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Effect of pulsed electric field pretreatment on shrinkage, rehydration capacity and texture of freeze-dried plant materials

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Abstract

For this study, strawberries and red bell pepper were pre-treated with pulsed electric fields (PEF) to reduce the negative effects on physical properties of the products after freeze-drying. PEF treatment was carried out at constant electric field strength of E=1.0 kV/cm and specific energy input was varied between 0.3–6.0 kJ/kg (treatment time 2.0–28.6 ms). Additionally, the impact of different pre-freezing temperatures (-4 and -40 °C) on the final product quality was described. Investigations showed that due to PEF treatment a significant reduction of the shrinkage phenomena for both bell peppers and strawberries was detected compared to untreated samples with 30 % and 50 % lower volume losses, respectively. The rehydration capacity of PEF pre-treated freeze-dried samples increased for both matrices up to 50 %. Furthermore, the mechanical properties of the final product were improved for both matrices with a significant firmness reduction up to 60 %. The results of this study suggest that PEF can be an effective pretreatment with low energy requirements to improve the quality of freeze-dried fruits and vegetables.

1. Introduction

Freeze-dried products get more and more attention and are used directly as snack products or in a broad range of foods, such as dried soups, chocolate or breakfast cereals and cereal bars. The freeze-drying process better maintains the natural shape of the raw material and the nutritional and sensory properties compared to hot air drying since the product is stabilised by freezing and removing water based on sublimation (Fellows, 2009). Freeze-drying is performed under vacuum and consists of three main steps: freezing, primary drying (sublimation) and secondary drying (desorption). In particular, freezing temperature and ice morphology can significantly affect the freeze-drying process by modulating the mass transfer and thus the rate of primary and secondary drying (Kochs, Körber, Nunner, & Heschel, 1991; Searles, Carpenter, & Randolph, 2001).

To obtain high quality dried products various authors recommended the pretreatment of fruits and vegetables with pulsed electric fields (PEF) to affect economic aspects and quality parameters of different drying processes. The permeabilization of the cell membrane by PEF leads to reduced drying time through the acceleration of water transport from the biological tissue (Wu & Zhang, 2014). PEF pre-treated carrots (E=1–1.5 kV/cm; n=20 pulses) subjected to hot air drying showed an increased drying rate and improved final product quality in comparison to an untreated control (Gachovska, Simpson, Ngadi, & Raghavan, 2009). Similar findings were stated by Lamanauskas, Šatkauskas, Bobinaitė, and Viškelis (2015), who reported a reduction of the drying time of kiwifruits (T= 50 °C) by the application of PEF (E= 5 kV/cm) without affecting the colour and the ascorbic acid content of the product. Janositz, Noack, and Knorr (2011) investigated the drying of potato slices and detected an enhanced release of cell liquid during hot air drying for the PEF pre-treated samples. In general, the drying efficiency was found to improve in the range of 40–70 % by PEF (Toepfl, 2006). Furthermore, it is already known that PEF affects the freezing process, leading to smaller ice crystals and better product quality after thawing (Jalté, Lanoisellé, Lebovka, & Vorobiev, 2009; Shayanfar, Chauhan, Toepfl, & Heinz, 2014; Wiktor, Schulz, Voigt, Witrowa-Rajchert, & Knorr, 2015). As reported by Jalté et al. (2009), Ben Ammar, Lanoisellé, Lebovka, Van Hecke, and Vorobiev (2010), Parniakov, Bals, Mykhailyk, Lebovka, and Vorobiev (2016) and Lammerskitten et al. (2019), the application of PEF as pretreatment for freeze-drying leads to a significant reduction of undesirable shrinkage of apples and potatoes. Moreover, the reduction of shrinkage and collapse phenomena by PEF affects the rehydration capacity of the final dried product (Jalté et al., 2009; Parniakov, Bals, Lebovka, & Vorobiev, 2016), which is especially relevant for the use in instant soups and cereal products. However, in the previous studies, the volume reduction was detected only by visual evaluation, and the mechanisms related to PEF and decreased volume reduction during freeze-drying are still under discussion. Parniakov, Bals, Lebovka, et al. (2016) observed that during the freeze-drying process the temperature in the core of PEF pre-treated samples remains at lower temperatures for a longer time in comparison to untreated samples. Thereby, the frozen water inside the sample protects the original shape.

This work aims to contribute to the further clarification of underlying mechanisms by exact quantification of the volume reduction using 3D-scanning and by measuring the rehydration capacity of freeze-dried strawberries and bell peppers. Furthermore, different freezing temperatures (-40 °C and -4 °C) are investigated in order to take into consideration different states regarding ice crystal size and distribution. Moreover, the impact on texture was investigated of freeze-dried samples over a storage period of 30 days.

