NAUKI INŻYNIERSKIE I TECHNOLOGIE ENGINEERING SCIENCES AND TECHNOLOGIES
4(27) • 2017

ISSN 2080-5985
e-ISSN 2449-9773

Urszula Tylewicz
University of Bologna, Department of Agricultural and Food Sciences
e-mail: urszula.tylewicz@unibo.it

EFFECT OF PULSED ELECTRIC FIELD (PEF) ON MASS TRANSFER AND QUALITY PARAMETERS OF OSMODEHYDRATED FRUITS – A REVIEW

WPŁYW PULSACYJNEGO POLA ELEKTRYCZNEGO (PEF) NA WYMIANĘ MASY I JAKOŚĆ OWOCÓW ODWODNIONYCH OSMOTYCZNIE – PRZEGLĄD BADAŃ

DOI: 10.15611/nit.2017.4.05
JEL Classification: L66

Summary: Recently the development of intermediate moisture food products has received huge attention due to the consumer demand for minimally processed products. The removal of moisture is a very important unit operation in food processing, since it enables to stabilize food products and improve their quality retention during storage. Osmotic dehydration (OD) is a useful technology to partially remove water from food material such as fruit and vegetables prior to other stabilising techniques e.g. drying or freezing, at the same time a counter-current solute inflow into the tissue takes place. Unfortunately the cellular membrane exerts high resistances to transfers, therefore the OD is a very long process. There are many pre-treatments that can be used in order to accelerate the mass transfers. Pulsed electric field (PEF) has been recently considered as an alternative pre-treatment method allowing non-thermal damage the cell membranes prior to OD. PEF treatment leads to the electroporation of the cell membrane by applying an external electric field, in the form of short pulses, to the cellular tissue placed between two electrodes. Electroporation of the cell membranes could promote reversible or irreversible pore formation and cell disintegration, depending on both the intensity of the electric field strength applied and the characteristics of the raw materials. The formation of the pores facilitates the water removal from the tissue. Moreover, since PEF is a non-thermal technology it allows to maintain a high quality level in terms of colour and the nutritional value of the final product.

Keywords: fruit quality, PEF, osmotic dehydration, mass transfer.

Streszczenie: W ostatnich latach duży nacisk jest kładziony na otrzymywanie produktów spożywczych o zredukowanej wilgotności z uwagi na zainteresowanie konsumentów produktami o małym stopniu przetworzenia. Usuwanie wilgoci jest bardzo ważną operacją jednostkową w przetwarzaniu żywności, ponieważ umożliwia stabilizację produktów spożywczych i poprawę ich jakości podczas przechowywania. Odwadnianie osmotyczne (OD) jest przydatną technologią do częściowego usuwania wody z artykułu spożywczego, jak owoce i warzywa, jako obróbka wstępna przed procesami takimi jak suszenie lub zamrażanie. Jednocześnie następuje przepływ substancji osmotycznej do tkanki. Niestety, błona komórkowa ma wysoką oporność na przepływ wody czy substancji osmotycznej, dlatego też OD jest bardzo długim procesem. Istnieje wiele operacji wstępnych, które można wykorzystać w celu przyspieszenia przepływu masy. Pulsacyjne pole elektryczne (PEF) zostało ostatnio zaproponowane jako alternatywna metoda wstępnej obróbki pozwalająca na uszkodzenie membran komórkowych przed OD, bez udziału wysokich temperatur. Aplikacja PEF prowadzi do elektroporacji błony komórkowej przez zastosowanie zewnętrznego pola elektrycznego, w postaci krótkich impulsów, na tkankę komórkową umieszczoną między dwiema elektrodami. Elektroporacja błon komórkowych może sprzyjać odwracalnemu lub nieodwracalnemu tworzeniu się porów i dezintegracji komórkowej, która zależy zarówno od natężenia zastosowanego pola elektrycznego, jak i charakterystyki surowców. Tworzenie się porów ułatwia usuwanie wody z tkanki. Ponadto, biorąc pod uwagę, iż PEF jest technologią nietermiczną, pozwala ona zachować wysoką jakość (kolor i wartość odżywcza) produktu końcowego.

Słowa kluczowe: jakość owoców, PEF, odwadnianie osmotyczne, wymiana masy.

1. Osmotic dehydration (OD) process

Osmotic dehydration (OD) is a partial dewatering of plant tissue, which allows reducing the water activity (a_w) of the products without a phase change. During OD treatment there is an deployment of a hypertonic solution, which leads to the removal of water due to the differences in osmotic pressure between the solution and the fruit tissue. Together with water there is the counter-current migration of solutes into the plant tissue. This process is commonly applied in industry in order to obtain minimally processed fruit products with intermediate moisture content or as a pre-treatment for further processes such as drying or freezing [Khan 2012; Yadav, Singh 2014]. This could be considered as one of the most important treatments for food preservation, since it presents some benefits such as the retention of flavour, colour, texture, inhibiting the enzymatic browning and the energy costs decrease [Tylewicz et al. 2009; Tylewicz et al. 2011; Khan 2012; Panarese et al. 2012].

