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EFFECT OF PULSED ELECTRIC FIELDS PRE-TREATMENT ON MASS TRANSPORT DURING THE OSMOTIC DEHYDRATION OF ORGANIC KIWIFRUIT

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ABSTRACT

Recently, some authors have applied pulsed electric fields (PEF) as a pre-treatment of osmotic dehydration, showing a faster kinetics of dehydration. Osmotic dehydration of fruit tissue shows complex mass transfer mechanism associated with active and passive transports of the vegetal matrix, usually driven by electrolytes. The aim of this work was to analyze the effect of different PEF values (100, 250, 400 V/cm) as a pre-treatment of the osmotic dehydration (61.5 °Brix, up to 120 min) on mass transport mechanism of organic kiwifruit.

A thermodynamic model able to describe the mass transfer and tissue deformation in kiwifruit was developed. It was possible to conclude that pulsed electric field as a pre-treatment, remove a part of the native electrolytes, reducing the activity of protein active pumps, leaving alone the passive protein channels as a main mass transmembrane transport and therefore affecting to the regular functionality of cell homeostasis system.

Keywords: kiwifruit, Pulsed Electric Fields, osmotic dehydration, mass transfer, thermodynamics, phenomenological coefficients.

NOTATION

a_j	activity of the chemical specie j (-)
R	ideal gases universal constant (J mol $^{-1}$ K^{-1})
T	temperature (K)
S	entropy (J K^{-1})
P	absolute pressure (Pa)
F	Force (N)
F	Faraday Constant (C mol^{-1})
V	volume (m^3)
l	elongation (m)
L	Phenomenological coefficient (mol^2 J^{-1} s^{-1} m^{-2})
n	number of moles (mol)
M	mass (g)
Mr	molecular weight (g mol^{-1})
x	mass fraction (g g^{-1})

S	surface (m^2)
J	molar flux (mol s^{-1} m^{-2})
t	time (min)
G	Gibbs free energy (J)
e	charge (C)
s	molar partial entropy (J K^{-1} mol^{-1})
z	Valence of each electrolyte (-)

Greek Alphabet

ψ	electric potential (J mol^{-1} C^{-1})
μ	chemical potential (J mol^{-1})
ν	molar partial volume of the specie j (L mol^{-1})

Subscripts

w	water
t	treatment time
0	initial time
s	sucrose
i	principal chemical species
j	any chemical species

Superscripts

s	surface
OD	osmotic dehydration solution
PT	passive transport
AT	active transport

1. Introduction

Osmotic dehydration (OD) is a widely used preservation technique which consists in the reduction of food water activity by immersing a biological tissue in hypertonic solutions (Castro-Giráldez, Fito, Dalla Rosa, & Fito, 2011a). The difference in water chemical potential between the internal liquid phase and external solution promotes the release of water from the food into the osmotic medium with the simultaneous incorporation of the solute into the product (Panarese et al., 2012).

Cellular systems evolve by free energy gradients known as passive transports (Tyerman, Bohnert, Maurel, Steudle, & Smith, 1999); however, occasionally biological systems require that the chemical species move in the opposite direction to these energy gradients; therefore, biological systems have developed transport mechanisms based on protein channels (Agre, Bonhivers, & Borgnia, 1998), which work with energy consumption as ATP (Ferrari, Sarantopoulos, Carmello-Guerreiro, & Hubinger, 2013). When a biological tissue is subjected to a dehydration process, the cells suffer water losses which produces cell stress. The mechanisms of the tissue to survive to this level of water stress are multifold. While cell is losing water by passive transport, driven by the water chemical potential gradient, multiple mechanisms to preserve the intracellular water content are developed, such as active water pump transport or the vesicles process formation (Tylewicz, Romani, Widell, & Galindo, 2013), maintaining cell homeostasis and protecting the function of the structure (Bohnert & Jensen, 1996).

Kiwifruit has a complex organized cellular structure where the cells are interconnected by plasmodesmatas, which allow them to generate solute and solvent fluxes by symplastic ways. The mass transfer throughout the extracellular space is

named apoplastic way. Finally, the transport between intra and extra cellular space is the transmembrane transport where the passive water transport is given by protein channels named aquaporins (Maurel & Chrispeels, 2001). The main active transports pumps are: Ca^{2+}, Na^{+} and Na^{+}/K^{+}, which are the responsible of the transport of water, sucrose and electrolytes, respectively.

It should be taking into account that OD treatment removes the water from materials (fruits and vegetables) only partially (Rastogi, Eshtiaghi, & Knorr, 1999). Therefore, the combined use of OD treatment with other techniques such as Pulsed Electric Fields (PEF) represents a promising tool to improve mass transfer, increasing yields and reducing processing times (Rastogi & Niranjan, 1998).

PEF is a non-thermal promising technology which consists on applying electric fields pulsed through a material placed between two electrodes for very short periods of time (microseconds to milliseconds) (Dellarosa et al., 2016; Parniakov, Lebovka, Bals, & Vorobiev, 2015; Puértolas, Luengo, Álvarez, & Raso, 2012), increasing the osmotic yield (Baier, Bußler, & Knorr, 2015).