2. Material and methods

2.1. Raw material

Commercial strawberries (*Fragaria* x *ananassa* var. Elsanta) from Germany and commercial red bell peppers (*Capsicum annuum L.* var. Roberta) from a local Austrian producer were used. Raw materials were selected of good and uniform quality, rotten and unripe fruits were removed. Ripe strawberries and bell peppers were immediately used or stored under controlled conditions (4 °C) and used within 7 days. The strawberries were used in a whole, only a manual washing with water was performed, and the green sepals were removed. The red bell peppers were washed and cylinders with a diameter of 3.0 ± 0.1 cm and a thickness of 0.6 ± 0.2 cm were obtained using a cylindrical cutter.

2.2. PEF treatments

The PEF treatments were performed using a PEF batch system (Cellcrack 1, DIL, Germany) consisting of a high voltage power supply, a capacitor with 0.5 µF and a spark gap used as switch. A treatment chamber consisting of parallel plate electrodes with a distance of 13.5 cm and a total volume of 4.0 L was used. For each treatment, 500 ± 10 g of strawberries (n= 40) or 100 ± 10 g of bell peppers (n=20) were placed in the treatment chamber and filled up with tap water (T= 25 ± 1 °C, conductivity 320–350 µS/cm), to a final weight of 3.0 and 1.5 kg, respectively. Exponential decay pulses with a pulse width of 100 µs for the strawberries and 143 µs for the bell peppers, and a frequency of 1 Hz were applied. The pulse width was determined at 37 % of the peak voltage detected with a high voltage probe (P6015A, Tektronix, UK) and an oscilloscope (TBS 1102B-EDU, Tektronix, UK). The field strength was set to 1.0 kV/cm, and the number of pulses was varied between 20 and 200. Thus, the treatment time varied between 2.0–28.6 ms. The applied pulses delivered a pulse energy of 45.5 J and resulted in a total specific energy input for strawberry and bell pepper between 0.3–1.5 and 0.7–6.0 kJ/kg, respectively. Strawberries and bell peppers samples were prepared as control reference (untreated) by immersion in tap water for a duration equal to the duration of the PEF treatment and at the same sample/water ratio. At least three repetitions per treatment condition were conducted for both raw materials.

2.3. Cell disintegration index (CDI)

The degree of cell permeabilization after PEF treatment was determined by calculating the cell disintegration index (CDI). The electrical conductivity was measured with an impedance measurement device (Impedance Analyser, Sigma Check, Germany) in the frequency range of 1.4 kHz to 11.2 MHz using a cylindrical sample (diameter 1.0 cm, length 1.0 cm). Impedance curves were obtained for both, the intact and the PEF pre-treated samples. Related CDI was calculated using the equation described by Knorr and Angersbach (1998) considering impedance values at a frequency of 5.5 and 1400 kHz. The value of CDI varies between 0 representing intact cells and 1 representing totally disintegrated cells. A reference sample with maximum CDI was obtained by applying three freezing and thawing cycles.

2.4. Freeze-drying process

PEF treated and control samples were placed on stainless steel plates in a single layer, not in contact with each other, and frozen in a blast freezer (Blast Freezer IF101L, Sagi, Italy) at temperatures of -4 ± 2 and -40 ± 2 °C for a minimum duration of 2 h. Prior to freeze-drying, samples were tempered at -40 °C for 2 h. The frozen samples were placed onto shelves in a lab scale freeze-drier (FreeZone 6, LABCONCO, USA) without additional shelf heating. The condenser was pre-cooled to -45 ± 2 °C before the samples were placed in the freeze drier. The freeze-drying process was performed for 72 h, and the chamber pressure was maintained at 0.5 ± 0.02 mbar throughout the drying process. During the freeze-drying, the temperature of the untreated and PEF treated (0.7 kJ/kg) strawberries frozen at -40°C was recorded with two thermocouples placed at the core and at the external layer of the samples by a temperature monitoring system (E-VAL flex, Ellab, Denmark). After the freeze-drying process, part of the samples was immediately used for physical analyses, and a representative sample of both raw materials was stored for 30 days in tightly sealed glass jars containing 4 g silica gel as water absorber (Carl Roth GmbH, Germany) at T=20 ± 1 °C in the dark.

2.5. Determination of volume reduction

The volume reduction measurement was performed to evaluate the extent of the shrinkage phenomenon that can occur during the freeze-drying process. The volume of the same strawberry was measured before the treatment and after the conducted freeze drying process using a 3D laser scanner (BVM 6600, Perten Instruments, Sweden). The surface area of the bell peppers was determined using an image capture system (DigiEye, version 2.8, VeriVide, UK). The pictures of each sample were analysed by using image J (National Institute of Health, USA) to calculate the difference of the diameter after the freeze-drying. The thickness of the freeze-dried bell peppers was manually determined with a vernier caliper. Measurement was performed with at least five samples per treatment condition.