The efficiency of the osmotic dehydration process is influenced by a number of factors such as temperature, sample sizes and geometry, concentration of osmotic solution, ratio between material to solution, and agitation.

Temperature is an important factor because the increase of this parameter causes the reduction of the viscosity of the solution and the mass exchange process is intensified [Seguí et al. 2010]. When increasing the temperature from 25 to 45°C, a higher mass transfer was observed in kiwifruit samples dehydrated in sucrose solution [Tylewicz et al. 2011]. Also Falade et al. [2007] observed that water loss and solid gain increase with the increase of solution concentration and temperature during osmotic dehydration of watermelon. The porous structure of tissue influences the release of trapped air from the tissue resulting in the more effective removal of water by osmotic pressure.

The type of osmotic substance also affects the quality of the final product. Substances used for osmotic dehydration are solutions of sugars, sodium chloride, sorbitol, or other substances acceptable for the consumer, which can produce high osmotic pressure allowing for the reduction of water activity of the dehydrated material [Ciurzyńska et al. 2016].

The shape of the material is very important, too big samples could slower the dehydrate rate because the length of diffusion path is higher. Similarly, the increase in the agitation level, higher solution concentration and high enough product mass to solution ratio which permit to maintain the constant driving force, increase the rate of dehydration [Rastogi et al. 2002]. However, in general the OD treatment is a time-consuming process, therefore many other pre-treatments could be used before OD in order to increase the velocity of mass transfer kinetics, one of them could be the pulsed electric field.

2. Pulsed electric field (PEF)

Pulsed electric field is a non-thermal technology which leads to the electroporation of the cell membrane by applying an external electric field to the cellular tissue placed between two electrodes. The electric field could be applied in the form of short pulses (from several nanoseconds to several milliseconds) with an electric field strength from 100-300 V/cm to 20-80 kV/cm [Barba et al. 2015]. Electroporation generally involves the polarization of membranes, the creation of pores and their expansion. Electroporation of the cell membranes could promote reversible or irreversible pore formation and cell disintegration, depending on both the intensity of the electric field strength applied and the characteristics of the raw materials. The reversible electroporation (the created pores reseal immediately after removing the electrical field) could be used to incorporate different functional substances into the vegetal tissue, assuring the survival of the electrically stimulated cells. Higher intensities of PEF promote, instead, irreversible tissue permeabilization (permanent membrane damage) and consequently cell death [Donsì et al. 2010].

In the last few years the use of pulsed electric field technology for food processing has been widely studied. PEF processing offers several advantages: to improve the extraction process [Barba et al. 2015], to enhance the mass transport phenomena [Donsì et al. 2010; Wiktor et al. 2013] and to inactivate enzymes [Elez-Martínez et al. 2007] and microorganisms [Saldaña et al. 2014]. Therefore, the potential of the PEF applications in the food industry is huge and has been reviewed by [Barba et al. 2015]. Since the effects of PEF are strictly related to the applied process parameters, namely pulse shape, number, duration, frequency and electric field strength, their accurate control is fundamental for industrial implementation.

2.1. Low intensity PEF application

In particular, low intensity PEF treatments could be used to induce an effect on mass transport phenomena or to have an impact on cell structure modification. PEF pretreatment could enhance the performance of processes such as osmotic dehydration, drying, freeze-drying, freezing, extraction, etc., reducing processing time and saving energy [Traffano-Schiffo et al. 2016; Tylewicz et al. 2016; Wiktor et al. 2013].

PEF promotes the structural changes on a cellular level and water redistribution between different cellular compartment, thus resulting in changes in tissue material properties. In fact, several studies reported the changes in texture and colour parameters of different plant tissues subjected to the PEF processing, which could consequently affect the final product quality characteristics [Siemer et al. 2014].

The PEF process is designated as a gentle and waste-free technology. Its use has the potential for continuous application, instant distribution throughout an electrically-conductive food, short treatment time, low energy requirements and allows food to retain its colour, flavour and nutritive value. This technology offers great potential to the food industry because it can be applied to a wide range of products, as well as being an effective pre-processing technology, to improve heat and mass transfers [Knorr et al. 2002].

In general the benefits of PEF treatment for fruit and vegetable processing can be summarised as follows: improve process yield and process velocity, improve food quality (e.g. reduce fat uptake during frying, reduce impact on sensory properties, increase health-related compounds), decrease the intensity of other processing variables (e.g. temperature, grinding degree), and/or increase the cost efficiency of the operation (e.g. reduce energy consumption) [Hui 2007].

