on firmness. *Journal of the Science of Food and Agriculture, 79*, 1406–1412.

Farahnaky, A., Azizi, R., & Gavahian, M. (2012). Accelerated texture softening of some root vegetables by Ohmic heating. *Journal of Food Engineering, 113*, 275–280.

FDA. (2011). In *Kinetics of microbial inactivation for alternative food processing technologies – Ohmic and inductive heating*. D. o. H. a. h. Services.

Fellows, P. J. (2000). Processing using electric fields, high hydrostatic pressure, light or ultrasound. In *Food processing technology Principles and Practices*. CRC Press.

Gavahian, M., Farahnaky, A., Javidnia, K., & Majzoobi, M. (2012). Comparison of ohmic-assisted hydrodistillation with traditional hydrodistillation for the extraction of essential oils from Thymus vulgaris L. *Innovative Food Science & Emerging Technologies, 14*, 85–91.

Gonzalez, M. E., & Barrett, D. M. (2010). Thermal, high pressure, and electric field processing effects on plant cell membrane integrity and relevance to fruit and vegetable quality. *Journal of Food Science, 75*, R121–R130.

Goullieux, A., & Pain, J. P. (2005). In *Ohmic heating*. London: Elsevier.

Herting, G., Wallinder, I. O., & Leygraf, C. (2008). Corrosion-induced release of chromium and iron from ferritic stainless steel grade AISI 430 in simulated food contact. *Journal of Food Engineering, 87*, 291–300.

Icier, F. (2009). Influence of ohmic heating on rheological and electrical properties of reconstituted whey solutions. *Food and Bioproducts Processing, 87*, 308–316.

Icier, F. (2010). Ohmic blanching effects on drying of vegetable byproduct. *Journal of Food Process Engineering, 33*, 661–683.

Icier, F., & Ilicali, C. (2004). Electrical conductivity of apple and sourcherry juice concentrates during ohmic beating. *Journal of Food Process Engineering, 27*, 159–180.

Icier, F., & Ilicali, C. (2005a). The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. *European Food Research and Technology, 220*, 406–414.

Icier, F., & Ilicali, C. (2005b). Temperature dependent electrical conductivities of fruit purees during ohmic heating. *Food Research International, 38*, 1135–1142.

Icier, F., Izzetoglu, G. T., Bozkurt, H., & Ober, A. (2010). Effects of ohmic thawing on histological and textural properties of beef cuts. *Journal of Food Engineering, 99*, 360–365.

Icier, F., Yildiz, H., & Baysal, T. (2006). Peroxidase inactivation and colour changes during ohmic blanching of pea puree. *Journal of Food Engineering, 74*, 424–429.

Icier, F., Yildiz, H., & Baysal, T. (2008). Polyphenoloxidase deactivation kinetics during ohmic heating of grape juice. *Journal of Food Engineering, 85*, 410–417.

Imai, T., Uemura, K., Ishida, N., Yoshizaki, S., & Noguchi, A. (1995). Ohmic heating of Japanese white radish Rhaphanus sativus L. *International Journal of Food Science and Technology, 30*, 461–472.

Imai, T., Uemura, K., & Noguchi, A. (1998). Heating rate of egg albumin solution and its change during ohmic heating. *Process-Induced Chemical Changes in Food, 434*, 101–108.

Imai, T., Uemura, K., Yoshizaki, S., & Noguchi, A. (1996). Changes in heating rate of egg albumin solution during ohmic heating. *Journal of the Japanese Society for Food Science and Technology-Nippon Shokuhin Kagaku Kogaku Kaishi, 43*, 1249–1255.

Ito, R., Fukuoka, M., & Hamada-Sato, N. (2014). Innovative food processing technology using ohmic heating and aseptic packaging for meat. *Meat Sci, 96*, 675–681.

Jakob, A., Bryjak, J., Wojtowicz, H., Illeova, V., Annus, J., & Polakovic, M. (2010). Inactivation kinetics of food enzymes during ohmic heating. *Food Chemistry, 123*, 369–376.