2.6. Rehydration capacity

The rehydration capacity was determined according to Agnieszka and Andrzej (2010), including some modifications. After the freeze-drying treatment, whole strawberries and bell pepper cylinders were submerged in 100 mL of deionised water (20 ± 1 °C), and the weight was recorded before and after different immersion times (1, 5, 15, 60 min). To keep the samples submerged during the rehydration measurement a device consisting of a thin iron wire and a plastic net was used. The dry matter was determined at the end of the rehydration procedure in an oven at 105 ± 2 °C until a constant weight was achieved (AOAC,1995). The results were expressed as rehydration percentage according to Meda and Ratti (2005). Measurement was performed with five samples per treatment condition.

2.7. Mechanical properties

The mechanical properties of the freeze-dried samples were determined by texture analyser (TA-XT Plus, Stable Micro System, UK), equipped with a 5.0 kg load cell. The penetration test was applied on whole strawberries and bell pepper cylinders frozen at -40°C with a cylindrical probe (2.0 mm), at a constant speed of 4.0 mm/s. The mechanical properties were defined by the maximum positive force [N] which represents the hardness of the dried samples (Wang, Zhang, & Mujumdar, 2010). Measurement was performed with ten samples per treatment condition.

2.8. Statistics

The statistical analysis was done with STATISTICA 10 software (Statsoft, USA). The significance level for the one-way ANOVA was set to $p < 0.05$ and the Tukey test was applied to assess significant differences between investigated parameters. The plotted results are reported as mean value ± standard deviation.

3. Results and Discussion

3.1. Cell disintegration index

The cell disintegration index (CDI), obtained by the impedance analysis is commonly used to evaluate the effects of different PEF parameters applied regarding the permeabilization effect in plant products (Angersbach, Heinz, & Knorr, 1999). The impact of PEF pretreatment at fixed electric field strength (1 kV/cm) and varied specific total energy input on strawberry and bell pepper is shown in Figure 1. It is evident that samples showed a statistically different cell disintegration depending on the applied energy input, with increasing energy input leading to an increase in the CDI. Increasing the energy input from 0.3 to 1.5 kJ/kg for strawberry and 0.7 to 6 kJ/kg for bell pepper leads to increased cell disruption of 25 and 30 %, respectively. The results obtained for the peppers are in accordance with those reported in previous studies (Ade-Omowaye, Rastogi, Angersbach, & Knorr, 2002, 2003; Jalté et al., 2009). In accordance to Angersbach, Heinz, and Knorr (2000), the investigations additionally demonstrate that depending on the selected raw material, applied energy inputs reached significant differences regarding CDI. For a CDI of 0.6 for strawberries, the application of 0.3 kJ/kg is sufficient. In comparison, 1.5 kJ/kg is required for reaching a similar CDI for bell peppers. The most intensive PEF treatment resulted in a CDI of 0.77 for strawberries also showing increased softness and leakage of intracellular content, which could compromise the mechanical processing in industrial scale. However, for bell pepper, these effects and especially the aforementioned leakage were not detectable for the applied energy inputs. The different response to the PEF treatment can be explained by the different intrinsic characteristics of the investigated plant products, such as cell shape and size, electric conductivity, pH or ionic strength (Puértolas, Luengo, Álvarez, & Raso, 2012; Toepfl, Siemer, Saldaña-Navarro, & Heinz, 2014).