3. Effect of PEF on mass transfer in fruits during OD

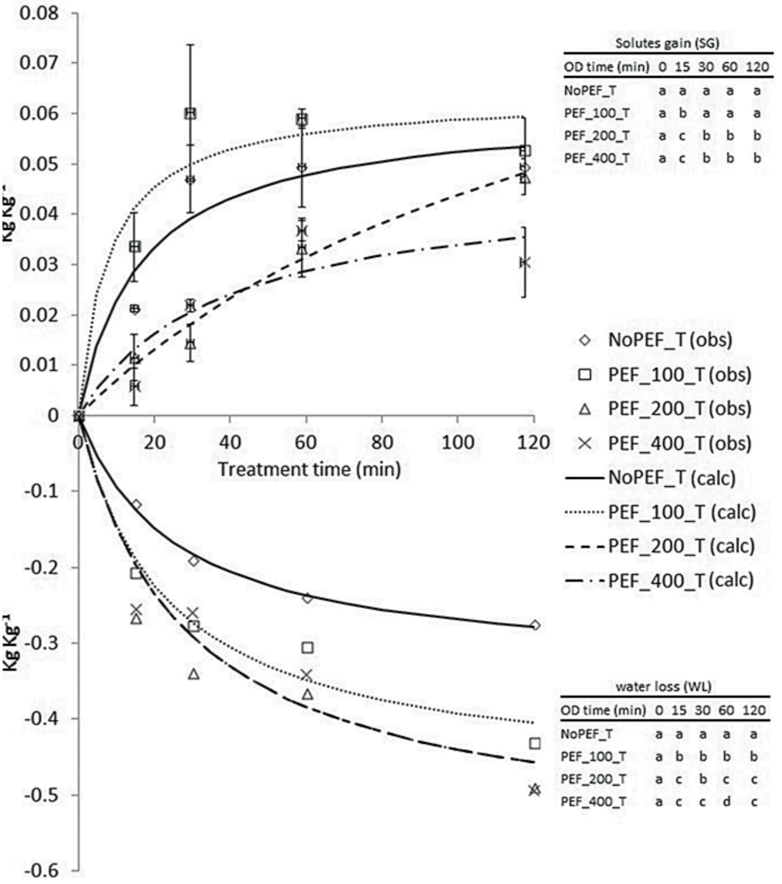
During the osmotic dehydration, due to the differences in osmotic pressure between food and osmotic solution, important mass transfer phenomena take place. There is an important water flow from the tissue into the osmotic solution, while at the same time occurs counter flow diffusion of solutes from osmotic solution into the fruit tissue.

PEF has been reported to increase the permeability of plant cells with a positive influence on mass transfer in further processes. The first work demonstrating the potential of PEF in accelerating mass transfer rates during OD of carrots was performed by [Rastogi et al. 1999]. They stated that the effective diffusion coefficients of water and solute increased exponentially with the increase of electric field strength.

Since then, PEF treatment has been widely studied to evaluate its effect on mass transfer phenomena in different fruit and vegetables. The response of the different tissue to the PEF treatment at low intensities (100 V/cm) has been shown to be strongly influenced by tissue microstructure.

In kiwifruit slices treated with sucrose osmotic solution at 61.5 % (w/w) it was able to substantially increase the water losses by about 10 % [Traffano-Schiffo et al. 2016].

In strawberry half subjected to the osmotic treatment in sucrose and trehalose at the same concentration of 40% (w/w) the water loss increase was also observed, which was higher at the end of the process (120 min) for samples dehydrated in



Solutes gain (SG)

OD time (min)	0	15	30	60	120
NoPEF_T	a	a	a	a	a
PEF_100_T	a	b	a	a	a
PEF_200_T	a	c	b	b	b
PEF_400_T	a	c	b	b	b

water loss (WL)

OD time (min)	0	15	30	60	120
NoPEF_T	a	a	a	a	a
PEF_100_T	a	b	b	b	b
PEF_200_T	a	c	b	c	c
PEF_400_T	a	c	c	d	c

The same letter on the same column means no significant difference between the samples by the Duncan test ($p < 0.05$).

Te same litery w tej samej kolumnie oznaczają brak statystycznej różnicy między próbkami na podstawie testu Duncana ($p < 0,05$).

Fig. 1. Kinetics of water loss and solutes uptake during OD of strawberries in trehalose solution, modelled according to Peleg's equation
Rys. 1. Kinetyka usuwania wody i wnikania suchej substancji (na podstawie modelu Peleg) podczas OD truskawek w roztworze trehalozy

Source: adapted from [Tylewicz et al. 2017].
Źródło: dostosowane z [Tylewicz i in. 2017].

trehalose solution [Tylewicz et al. 2017]. Figure 1 shows the kinetics of water loss and solutes uptake during OD, modelled according to Peleg's equation using the data presented in [Tylewicz et al. 2017], in a trehalose solution.