Jones, F. (1897). In *Apparatus for electrically treating liquids*. USA: D. W. a. T. Office.

Jun, S., & Sastry, S. (2005). Modeling and optimization of ohmic heating of foods inside a flexible package. *Journal of Food Process Engineering, 28*, 417–436.

Kamonpatana, P., Mohamed, H. M. H., Shynkaryk, M., Heskitt, B., Yousef, A. E., & Sastry, S. K. (2013a). Mathematical modeling and microbiological verification of ohmic heating of a multicomponent mixture of particles in a continuous flow ohmic heater system with electric field parallel to flow. *Journal of Food Science, 78*, E1721–E1734.

Kamonpatana, P., Mohamed, H. M. H., Shynkaryk, M., Heskitt, B., Yousef, A. E., & Sastry, S. K. (2013b). Mathematical modeling and microbiological verification of ohmic heating of a solid-liquid mixture in a continuous flow ohmic heater system with electric field perpendicular to flow. *Journal of Food Engineering, 118*, 312–325.

Kessler, H. G. (1996). *Lebensmittel- und Bioverfahrenstechnik – Molkereitechnologie*. München: Verlag A. Kessler.

Knirsch, M. C., dos Santos, C. A., Vicente, A. A. M. D. S., & Pennaa, T. C. V. (2010). Ohmic heating – A review. *Trends in Food Science & Technology, 21*, 436–441.

Knorr, D., Engel, K. H., Vogel, R., Kochte-Clemens, B., Eisenbrand, G., & Senate Commission on Food Safety of the German Research, F. (2008). Statement on the treatment of food using a pulsed electric field. Opinion of the senate commission on food safety (SKLM) of the german research foundation (DFG). *Mol Nutr Food Res, 52*, 1539–1542.

Kohn, S. (1933). *Electric Frankfurter Grill*. US Patent 1974715 A.

Kulshrestha, S., & Sastry, S. (2003). Frequency and voltage effects on enhanced diffusion during moderate electric field (MEF) treatment. *Innovative Food Science & Emerging Technologies, 4*, 189–194.

Kulshrestha, S. A., & Sastry, S. K. (2010). Changes in permeability of moderate electric field (MEF) treated vegetable tissue over time. *Innovative Food Science & Emerging Technologies, 11*, 78–83.

Lakkakula, N. R., Lima, M., & Walker, T. (2004). Rice bran stabilization and rice bran oil extraction using ohmic heating. *Bioresource Technology, 92*, 157–161.

Lebovka, N. I., Bazhal, M. I., & Vorobiev, E. (2000). Simulation and experimental investigation of food material breakage using pulsed electric field treatment. *Journal of Food Engineering, 44*, 213–223.

Lebovka, N. I., Praporscic, I., Ghnimi, S., & Vorobiev, E. (2005). Does electroporation occur during the ohmic heating of food? *Journal of Food Science, 70*, E308–E311.

Lee, S. Y., Ryu, S., & Kang, D. H. (2013). Effect of frequency and waveform on inactivation of Escherichia coli O157:H7 and Salmonella enterica Serovar Typhimurium in salsa by ohmic heating. *Applied and environmental microbiology, 79*, 10–17.

Lee, S. Y., Sagong, H. G., Ryu, S., & Kang, D. H. (2012). Effect of continuous ohmic heating to inactivate Escherichia coli O157:H7, Salmonella Typhimurium and Listeria monocytogenes in orange juice and tomato juice. *Journal of applied microbiology, 112*, 723–731.

Legrand, A., Leuliet, J. C., Duquesne, S., Kesteloot, R., Winterton, P., & Fillaudeau, L. (2007). Physical, mechanical, thermal and electrical properties of cooked red bean (Phaseolus vulgaris L.) for continuous ohmic heating process. *Journal of Food Engineering, 81*, 447–458.