Figure 1

3.2. Freeze-drying kinetics

Since the characteristics of a freeze-dried product depend on the material temperature during the process (Roos, 1997), the temperature of the outer layer (Out) and the inner layer (In) of PEF treated (0.7 kJ/kg) and untreated strawberries were monitored during the freeze-drying process (Figure 2). The outer layer of the untreated and treated sample (Out_Untreated and Out_PEF) show the same trend and it was not possible to highlight significant differences during the course of freeze-drying. Just after the beginning of the freeze-drying process, the outer layers showed an increase in temperature, indicating the rapid removal of water from the external layer. The temperature for both inner layers (In_Untreated and In_PEF) was constant or slightly decreased in the first phase of the process and then increased up to the shelf temperature. During the freeze-drying process, the rapid increase of the temperature in the core of the product can be considered as the end of primary drying (sublimation) and the beginning of secondary drying (desorption) (Kramer et al., 2009). The untreated sample recorded a constant temperature for 9 h, afterwards the temperature slightly increased until it reached the shelf temperature. The inner section of the PEF treated sample showed a lower temperature, with a minimum value of -17.36 °C, within 19.5 h from the start of freeze-drying, followed by a rapid temperature increase. The untreated and PEF treated samples reached the shelf temperature after 39.3 and 38.6 h, respectively. These results illustrate that PEF has no significant effect on the duration of the freeze-drying process. However the increased pore formation leads to a prolonged sublimation step and thus stabilizes the shape of the final product. Similar concepts were reported by Parniakov, Bals, Lebovka, et al. (2016). In their study, PEF treated apples, depending on the degree of cell disintegration, show lower temperatures during freeze-drying and a delayed temperature rise. During fast freezing, small ice crystals occur that result in the formation of small pores after their sublimation. This can result in a higher resistance to mass transfer and thus representing a limit for sublimation (Patapoff & Overcashier, 2002). The resistance to the passage of water vapour can increase the temperature at the sublimation interface resulting in partial melting of the ice, which leads to the plasticization of solids and structural collapse (Harnkarnsujarit, Charoenrein, & Roos, 2012). The effect of PEF pretreatment can be compared to slow freezing, with the formation of large ice crystals in the extracellular space. This promotes low dried product resistance and low product temperature with reduced consequences on the volume changes of freeze-dried products (Assegehegn, Brito-de la Fuente, Franco, & Gallegos, 2018; Harnkarnsujarit et al., 2012). However, the formation of small crystals can favour desorption for which a larger specific area is required (Hottot, Vessot, & Andrieu, 2004). Jalté et al. (2009) also stated that the application of PEF favours the mass transfer during freezing and the formation of larger ice crystals especially in the extracellular space, which promotes sublimation and keeps the samples at lower temperatures for a longer time. Moreover, Rambhatla, Obert, Luthra, Bhugra, and Pikal (2005) suggested that the shrinkage occurs during early secondary drying when the moisture of the product is still high and the temperature is close to the glass transition temperature.

Figure 2

3.3. Volume reduction

During different drying processes, the water removal causes changes on the physical structure of food and phenomena such as shrinkage can occur determining loss of the structural properties and thus the quality of the product and consumer acceptance (Agudelo-Laverde, Schebor, & del Pilar Buera, 2014). Collapsed or shrunk products show poor rehydration characteristics and uneven and extended drying (Tsourouflis, Flink, & Karel, 1976). Drying at sufficiently low temperatures permits to limit the effect on the physical structure of the samples thus freeze-drying allows better results compared to other dehydration methods (Krokida, Karathanos, & Maroulis, 1998). As mentioned before, to avoid the increase of temperature and thus the shrinkage, an increased mass transfer is required and can be achieved through pretreatments such as PEF or slow freezing. The effects of PEF pretreatment regarding volume reduction after the freeze-drying of whole strawberries and bell pepper discs are shown in Figure 3. The untreated strawberries frozen at -40 °C show a volume reduction of approximately 48 ± 16 %. In comparison, the PEF treated strawberries show significantly lower volume reduction. The lowest energy input (0.3 kJ/kg) results in the highest reduction with only 19 ± 8 % of volume loss and an energy input of 1.5 kJ/kg leads to a volume reduction of 15 ± 6 %. The PEF treated samples show not only a lower volume reduction but also a lower variability of the data, which reflects a higher homogeneity of the product indicating that cell disintegration due to PEF reduces mass transfer barriers in the frozen product and results in a more uniform tissue structure. Additionally, the beneficial shrinkage behaviour of the PEF pre-treated freeze-dried matrices is of main importance for marketing purposes. The observed volume reduction for strawberries was higher than reported by Shishehgarha, Makhlouf, and Ratti (2002). This might be attributed to different raw material properties and slightly different process conditions. For the bell peppers frozen at -40 °C (Figure 3b) similar findings were obtained, thereby the PEF pretreatment leads to a volume reduction of approximately 30 % independent from the applied energy input. The untreated samples showed a volume change higher than 80 %. The volume reduction of strawberries frozen at -4 °C was 15.1 % for the untreated and 7.1–9.0 % for the PEF treated samples. For the bell peppers frozen at -4 °C, the untreated samples showed a volume change of 62.9 % and the PEF pretreatment leads to a volume reduction of 33.7–46.0 %. For the untreated samples frozen at -4 °C a significant reduction of shrinkage phenomenon occurs compared with the fast freezing. As discussed earlier, this can be attributed to the formation of larger ice crystals, which favour a more rapid removal of the water vapour during sublimation. However, for PEF treated samples, the benefit of the higher freezing temperature is less pronounced or, in other words, when freezing at higher temperatures, only a small additional benefit can be derived from PEF pretreatment. The PEF treated strawberries were only slightly improved by the higher freezing temperature and no significant difference between the different freezing temperatures could be observed in the case of PEF treated bell peppers. The differences between the two matrices can be due to their different composition which affects the collapse temperature (Bhandari & Howes, 1999). These results confirm that the main aspect that limits the shrinkage phenomenon is the improvement of the mass transfer that allows keeping the temperature of the samples lower than their glass transition temperatures (T_g) for a longer time. In accordance with Levi and Karel (1995), the collapse phenomenon is a dynamic process occurring when the process temperature is above the T_g. Lammerskitten et al. (2019) further describe that the application of PEF treatment results due to the facilitated movement of components in a more homogeneous distribution of water and sugar inside of the investigated raw material and thereby sugars are less able to seals natural pores. The fact that the improvement resulting from a PEF treatment was most pronounced for the low freezing temperature at -40 °C represents a major benefit with industrial relevance. The current freezing processes are performed at low temperatures in order to allow short processing times and provide the appropriate freezing conditions especially for the manufacturing of individually quick frozen (IQF) product. Moreover, the low heat transfer coefficient of slow freezing leads beside long holding times to significant quality loss (Singh & Wang, 1977). In that case, the PEF treatment can significantly contribute to an improved quality without losing the benefits of the lower freezing temperature.