Comparing the observed and calculated values of mass fraction in the figures and considering that R^2 values ranged between 0.852 and 0.997, the model confirmed to be able to efficiently describe the mass transfer phenomena during OD. Water loss in the trehalose-based solution was characterized by a high initial rate with equilibrium values of 0.56 kg/kg for water. At the end of the treatment the samples treated at 200 and 400 V cm^{-1} reached the highest WL of about 50 % with an equilibrium value of respectively 0.39 and 0.35 kg/kg.

Instead, for apple cylinders, no effect on mass transfer was observed during OD treatment performed for 60 min in a sucrose solution, while presenting an increase only at the end of the process (120 min) [Dellarosa et al. 2016]. Moreover, the different response of apple tissue to the electric field could be due to the differences in conductivity of the samples as well as the total energy input delivered to the samples. The application of a higher electric field strength such as 250 V/cm increased the water loss, while the application of 400 V/cm did not further improve this parameter in the kiwifruit samples [Traffano-Schiffo et al. 2016], and strawberries [Tylewicz et al. 2017), while promoting an increase of water loss proportional to the electric field applied in apple tissue [Dellarosa et al. 2016].

Interesting results were obtained concerning the solid gain. In the apple samples treated in sucrose, the PEF pre-treatment promoted an increase of solutes uptake [Dellarosa et al. 2016], while in kiwifruit the PEF pre-treated samples at 100 V/cm presented a lower sucrose mass gain in comparison to these untreated, opening an amazing opportunity in the design of new fruit products with a high dehydration level and lower sugar content [Traffano-Schiffo et al. 2016]. Concerning strawberries, in samples treated in the sucrose solution the PEF pre-treatment promoted an increase of solutes, while in the trehalose solution samples treated with 400 V/cm presented a lower solid uptake after 120 min of treatment [Tylewicz et al. 2017].

Yu et al. [2018] showed higher rates of water loss and a solid gain during osmotic dehydration of blueberries by PEF pre-treatment (3 kV/cm field strength, 1 μs pulse width, 200 pulses per second, and a total treatment time of 5 min) reducing the dehydration time from 130 to 48 h.

Amami et al. [2006] studied the osmotic dehydration mechanism of an apple sample pre-treated by PEF at 0.9 kV/cm over a range of 44.5-65° Brix sucrose concentrations. They observed that the increase of the initial solute concentration and the PEF treatment resulted in an acceleration of the osmotic dehydration in terms of higher water loss (WL) and higher solid gain (SG) than the untreated samples. The coefficients of the effective diffusion of water and solute were higher for samples pre-treated electrically.

Amami et al. [2014] applied PEF pre-treatment on tissues of apple (0.90 kV/cm), carrot (0.30 kV/cm) and banana (0.60 kV/cm) prior to being osmotically dehydrated in an agitated flask at an ambient temperature using a 65% sucrose solution as osmotic medium. The dehydration was more pronounced in carrot probably due to the higher initial water content than the fresh banana and apple. Under atmospheric pressure, samples treated by PEF dehydrated in five agitation speeds displayed a higher water loss (4-35%) than untreated samples. After 4 h of OD process, the PEF treated samples had a 15-60% greater solid gain more than the untreated samples. Indeed, when membranes lose their functionality under PEF, external solutes diffuse freely to all parts of the tissue, not only to the open intercellular spaces. For bananas, water loss increased with treatment time. About 45% of the water loss occurred after 240 min for the highest speed of agitation of PEF conditions.

In another paper Amami et al. [2007] studied the centrifugal osmotic dehydration and rehydration of carrot tissue treated by a pulsed electric field. Water loss was higher while solid gain decreased with the increase of centrifugal acceleration and with the application of PEF at 0.6 kV/cm. For instance, after 4 h of OD, the WL was 42% and 49.4% in the absence of centrifugal acceleration, while it increased to 63% and 72.5% at 5430g, respectively for the untreated and PEF treated samples. Concerning the SG, it was 4.8% and 6.31% in the absence of centrifugal acceleration, while it decreased to 3% and 4.33% at 5430g, respectively for untreated and PEF treated samples. This behaviour of mass transfer reveal that the application of PEF in combination with centrifugal OD could be used when the maximal dehydration of the product is required, while the solids uptake should be limited. In this work the PEF pre-treatment also resulted as effective for an increase of the rehydration capacity of osmotically dehydrated carrot samples.

Ade-Omowaye et al. [2003] studied the application of different intensities of PEF (1, 1.5 and 2 kV/cm) with a constant pulse number of 20 at a pulse duration of 400 μs on diffusion rates during osmotic dehydration of red bell peppers in two different solutions. The water loss using sucrose/sodium chloride solution for the untreated samples was 24% while with the application of PEF, 35-37% of water loss was recorded. With the second solution (sucrose at 50°Brix), the untreated sample lost about 39% water, while an improvement of between 24-25% in the amount of water released by the PEF pre-treated samples compared to the untreated ones was observed. However, the increase of the intensity of the electric field strength did not promote an increase in the water loss of the samples. The authors explained that this was probably due to the accumulation of solutes in the superficial layer caused by the initial fast rate, thus presenting a great barrier to water outflow from the cell. In general, a low enhancement in the solute infusion with PEF pre-treatment was observed, which could be associated in part to the molecular size of the osmotic solute in comparison to the pore area induced within the cell membrane by the PEF treatment.