Leizerson, S., & Shimoni, E. (2005a). Effect of ultrahigh-temperature continuous ohmic heating treatment on fresh orange juice. *Journal of Agricultural and Food Chemistry, 53*, 3519–3524.

Leizerson, S., & Shimoni, E. (2005b). Stability and sensory shelf life of orange juice pasteurized by continuous ohmic heating. *Journal of Agricultural and Food Chemistry, 53*, 4012–4018.

Lemmens, L., Tiback, E., Svelander, C., Smout, C., Ahrne, L., Langton, M., et al. (2009). Thermal pretreatments of carrot pieces using different heating techniques: Effect on quality related aspects. *Innovative Food Science & Emerging Technologies, 10*, 522–529.

Li, F. D., Li, L. T., Li, Z. G., & Tatsumi, E. (2004). Determination of starch gelatinization temperature by ohmic heating. *Journal of Food Engineering, 62*, 113–120.

Lima, M., Heskitt, B. F., Burianek, L. L., Nokes, S. E., & Sastry, S. K. (1999). Ascorbic acid degradation kinetics during conventional and ohmic heating. *Journal of Food Processing and Preservation, 23*, 421–434.

Lima, M., & Sastry, S. K. (1999). The effects of ohmic heating frequency on hot-air drying rate and juice yield. *Journal of Food Engineering, 41*, 115–119.

Louarme, L., & Billaud, C. (2012). Evaluation of ascorbic acid and sugar degradation products during fruit dessert processing under conventional or ohmic heating treatment. *Lwt-Food Science and Technology, 49*, 184–187.

Malanin, K., Lundberg, M., & Johansson, S. G. (1995). Anaphylactic reaction caused by neoallergens in heated pecan nut. *Allergy, 50*, 988–991.

Maleki, S. J., Chung, S. Y., Champagne, E. T., & Raufman, J. P. (2000). The effects of roasting on the allergenic properties of peanut proteins. *J Allergy Clin Immunol, 106*, 763–768.

Marcotte, M., Ramaswamy, H. S., & Sastry, S. (2014). *Ohmic heating in food processing (Electro-Technologies for food processing)*.

Marra, F., Zell, M., Lyng, J. G., Morgan, D. J., & Cronin, D. A. (2009). Analysis of heat transfer during ohmic processing of a solid food. *Journal of Food Engineering, 91*, 56–63.

Masthoff, L. J., Hoff, R., Verhoeckx, K. C., van Os-Medendorp, H., Michelsen-Huisman, A., Baumert, J. L., et al. (2013). A systematic review of the effect of thermal processing on the allergenicity of tree nuts. *Allergy, 68*, 983–993.

McConnell, S. V., & Oisson, R. P. (1938). *Wiener Vending Machine*. US Patent 2139690 A.

Mercali, G. D., Jaeschke, D. P., Tessaro, I. C., & Marczak, L. D. F. (2012). Study of vitamin C degradation in acerola pulp during ohmic and conventional heat treatment. *Lwt-Food Science and Technology, 47*, 91–95.

Mercali, G. D., Jaeschke, D. P., Tessaro, I. C., & Marczak, L. D. F. (2013). Degradation kinetics of anthocyanins in acerola pulp: Comparison between ohmic and conventional heat treatment. *Food Chemistry, 136*, 853–857.

Mizrahi, S. (1996). Leaching of soluble solids during blanching of vegetables by ohmic heating. *Journal of Food Engineering, 29*, 153–166.

Moreno, J., Simpson, R., Baeza, A., Morale, J., Munoz, C., Sastry, S., et al. (2012a). Effect of ohmic heating and vacuum impregnation on the osmodehydration kinetics and microstructure of strawberries (cv. Camarosa). *Lwt-Food Science and Technology, 45*, 148–154.

Moreno, J., Simpson, R., Pizarro, N., Parada, K., Pinilla, N., Reyes, J. E., et al. (2012b). Effect of ohmic heating and vacuum impregnation on the quality and microbial stability of osmotically dehydrated strawberries (cv. Camarosa). *Journal of Food Engineering, 110*, 310–316.