Figure 3

3.4. Rehydration

Rehydration of food is a complex phenomenon affected by numerous factors like pre-drying treatments, drying technology and conditions, food structure, composition and medium viscosity (Alejandro Marabi & Saguy, 2004). A study conducted by A. Marabi, Livings, Jacobson, and Saguy (2003) showed that for freeze-dried samples the most crucial mechanism is capillary diffusion. In Table 1 the results of the rehydration capacity and behaviour of strawberries and bell peppers immediately after the freeze-drying process are shown. Regardless of the freezing temperature, significant advantages in terms of rehydration ability were determined for both matrices by the application of PEF. Freeze-dried strawberries frozen at -40 °C had better rehydration capacity for energy inputs higher than 0.7 kJ/kg. After just one minute of immersion, the PEF treated strawberries indicate a 49.5–70.7 % higher rehydration rate than the untreated samples. After 15 min of immersion, it was possible to detect differences depending on the applied PEF treatment intensity. Strawberries frozen at -4 °C showed a decrease of the rehydration rate compared to the sample subjected to rapid freezing. Also for the products frozen at -4 °C, the PEF treated samples showed a better rehydration compared to the untreated samples. In particular, the sample treated with the highest PEF intensity (1.5 kJ/kg) had a statistically higher rehydration at all immersion times. As for the samples frozen at -40 °C, after just one minute of immersion, the PEF treated samples show a rehydration being 52.5–68.6 % higher than the untreated sample. It can be assumed that the freezing process at -4 °C has a significant influence on the final structure of the freeze-dried strawberries as the rehydration capacity can be considered as a valid measure to assess the state of injury caused by pretreatments and drying process (Krokida et al., 1998).

The behaviour of freeze-dried peppers frozen at -40 °C was similar to the strawberries. However, up to 15 min of immersion only the sample treated with the highest PEF intensity (6.0 kJ/kg) showed a statistically higher rehydration. After 60 min of immersion, the rehydration of PEF treated samples was 22.1–54.0 % higher compared with the untreated control. For freeze-dried bell peppers frozen at -4 °C the freezing temperature didn't affect the rehydration capacity and the PEF treated samples showed again a higher rehydration already after the first minute of immersion compared to the untreated samples. Generally, the increased number of pores in the membrane induced by PEF favours the capillary diffusion process and may cause the increased rehydration capacity of the PEF treated samples. Jalté et al. (2009) and Parniakov, Bals, Mykhailyk, et al. (2016) stated similar results for potatoes and apples, relating the better rehydration for PEF treated samples to a higher porosity of the vegetable matrix after the freeze-drying process. Furthermore, the different rehydration ability of the investigated matrices could be described by their specific cellular and microstructural properties, considering that the rehydration capacity is closely dependent by the used plant material (Witrowa-Rajchert & Lewicki, 2006). In particular, Lee, Farid, and Nguang (2006) reported that different plant materials can have different rehydration rates according to their microscopic structure even when the drying conditions are the same.

Table 1

3.5. Texture

Texture is one of the most important physical parameter for dehydrated products, which can drastically influence the consumer's acceptability (Fan, Zhang, & Mujumdar, 2018). The mechanical properties of dried food products are affected by moisture content, food composition, pH, and the ripening stage of the raw material (Sagar & Kumar, 2010). For the determination of the mechanical properties of the freeze-dried strawberries and bell peppers texture measurement was conducted. The results of the penetration test measured after freeze-drying and 30 days of storage are plotted in Figure 4. The maximum force decreases significantly from 8.6 to 4.2–4.5 N for strawberry and from 8.4 to 2.4–3.3 N for bell pepper due to the applied PEF pretreatment independent of the treatment intensity. It can be stated that the PEF decreased the hardness of freeze-dried strawberries and bell peppers by 47.4–50.7 % and 61.1–71.1 % respectively, when compared to the untreated samples. Ben Ammar et al. (2010) and Lammerskitten et al. (2019) also reported a noticeable softening for freeze-dried PEF pre-treated potatoes and apples. The softer structure of the pre-treated samples can be explained by the increased pore formation due to PEF, which leads to reduced shrinkage and higher porosity of the samples (Chauhan, Shayanfar, & Toepfl, 2019).