4. Effect of PEF on fruit tissue colour during OD

The colour of plant tissue is one of the key food parameter, which is important from the consumer's point of view. During the technological processes the colour of food could be affected by the physical and chemical changes.

For the strawberries samples no change in L* parameters was observed by [Tylewicz et al. 2017]. The application of PEF at the intensity of 100 V/cm promoted a significant increase of this parameter, and a decrease due to the application of PEF at highest intensity. The darkening of the PEF treated samples at 400 V/cm could be related to the higher release of enzymes such as peroxidase (POD) and polyphenol oxidase (PPO) and their substrates after the electroporation of the strawberry cells membrane. Concerning the hue angle-h° colour parameter, OD in trehalose solution promoted a decrease of this parameter. The application of PEF promoted a further decrease of the red hue in comparison to the untreated samples (Figure 2).

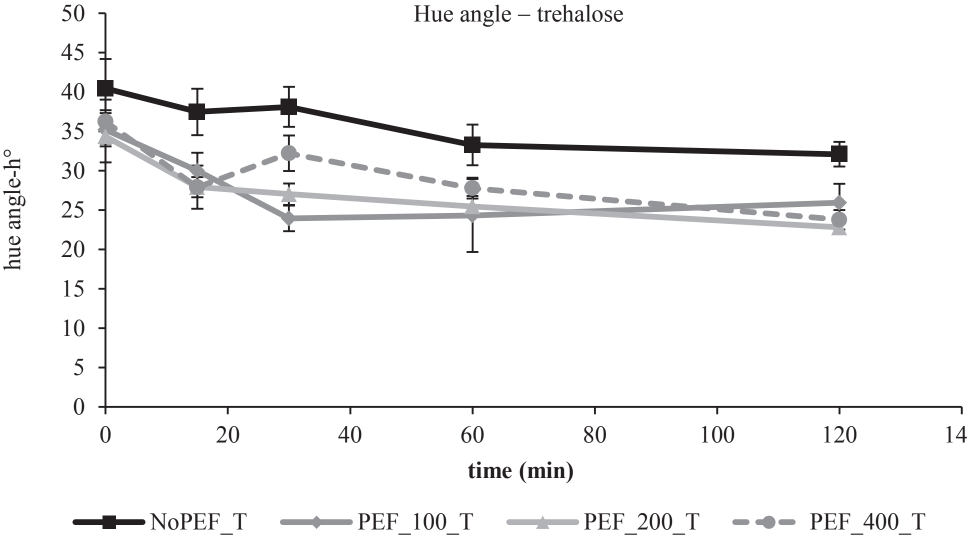


Fig. 2. Hue angle (h° colour parameter) of untreated and PEF pre-treated strawberry samples, as a function of the osmotic dehydration time in trehalose-based solution
Rys. 2. Odcień koloru (parametr barwy h°) próbek truskawek poddanych lub nie obróbce wstępnej przy pomocy PEF-u, jako funkcja czasu odwadniania osmotycznego w roztworze trehalozy

Source: own elaboration based on data presented in [Tylewicz et al. 2017].
Źródło: opracowanie własne na podstawie danych przedstawionych w [Tylewicz et al. 2017].

The reduction of hue angle (h°) colorimetric parameter could be due to both the solubilisation of pigments in the osmotic solution and the degradation of anthocyanin induced by PEF-treatment [Fathi et al. 2011]. Wiktor et al. [2015] observed that the effect of PEF treatment strongly depends on the raw material properties and the treatment conditions. In fact the authors noticed the different behaviour of the carrot and apple tissue subjected to the electric field at different intensities. In both cases browning of the tissue was observed, however in carrots it was more pronounced when the low voltage treatment was applied, while in apple when high voltage was used.

The colour of osmotically dehydrated carrot and banana was also studied by Amami et al. [2014]. Regarding the agitation speed progresses, the carrot became darker, due to enzymatic browning. Compared to the fresh sample, the increase in redness ($a^* > 0$) and yellowness ($b^* > 0$) was evident for the osmotically dehydrated carrot. PEF increased the brightness of carrot samples (as reflected by positive L^* values with a higher Re number) while the colour of static sample darkened (as reflected by negative L^* values). The carrot after PEF treatment and osmotic dehydration had colour characteristics close to those of the fresh natural colour. The PEF pre-treated banana instead had the highest L^* values compared to the untreated one (which increased with Re number), implying greater product brightness which might be a result of greater pigment leaching. Ade-Omowaye [2001] reported that a prolonged pulse application induced reactions leading to darker products showing lower L values ($L^* < 0$). However, the relative increase in redness displayed for all osmotically PEF pre-treated samples was small compared to the significant increase for untreated samples.