Moreno, J., Simpson, R., Sayas, M., Segura, I., Aldana, O., & Almonacid, S. (2011). Influence of ohmic heating and vacuum impregnation on the osmotic dehydration kinetics and microstructure of pears (cv. Packham's Triumph). *Journal of Food Engineering, 104*, 621–627.

Naveh, D., Kopelman, I. J., & Mizrahi, S. (1983). Electroconductive thawing by liquid contact. *Journal of Food Technology, 18*, 171–176.

Ozkan, N., Ho, I., & Farid, M. (2004). Combined ohmic and plate heating of hamburger patties: Quality of cooked patties. *Journal of Food Engineering, 63*, 141–145.

Palaniappan, S., Sastry, S. K., & Richter, E. R. (1992). Effects of electroconductive heat treatment and electrical pretreatment on thermal death kinetics of selected microorganisms. *Biotechnol Bioeng, 39*, 225–232.

Park, S. H., Balasubramaniam, V. M., Sastry, S. K., & Lee, J. Y. (2013). Pressure-ohmic-thermal sterilization: A feasible approach for the inactivation of Bacillus amyloliquefaciens and Geobacillus stearothermophilus spores. *Innovative Food Science & Emerging Technologies, 19*, 115–123.

Park, I. K., & Kang, D. H. (2013). Effect of electropermeabilization by ohmic heating for inactivation of E. coli O157:H7, Salmonella enterica serovar typhimurium and Listeria monocytogenes in buffered peptone water and apple juice. *Appl Environ Microbiol, 79*(23), 7122–7129.

Park, J. W., & Yongsawatdigul, J. (1998). Gelation properties of fish proteins under ohmic heating. *Abstracts of Papers of the American Chemical Society, 215*. U19–U19.

Park, J. W., Yongsawatdigul, J., & Kolbe, E. (1998). Proteolysis and gelation of fish proteins under ohmic heating. *Process-Induced Chemical Changes in Food, 434*, 25–34.

Pataro, G., Barca, G. M. J., Pereira, R. N., Vicente, A. A., Teixeira, J. A., & Ferrari, G. (2014). Quantification of metal release from stainless steel electrodes during conventional and pulsed ohmic heating. *Innovative Food Science & Emerging Technologies, 21*, 66–73.

Pataro, G., Donsi, G., & Ferrari, G. (2011). Aseptic processing of apricots in syrup by means of a continuous pilot scale ohmic unit. *Lwt-Food Science and Technology, 44*, 1546–1554.

Pereira, R., Martins, J., Mateus, C., Teixeira, J. A., & Vicente, A. A. (2007). Death kinetics of Escherichia coli in goat milk and Bacillus licheniformis in cloudberry jam treated by ohmic heating. *Chemical Papers, 61*, 121–126.

Pongviratchai, P., & Park, J. W. (2007). Electrical conductivity and physical properties of surimi-potato starch under ohmic heating. *Journal of Food Science, 72*, E503–E507.

Praporscic, I., Ghnimi, S., & Vorobiev, E. (2005). Enhancement of pressing of sugar beet cuts by combined ohmic heating and pulsed electric field treatment. *Journal of Food Processing and Preservation, 29*, 378–389.

Prometheus. (2014). *Process contaminants: Mitigation and elimination techniques for high-quality food and their evaluation using sensors and simulation*. Projekt Completion Report, EU FP7 project, Grant agreement number 265558 http://processing-contaminants-prometheus.com.

Roux, S., Courel, M., Birlouez-Aragon, I., Municino, F., Massa, M., & Pain, J. P. (2011). Comparison of continuous ohmic heating and steam injection for the sterilization of infant formula. In *Conference on novel technologies for sustainable dairy products. IDF world dairy summit, Parma Italy*.