The product stability was evaluated by measuring the textural properties after a storage period of 30 days. No significant changes of firmness were found for both untreated products after 30 days of storage. Also, the firmness of the PEF pre-treated products was found to remain unchanged over the storage period. It has to be mentioned that the product stability especially the crispiness of freeze-dried products is particularly affected by the humidity during storage, therefore the selection of suitable packaging material and storage conditions is crucial for the transfer of results. In the current study, appropriate storage avoided changes in the moisture content of the samples during storage which could result in changes of the textural properties of the products.

Figure 4

4. Conclusion

The pore formation due to the applied PEF treatment prior to freeze-drying reduces the shrinkage phenomenon and increases the rehydration capacity of freeze-dried strawberries and bell peppers. The present results indicate that the improved mass transfer resulting from the application of PEF promotes the primary drying by keeping the product temperature at lower values for a longer time. This affects the product structure in a way that shrinkage and collapse of the tissue are reduced. The beneficial effects on volume reduction have already been observed at the lowest applied energy input and CDI. Besides the cell disintegration achieved by PEF treatment, the volume reduction can be further reduced by increasing the cell disintegration and mass transfer due to slow freezing and related formation of larger ice crystals. Moreover, regardless of freezing temperature, PEF treated samples show higher rehydration capacity compared to untreated samples. Further basic research is needed in order to clarify the underlying mechanisms of this process-structure-function interaction affecting the freezing and freeze-drying behaviour. However, based on the obtained results, the application of PEF treatment in industrial scale especially at low freezing temperatures seems to be a promising approach to preserve the initial shape and improve the rehydration of freeze-dried fruits and vegetables.

5. Conflict of interest

The author have no conflict of interest

6. Acknowledgement

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Table 1 Rehydration capacity (%) of untreated and PEF pre-treated (1 kV/cm) freeze-dried strawberry and bell pepper over a rehydration time of 60 min at 20°C. Different letters in the same column of each raw material indicate significant differences (p<0.05)

Rehydration time [min]	1		5		15		60	
Freezing temperature [°C]	-40	-4	-40	-4	-40	-4	-40	-4
Energy input [kJ/kg]	strawberry							
untreated	3.27±1.50a	2.10±0.69a	4.69±2.06a	2.70±0.87a	5.95±2.33a	3.37±1.01a	8.62±2.91a	5.54±1.38a
0.3	6.48±1.51ab	4.44±1.73ab	8.87±2.56ab	5.84±2.28ab	10.65±2.68ab	7.50±2.79ab	13.96±3.17ab	10.92±3.08ab
0.7	11.16±3.48b	6.66±4.29ab	13.21±3.65b	8.89±4.99ab	14.73±3.29bc	11.03±5.46ab	17.69±2.99bc	15.68±6.34b
1.5	10.94±4.50b	4.55±0.83b	13.99±3.79b	6.64±1.18b	16.07±3.38c	8.46±1.68b	19.61±3.18c	12.94±2.51b
Energy input [kJ/kg]	bell pepper							
untreated	6.62±0.94a	7.68±1.4a	9.56±1.22a	11.56±1.4a	12.73±1.79a	15.54±2.24a	18.99±2.02a	22.71±1.93a
1.5	8.93±1.05a	14.85±5.29ab	13.64±2.07a	23.06±6.64b	18.13±2.64ab	29.48±7.8b	24.44±3.9ab	38.99±8.37b
3	11.15±4.07a	15.21±4.68ab	16.16±3.85a	21.43±5b	21.32±3.92b	27.47±4.91b	29.83±3.14b	35.94±3.48b
6	24.29±7.37b	18.26±6.34b	30.5±7.42b	24±6.55b	35.24±7.19c	29.69±5.21b	41.35±6.52c	37.71±1.73b

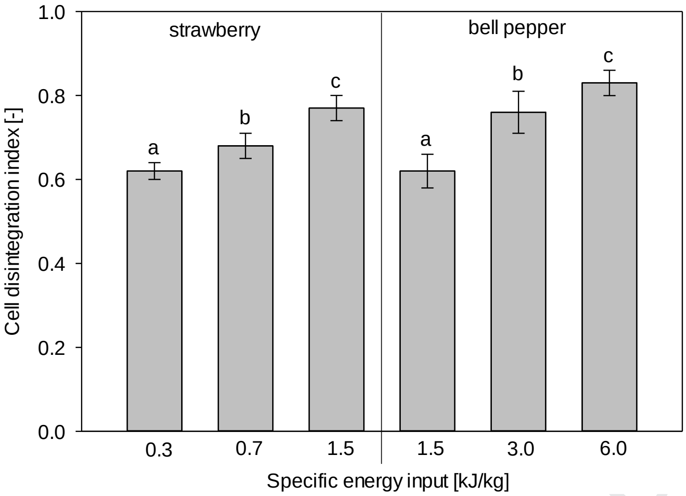

Figure 1 Cell disintegration index of PEF pretreated (1 kV/cm) strawberries and bell peppers related to different specific energy inputs. Different letters for each material indicate significant differences ($p<0.05$)