5. Effect of PEF on fruit tissue structure during OD

It is well known that OD induces plasmolysis, shrinkage of the vacuole compartment, changes in the size and structure of the cell walls of outer pericarp and dissolution of the middle lamella, which could be translated in a decreasing of the firmness of the plant tissue [Chiralt, Talens 2005; Panarese et al. 2012]. OD of untreated samples promoted a decrease of strawberry firmness, already 15 min after the treatment, and increased slightly during the OD treatment. PEF pre-treatment drastically reduced the hardness of strawberry samples; further, the PEF treated samples remained below the untreated ones during the whole OD process and the effect was proportional to the electric field strength applied [Tylewicz et al. 2017]. Also, Taiwo et al. [2003] observed the decrease in firmness of strawberry halves treated with PEF (1200 V cm_1; 350 ms) and then osmodehydrated for 4 h in binary (sucrose, NaCl) solution. The reduction of firmness of PEF treated samples could be due to the alteration of the membrane permeability due to the pores creation and the rupture of the internal structure, which promotes the softening of the tissue. The slight increase of the texture observed after longer OD times could be probably due to the penetration of Ca^{2+} into the strawberry tissue, which interact with pectic acid polymers to form cross bridges that reinforce the cell adhesion, thereby reducing cell separation, which is one of the major causes of plant tissue softening. This increase has not been observed in the samples treated at 400 V cm^{-1}, probably because the tissue was already completely disintegrated after the PEF treatment, and did not permit the incorporation of calcium ions in the cell walls. When the strawberry samples were dehydrated in the trehalose solution the decrease of firmness following the OD process was less marked. This behaviour could probably be due to the protective effect of trehalose on the tissue structure.

Amami et al. [2007] studied the texture in terms of relaxation curves of untreated and treated by PEF, and subsequently dehydrated/rehydrated, carrot samples. All samples demonstrated the viscoelastic behaviour. However, the rehydrated samples subjected to OD before drying presented a noticeably firmer structure than the samples that were directly dried without OD. This was probably due to the fact that osmotically dehydrated samples contain more solids than directly dried samples. The PEF pre-treatment promoted a slight decrease in the firmness of the rehydrated samples. However, the PEF treatment and OD under centrifugation somewhat decrease the elasticity of the samples compared to the untreated samples subjected to the OD under stirring. The textural study and the rehydration capacity showed that the products obtained with OD was less affected by the thermal treatment than the directly dried product.

6. Effect of PEF on fruit bioactive compound content during OD

Yu et al. [2018] observed that PEF pre-treatment of the samples did not have any effect on the total phenolics content in blueberry fruits in comparison to the untreated or thermal treated samples. However, after osmotic dehydration the samples treated with PEF showed lower loss (66%) in comparison to the control (79%), but a higher loss of polyphenols in comparison to the blanched samples (53%). By the end of osmotic dehydration when all the samples reached 3.5 C3G g/g i.d.m., PEF-50 samples had the lowest degradation loss and control samples had the highest degradation loss of all anthocyanins, chlorogenic acid, and three predominant flavonols (quercetin 3-galactoside, quercetin 3-glucoside, and myricetin 3-arabinoside). The inactivation of PPO during pre-treatment significantly increased the retention of anthocyanins, predominantly phenolic acids and flavonols, total phenolics, and antioxidant activity in the dehydrated blueberries. In contrast, control samples had the least migration loss, and PEF-50 samples had the most migration loss. Similarly to total phenolics, these four compounds physically migrated to the syrup solution during the dehydration process.

The OD time has a significant influence on the vitamin C content of the pre-treated samples. The longer the OD time, the lower the vitamin content was noted. [Taiwo et al. 2001] observed that the vitamin C content of PEF pre-treated apple at 2 h of OD treatment was 4.7 mg/100 g fresh sample while it was reduced to 0.5 mg at the 6th hour of OD.

A gradual increase in the retention of the vitamin C with an increase of field strength during osmotic dehydration of bell peppers was reported [Ade-Omowaye et al. 2003]. Though all the PEF treated samples had a vitamin C content lower than the untreated one due to the faster leaching of this compound (as a result of cell desintegration) into osmotic solution. The increase of vitamin C retention with increasing field strength was, however, attributed partly to the barrier created by the enhanced solute uptake during the OD using sucrose and sodium chloride [Ade-Omowaye et al. 2002]. The vitamin C retention consistently decreased until the application of 20 pulses after which the retention increased in samples pre-treated with 50 pulses. The trend recorded for vitamin C retention in this case was consistent with the trend observed for the conductivity values of osmotic solutions containing the pre-treated samples. The increase in this case was more than the value recorded for 10 pulses. The reduction in the vitamin retention was attributed to the electrical disruption of cells after PEF treatment and subsequent leaching of the cellular contents, including vitamin C, into the osmotic solutions. The vitamin C contents in all these studies were determined at the end of the OD process in which the moisture contents of PEF pre-treated samples were consistently lower than the untreated samples. The loss of ascorbic acid has been attributed to two main phenomena: the diffusion of fruit solutes (e.g. ascorbic acid) toward the dehydration solution, and chemical deterioration. Consequently it may be possible that untreated samples, if allowed to dehydrate to a moisture content similar to those of the PEF treated samples, may lose equal or higher quantities of vitamin C [Ade-Omowaye et al. 2001].