Ruan, R., Ye, X., Chen, P., Doona, C. J., & Taub, I. (2001). *Ohmic heating*. Cambridge: Woodhead Publishing Limited.

Sagong, H. G., Park, S. H., Choi, Y. J., Ryu, S., & Kang, D. H. (2011). Inactivation of

Escherichia coli O157:H7, Salmonella Typhimurium, and Listeria monocytogenes in orange and tomato juice using ohmic heating. *Journal of Food Protection, 74*, 899–904.

Salengke, S., & Sastry, S. K. (2007a). Effects of ohmic pretreatment on oil uptake of potato slices during frying and subsequent cooling. *Journal of Food Process Engineering, 30*, 1–12.

Salengke, S., & Sastry, S. K. (2007b). Models for ohmic heating of solid-liquid mixtures under worst-case heating scenarios. *Journal of Food Engineering, 83*, 337–355.

Samaranayake, C. P., & Sastry, S. K. (2005). Electrode and pH effects on electrochemical reactions during ohmic heating. *Journal of Electroanalytical Chemistry, 577*, 125–135.

Samaranayake, C. P., Sastry, S. K., & Zhang, H. (2005). Pulsed ohmic heating – A novel technique for minimization of electrochemical reactions during processing. *Journal of Food Science, 70*, E460–E465.

Sarkis, J. R., Jaeschke, D. P., Tessaro, I. C., & Marczak, L. D. P. (2013). Effects of ohmic and conventional heating on anthocyanin degradation during the processing of blueberry pulp. *Lwt-Food Science and Technology, 51*, 79–85.

Schade, A. L. (1951). *Prevention of enzymatic discoloration of potatoes*. US Patent 2569075 A.

Schluter, O., Ehlbeck, J., Hertel, C., Habermeyer, M., Roth, A., Engel, K. H., et al. (2013). Opinion on the use of plasma processes for treatment of foods. *Molecular nutrition & food research, 57*, 920–927.

Sensoy, I., & Sastry, S. K. (2004a). Extraction using moderate electric fields. *Journal of Food Science, 69*, E7–E13.

Sensoy, I., & Sastry, S. K. (2004b). Ohmic blanching of mushrooms. *Journal of Food Process Engineering, 27*, 1–15.

Shim, J., Lee, S. H., & Jun, S. (2010). Modeling of ohmic heating patterns of multiphase food products using computational fluid dynamics codes. *Journal of Food Engineering, 99*, 136–141.

Shirsat, N., Brunton, N. P., Lyng, J. G., & McKenna, B. (2004c). Water holding capacity, dielectric properties and light microscopy of conventionally and ohmically cooked meat emulsion batter. *European Food Research and Technology, 219*, 1–5.

Shirsat, N., Brunton, N. P., Lyng, J. G., McKenna, B., & Scannell, A. (2004d). Texture, colour and sensory evaluation of a conventionally and ohmically cooked meat emulsion batter. *Journal of the Science of Food and Agriculture, 84*, 1861–1870.

Shirsat, N., Lyng, J. G., Brunton, N. P., & McKenna, B. (2004a). Ohmic processing: Electrical conductivities of pork cuts. *Meat Science, 67*, 507–514.

Shirsat, N., Lyng, J. G., Brunton, N. P., & Mckenna, B. M. (2004b). Conductivities and ohmic heating of meat emulsion batters. *Journal of Muscle Foods, 15*, 121–137.

Shynkaryk, M. V., Ji, T., Alvarez, V. B., & Sastry, S. K. (2010). Ohmic heating of peaches in the wide range of frequencies (50 Hz to 1 MHz). *Journal of Food Science, 75*, E493–E500.

SKLM. (2007). In *Stellungnahme zur Hochspannungsimpulsbehandlung von Lebensmitteln.* http://www.dfg.de/download/pdf/dfg_im_profil/reden_stellungnahmen/2007/sklm_hochspannungsimpulsbehandlung.pdf.