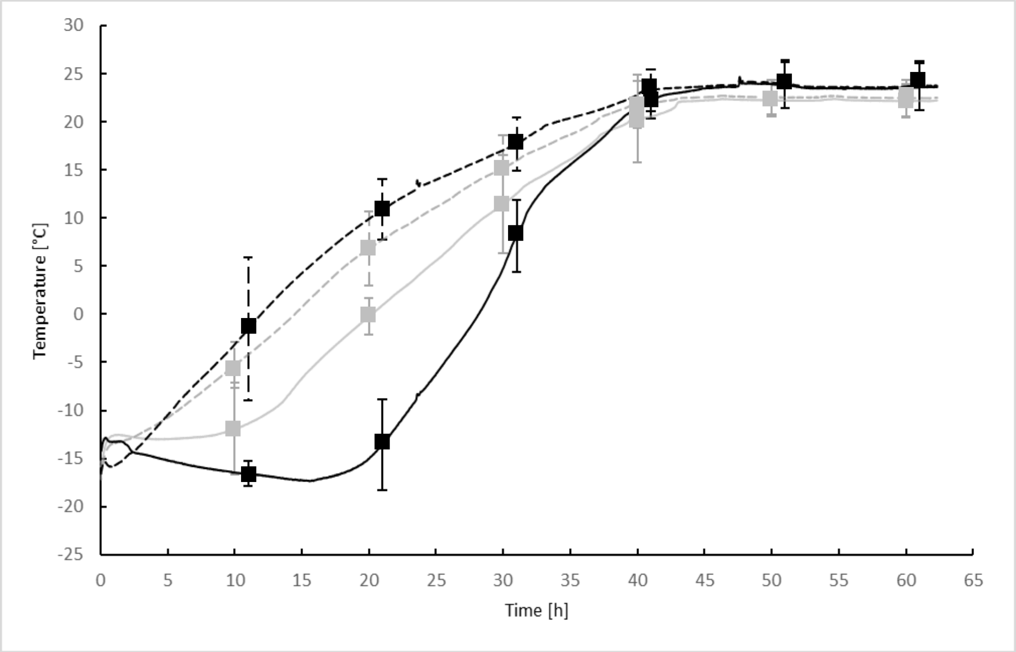

Figure 2 Temperature behaviour of the outer (dotted line) and inner (full line) layers of PEF treated ■ *(1kV/cm 0.7 kJ/kg) and untreated* ■ *strawberries during freeze-drying, freezing temperature -40 °C.*