7. Conclusions

PEF has been demonstrated to have potential as a non-thermal technology in the processing of minimally processed foods or intermediate moisture foods. The application of PEF resulted in cell membrane permeablization which increase the mass transfer phenomena. In fact the use of PEF as a pre-treatment showed to facilitate enhanced water loss during OD with a limited solute uptake resulting in healthier products with minimal alteration in product taste. Moreover, it allows to maintain the high quality of processed fruits. However, further studies are necessary in order to thoroughly understand the quality changes in the coupled PEF+ OD process, as well as the kinetics of nutrients degradation during these treatments.

Bibliography

Ade-Omowaye B.I.O., Angersbach A., Taiwo K.A., Knorr D., 2001, *Use of pulsed electric field pre-treatment to improve dehydration characteristics of plant based foods*, Trends in Food Science and Technology, 2(8), pp. 285-295.

Ade-Omowaye B.I.O., Rastogi N.K., Angersbach A., Knorr D., 2002, *Osmotic dehydration of bell peppers: influence of high intensity electric field pulses and elevated temperature treatment,* Journal of Food Engineering, 54(1), pp. 35-43.

Ade-Omowaye B.I.O., Rastogi N.K., Angersbach A., Knorr D., 2003, *Combined effects of pulsed electric field pre-treatment and partial osmotic dehydration on air drying behaviour of red bell peppers*, Journal of Food Engineering, 60(1), pp. 89-98.

Ade-Omowaye B.I.O., Talens P., Angersbach A., Knorr D., 2003, *Kinetics of osmotic dehydration of red bell peppers as influenced by pulsed electric field pretreatment*, Food Research International, 36(5), pp. 475-483.

Amami E., Fersi A., Khezami L., Vorobiev E., Kechaou N., 2007, *Centrifugal osmotic dehydration and rehydration of carrot tissue pre-treated by pulsed electric field*, LWT – Food Science and Technology, 40(7), pp. 1156-1166.

Amami E., Khezami L., Jemai A. B., Vorobiev E., 2014, *Osmotic dehydration of some agro-food tissue pre-treated by pulsed electric field: impact of impeller's Reynolds number on mass transfer and color.* Journal of King Saud University – Engineering Sciences, 26(1), pp. 93-102.

Amami E., Vorobiev E., Kechaou N., 2006, *Modelling of mass transfer during osmotic dehydration of apple tissue pre-treated by pulsed electric field*, LWT – Food Science and Technology, 39(9), pp. 1014-1021.

Barba F.J., Galanakis C.M., Esteve M.J., Frigola A., Vorobiev E., 2015, *Potential use of pulsed electric technologies and ultrasounds to improve the recovery of high-added value compounds from black--berries*, Journal of Food Engineering, 167, pp. 38-44.

Barba F.J., Parniakov O., Pereira S.A., Wiktor A., Grimi N., Boussetta N., Vorobiev E., 2015, *Current applications and new opportunities for the use of pulsed electric fields in food science and industry*, Food Research International, 77(4), pp. 773-798.

Ciurzyńska A., Kowalska H., Czajkowska K., Lenart, A., 2016, *Osmotic dehydration in production of sustainable and healthy food*, Trends in Food Science and Technology, 50, pp. 186-192.

Dellarosa N., Ragni L., Laghi L., Tylewicz U., Rocculi P., Dalla Rosa M., 2016, *Time domain nuclear magnetic resonance to monitor mass transfer mechanisms in apple tissue promoted by osmotic dehydration combined with pulsed electric fields*, Innovative Food Science and Emerging Technologies, 37, Part C, pp. 345-351.

Donsì F., Ferrari G., Pataro, G., 2010, *Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue*, Food Engineering Reviews, 2(2), pp. 109-130.

Elez-Martínez P., Suárez-Recio M., Martín-Belloso O., 2007, *Modeling the reduction of pectin methyl esterase activity in orange juice by high intensity pulsed electric field*, Journal of Food Engineering, 78(1), pp.184-193.

Falade K.O., Igbeka J.C., Ayanwuyi F.A., 2007, *Kinetics of mass transfer, and colour changes during osmotic dehydration of watermelon*, Journal of Food Engineering, 80(3), pp. 979-985.