Skudder, P. J. (1988). Ohmic heating: New alternative for aseptic processing of viscous foods. *Food Engineering Reviews, 60*, 99–101.

Somavat, R., Kamonpatana, P., Mohamed, H. M. H., & Sastry, S. K. (2012a). Ohmic sterilization inside a multi-layered laminate pouch for long-duration space missions. *Journal of Food Engineering, 112*, 134–143.

Somavat, R., Mohamed, H. M. H., Chung, Y. K., Yousef, A. E., & Sastry, S. K. (2012b). Accelerated inactivation of Geobacillus stearothermophilus spores by ohmic heating. *Journal of Food Engineering, 108*, 69–76.

Somavat, R., Mohamed, H. M. H., & Sastry, S. K. (2013). Inactivation kinetics of Bacillus coagulans spores under ohmic and conventional heating. *Lwt-Food Science and Technology, 54*, 194–198.

Stancl, J., & Zitny, R. (2010). Milk fouling at direct ohmic heating. *Journal of Food Engineering, 99*, 437–444.

Tadpitchayangkoon, P., Park, J. W., & Yongsawatdigul, J. (2012). Gelation characteristics of tropical surimi under water bath and ohmic heating. *Lwt-Food Science and Technology, 46*, 97–103.

Teissie, J., Golzio, M., & Rols, M. P. (2005). Mechanisms of cell membrane electropermeabilization: A minireview of our present (lack of ?) knowledge. *Biochimica Et Biophysica Acta-General Subjects, 1724*, 270–280.

Thomas, K., Herouet-Guicheney, C., Ladics, G., Bannon, G., Cockburn, A., Crevel, R., et al. (2007). Evaluating the effect of food processing on the potential human allergenicity of novel proteins: International workshop report. *Food and Chemical Toxicology, 45*, 1116–1122.

Toda, M., Heilmann, M., Ilchmann, A., & Vieths, S. (2014). The maillard reaction and food allergies: Is there a link? *Clinical chemistry and laboratory medicine, 52*, 61–67.

Toepfl, S., Heinz, V., & Knorr, D. (2007). *Food preservation by pulsed electric fields*. Cambridge: Woodhead Publishing Limited.

Tumpanuvatr, T., & Jittanit, W. (2011). Mathematical models for electrical conductivities of fresh juices,concentrated juices and purees undergoing ohmic heating. *Thai Journal of Agricultural Science, 44*, 312–318.

Varghese, K. S., Pandey, M. C., Radhakrishna, K., & Bawa, A. S. (2014). Technology, applications and modelling of ohmic heating: A review. *Journal of Food Science Technology, 51*, 2304–2317.

Vogel, L., Holzhauser, T., & Vieths, S. (2006). Development of a biological assay to determine the allergenic potential of foods. *Journal für Verbraucherschutz und Lebensmittelsicherheit, 1*, 317–324.

Wang, W. C., & Sastry, S. K. (1993). Salt diffusion into vegetable tissue as a pretreatment for ohmic heating – Electrical-conductivity profiles and vacuum infusion studies. *Journal of Food Engineering, 20*, 299–309.

Wang, W. C., & Sastry, S. K. (1997a). Changes in electrical conductivity of selected vegetables during multiple thermal treatments. *Journal of Food Process Engineering, 20*, 499–516.

Wang, W. C., & Sastry, S. K. (1997b). Starch gelatinization in ohmic heating. *Journal of Food Engineering, 34*, 225–242.

Wang, W. C., & Sastry, S. K. (1998). Changes in electrical conductivity of selected vegetables during multiple thermal treatments. *Journal of Food Process Engineering, 20*, 499, 21, 89–89.

Wang, W. C., & Sastry, S. K. (2000). Effects of thermal and electrothermal pretreatments on hot air drying rate of vegetable tissue. *Journal of Food Process Engineering, 23*, 299–319.

Wang, W. C., & Sastry, S. K. (2002). Effects of moderate electrothermal treatments on juice yield from cellular tissue. *Innovative Food Science & Emerging Technologies, 3*, 371–377.