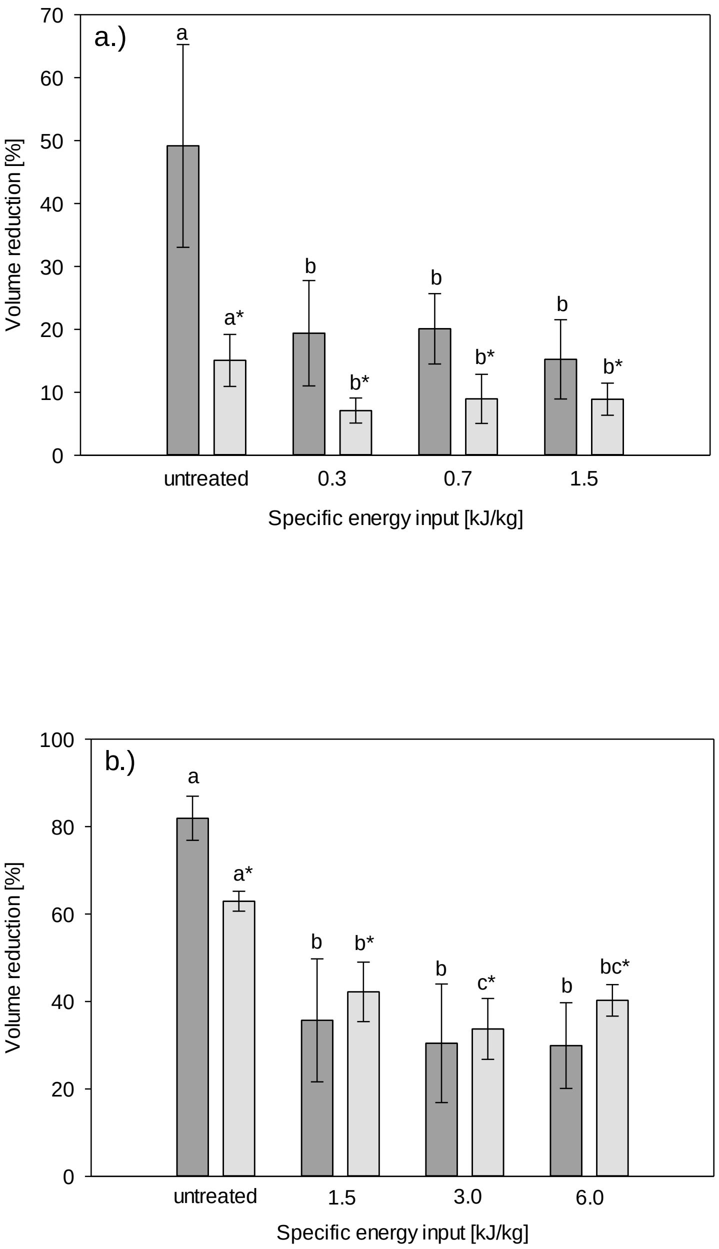

Figure 3 Volume reduction (%) resulting from freeze-drying of untreated and PEF pretreated (1 kV/cm) strawberries (a) and bell peppers (b) frozen at -40 (■) and -4 °C (□). Significant differences for equal freezing temperature (-40 °C=a, -4 °C=a) is indicated by different letters (p<0.05)*

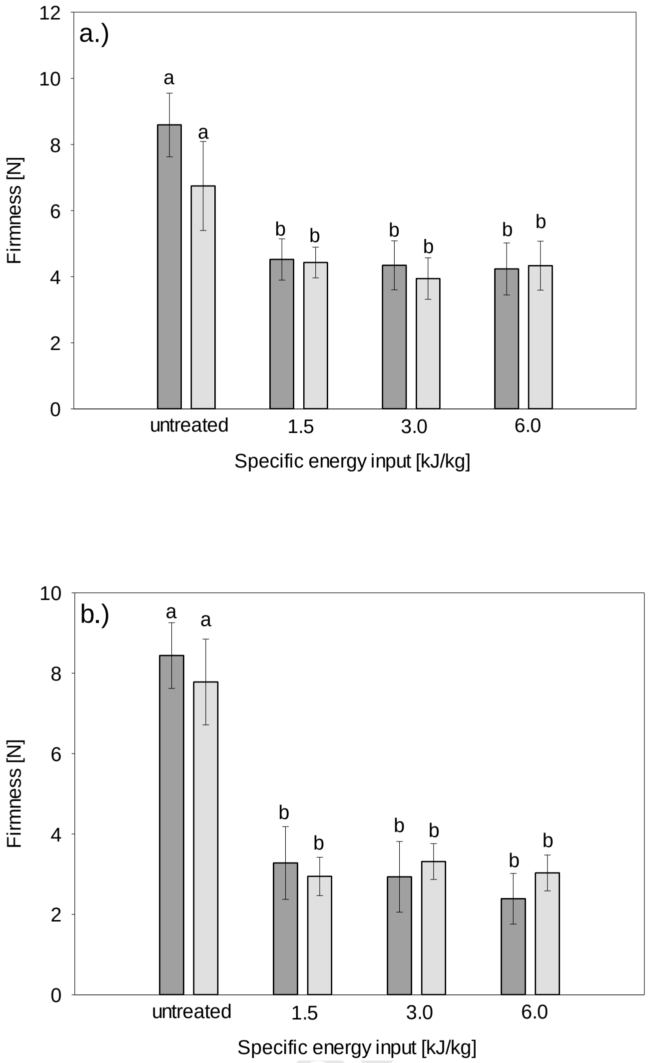

Figure 4 Texture measurement of PEF pretreated (1 kV/cm) and untreated freeze-dried strawberries (a) and bell peppers (b) immediately after processing (■)and 30 days of storage (□). Different letters indicate significant statistical differences (p< 0.05)

Highlights

- Quantitative determination of shrinkage phenomena was performed by innovative 3D scanning method
- PEF treatment significantly improved the freeze-drying process due to the enhanced mass transfer
- Volume loss and firmness were reduced and rehydration capacity increased for strawberries and bell pepper
- PEF effects are more pronounced at lower freezing temperatures as usually applied during industrial quick freezing processes
- The impact of PEF on selected physical parameters is already detectable at low energy inputs of 0.3 kJ/kg

Conflict of interest

We know of no conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome. As corresponding author, I confirm that the manuscript hast been read and approved for submission by all the named authors.

Author contribution statements

TF, MG and HJ conceived and planned the experiments.

TF and MG carried out the experiments and contributed to sample preparation.

TF, MG, PP and HJ contributed to the interpretation of the results.

TF and MG took the lead in writing the manuscript.

All authors provided critical feedback and helped shape the research, analysis and manuscript.