Fathi M., Mohebbi M., Razavi A.M.S., 2011, *Application of image analysis and artificial neural network to predict mass transfer kinetics and color changes of osmotically dehydrated kiwifruit*, Food Bioprocess Technology, 4(8), 1357-1366.

Hui Y.H., 2007, *Handbook of Fruits and Fruit Processing*, https://doi.org/10.1002/9780470277737.

Khan M.R., 2012, *Osmotic dehydration technique for fruits preservation-a review*, Pakistan Journal of Food Sciences, 22(2), pp. 71-85.

Knorr D., Ade-Omowaye B.I.O., Heinz V., 2002, *Nutritional improvement of plant foods by non-thermal processing*, Proceedings of the Nutrition Society, 61(2), pp. 311-318.

Panarese V., Laghi L., Pisi A., Tylewicz U., Dalla Rosa M., Rocculi P., 2012, *Effect of osmotic dehydration on Actinidia deliciosa kiwifruit: a combined NMR and ultrastructural study*, Food Chemistry, 132, 4, pp. 1706-1712.

Rastogi N.K., Eshtiaghi M.N., Knorr D., 1999, *Accelerated mass transfer during osmotic dehydration of high intensity electrical field pulse pretreated carrots*, Journal of Food Science, 64(6).

Rastogi N.K., Raghavarao K.S.M.S., Niranjan K. Knorr D, 2002. *Recent developments in osmotic dehydration: methods to enhance mass transfer*, Trends in Food Science and Technology, 13(2), pp. 48-59.

Saldaña G., Álvarez I., Condón S., Raso J., 2014, *Microbiological aspects related to the feasibility of pef technology for food pasteurization*, Critical Reviews in Food Science and Nutrition, 54(11), pp. 1415-1426.

Seguí L., Fito P.J., Fito P., 2010. *Analysis of structure-property relationships in isolated cells during OD treatments. Effect of initial structure on the cell behaviour*, Journal of Food Engineering, 99(4), pp. 417-423.

Siemer C., Aganovic K., Toepfl S., Heinz V., 2014, Chapter 6: *Application of Pulsed Electric Fields in Food. In Conventional and Advanced Food Processing Technologies*, ed. by Suvendu Bhattacharya. https://doi.org/10.1002/9781118406281.ch26.

Taiwo K.A., Angersbach A., Ade-Omowaye B.I.O., Knorr D., 2001, *Effects of pretreatments on the diffusion kinetics and some quality parameters of osmotically dehydrated apple slices*, Journal of Agricultural and Food Chemistry, 49(6), pp. 2804-2811.

Traffano-Schiffo M.V., Tylewicz U., Castro-Giraldez M., Fito P.J., Ragni L., Dalla Rosa M., 2016, *Effect of pulsed electric fields pre-treatment on mass transport during the osmotic dehydration of organic kiwifruit*, Innovative Food Science and Emerging Technologies, 38, pp. 243-251.

Tylewicz U., Aganovic K., Vannini M., Toepfl S., Bortolotti V., Dalla Rosa M., Oey I., Heinz V., 2016, *Effect of pulsed electric field treatment on water distribution of freeze-dried apple tissue evaluated with DSC and TD-NMR techniques*, Innovative Food Science and Emerging Technologies, 37, pp. 352-358.

Tylewicz U., Panarese V., Laghi L., Rocculi P., Nowacka M., Placucci G., Rosa M.D., 2011, *NMR and DSC Water Study During Osmotic Dehydration of Actinidia deliciosa and Actinidia chinensis Kiwifruit.* Food Biophysics, 6(2), pp. 327-333.

Tylewicz U., Rocculi P., Cocci E., Rosa M.D., Rzańca M., 2009, *Mass transfer phenomena during osmotic dehydration of yellow kiwifruit (Actinidia chinensis Pl. cv. Hort16A)*, Industrie Alimentari XLVIII.

Tylewicz U., Tappi S., Mannozzi C., Romani S., Dellarosa N., Laghi L., Ragni L., Rocculi P., Dalla Rosa M., 2017, *Effect of pulsed electric field (PEF) pre-treatment coupled with osmotic dehydration on physico-chemical characteristics of organic strawberries*, Journal of Food Engineering, 213, pp. 2-9.

Wiktor A., Iwaniuk M., Śledź M., Nowacka M., Chudoba T., Witrowa-Rajchert D., 2013, *Drying kinetics of apple tissue treated by pulsed electric field*, Drying Technology, 31(1), pp. 112-119.

Yadav A.K., Singh S.V., 2014, *Osmotic dehydration of fruits and vegetables: a review*, Journal of Food Science and Technology, 51(9), pp. 1654-1673.

Yu Y., Jin T.Z., Fan X., Wu J., 2018, *Biochemical degradation and physical migration of polyphenolic compounds in osmotic dehydrated blueberries with pulsed electric field and thermal pretreatments*, Food Chemistry, 239, pp. 1219-1225.