Wegner, L. H., Flickinger, B., Eing, C., Berghofer, T., Hohenberger, P., Frey, W., et al. (2011). A patch clamp study on the electro-permeabilization of higher plant cells: Supra-physiological voltages induce a high-conductance, K+ selective state of the plasma membrane. *Biochimica et Biophysica Acta (BBA)-Biomembranes, 1808*, 1728–1736.

Wu, H., Kolbe, E., Flugstad, B., Park, J. W., & Yongsawatdigul, J. (1998). Electrical properties of fish mince during multi-frequency ohmic heating. *Journal of Food Science, 63*, 1028–1032.

Yildiz-Turp, G., Sengun, I. Y., Kendirci, P., & Icier, F. (2013). Effect of ohmic treatment on quality characteristic of meat: A review. *Meat Science, 93*, 441–448.

Yildiz, H., Bozkurt, H., & Icier, F. (2009). Ohmic and conventional heating of pomegranate Juice: Effects on rheology, color, and total phenolics. *Food Science and Technology International, 15*, 503–512.

Yildiz, H., Icier, F., & Baysal, T. (2010). Changes in beta-carotene, chlorophyll and color of spinach puree during ohmic heating. *Journal of Food Process Engineering, 33*, 763–779.

Yongsawatdigul, J., Park, J. W., & Kolbe, E. (1995a). Electrical-conductivity of pacific whiting surimi paste during ohmic heating. *Journal of Food Science, 60*, 922.

Yongsawatdigul, J., Park, J. W., Kolbe, E., Abudagga, Y., & Morrissey, M. T. (1995b). Ohmic heating maximizes gel functionality of pacific whiting surimi. *Journal of Food Science, 60*, 10–14.

Yoon, S. W., Lee, C. Y. J., Kim, K. M., & Lee, C. H. (2002). Leakage of cellular materials from Saccharomyces cereviside by ohmic heating. *Journal of Microbiology and Biotechnology, 12*, 183–188.

Zareifard, M. R., Ramaswamy, H. S., Trigui, M., & Marcotte, M. (2003). Ohmic heating behaviour and electrical conductivity of two-phase food systems. *Innovative Food Science and Emerging Technologies, 4*, 45–55.

Zell, M., Lyng, J. G., Cronin, D. A., & Morgan, D. J. (2009). Ohmic cooking of whole beef muscle – Optimisation of meat preparation. *Meat Sci, 81*, 693–698.

Zell, M., Lyng, J. G., Cronin, D. A., & Morgan, D. J. (2010a). Ohmic cooking of whole beef muscle – Evaluation of the impact of a novel rapid ohmic cooking method on product quality. *Meat Science, 86*, 258–263.

Zell, M., Lyng, J. G., Cronin, D. A., & Morgan, D. J. (2010b). Ohmic cooking of whole turkey meat – Effect of rapid ohmic heating on selected product parameters. *Food Chemistry, 120*, 724–729.

Zhao, Y. Y., Kolbe, E., & Flugstad, B. (1999). A method to characterize electrode corrosion during ohmic heating. *Journal of Food Process Engineering, 22*, 81–89.

Zhong, T., & Lima, M. (2003). The effect of ohmic heating on vacuum drying rate of sweet potato tissue. *Bioresource Technology, 87*, 215–220.

Zhu, S. M., Zareifard, M. R., Chen, C. R., Marcotte, M., & Grabowski, S. (2010). Electrical conductivity of particle-fluid mixtures in ohmic heating: Measurement and simulation. *Food Research International, 43*, 1666–1672.

Zimmermann, U., & Neil, G. A. (1996). *Electromanipulation of cells*. Boca Raton, Florida: CRC Press.

Zimmermann, U., Pilwat, G., Beckers, F., & Riemann, F. (1976). Effects of external electrical fields on cell-membranes. *Bioelectrochemistry and Bioenergetics, 3*, 58–83.