Cell membrane is a semipermeable barrier conformed by phospholipid bilayer with native electric field, and is considered as a natural capacitor of the cell (Singh & Heldman, 2001). However, when the system is subjected to an external electric field bigger than the native one, changes in the electric conformation and also reorganization of phospholipidic bilayer are produced. This phenomenon could be cause of the cell membrane breakdown, and it is known as electroporation (Baier et al., 2015), a representative diagram can be seen in Figure 1. Another way of membrane breakdown is the electrocompression; when food is subjected to an external electric field the electric charges (particularly electrolytes, such as Ca^{2+}, Na^{+}

or K^+) accumulate at both sides of the cell membrane generating a potential difference through it. These charges attract each other, therefore the membrane suffers a compression, and as a consequence its original thickness is reduced. The elastic forces of the membrane oppose to the electric compression, but when the charge accumulation exceed the limit point of elasticity, pores are generated due to the disruption of it (Calderón-Miranda, Fernanda, Martín, Barbosa-Cánovas, & Swanson, 1998).

According to the intensity of the applied electric field, the numbers of pulses, and the temperature, the electroporation could be reversible or irreversible (Knorr, Angersbach, Eshtiaghi, Heinz, & Lee, 2001). In order to estimate the critical electric field of membrane breakdown, Zimmermann, Pilwat, Beckers, & Riemann (1976) applied voltage gradients in a simulated cell membrane. They reported values between 5 mV to 1 V at 20 ºC and 1.2 V at 4 ºC as an electric potential difference to cell membrane breakdown. If the average thickness of the phospholipidic bilayer is 4 nm (Briegel et al., 2009) and it is considered as a parallel plates system, the critical electric field obtained are 12.5 kV/cm to 2.13 MV/cm at 20ºC and 3 MV/cm at 4ºC. However, some effects in chemical transport by using PEF at lower electric fields intensities used as pre-treatment of OD have been reported. Rastogi, Eshtiaghi, & Knorr, (1999) have been able to accelerate the water mass transfer of carrots by applying electric fields between 0.22 to 1.6 kV/cm at 40ºC; Taiwo, Angersbach, Ade-Omowaye, & Knorr, (2001) have increased the water loss with a minimal alteration of apples using an intensity electric field of 1.4 kV/cm at 40ºC. Finally, Tedjo, Taiwo, Eshtiaghi, & Knorr, (2002), have obtained a moisture reduction without altering the taste of mangos by applying 1 to 3 kV/cm at 40ºC.

Moreover, PEF application in food processing maintains the activity of vitamins (Vega-mercado, Gongora-Nieto, Barbosa-Cánovas, & Swanson, 2007) and preserves some physical properties, such as color, texture or fresh taste (Calderón-Miranda, Fernanda, Martín, Barbosa-Cánovas, & Swanson, 1998).

The aim of this work was to analyze the effect of pulsed electric fields as a pre-treatment of the osmotic dehydration of kiwifruit, and determine the transport mechanism affected by the pre-treatment.

2. Material and methods

2.1. Raw material

Organic kiwifruits (*Actinidia deliciosa* cultivar ‘‘Hayward’’) were bought on a local market located in Cesena (Italia) and stored at 4±1 ºC until their processing. The fruits were tempered at 25 ºC, hand peeled and cut with a manual cork borer from the outer pericarp in order to obtain cylinders with homogeneous size of 8 mm diameter and a length of 10 mm (the core and the inner pericarp were removed). The refractometric indexes of the fruits used for the experiment were 13±1 ºBrix.

2.2. Experimental procedure

The fresh samples were characterized according the following parameters: mass, volume, refractometric index (ºBrix), water activity and moisture by quadruplicate. 12 sample cylinders were used for each treatment (576 samples). They were placed inside the Pulsed electric field (PEF) chamber and subjected to different electric fields strengths. Immediately after, the samples were weighed and introduced to the osmotic dehydration solution. Considering previous results, the OD treatment times

were 0, 10, 20, 30, 60 and 120 minutes. Due to the fact that the samples after treatments show concentration profiles, another batch of samples were reposed after the treatments at 4 ºC during 24 hours in decagon containers closed with parafilm® in order avoid the sample dehydration. Finally, mass, volume, ºBrix, water activity and moisture were measured as final determinations for fresh, treated and reposed samples.

2.3. Pulsed electric field (PEF) treatment

Pulsed electric field treatments were applied to the cylinders using a pulse generator equipment based on MOSFET technology and capacitors as energy tanks. The samples (12 cylinders per experiment) were placed in a rectangular treatment chamber equipped with two stainless steel electrodes (20 x 20 mm^2) with a separation between them of 30 mm and filled with 5 mL of tap water with known conductivity at 25 ºC.

PEF pre-treatments were done by applying three different pulsed electric field (100, 250 and 400 V/cm at 100 Hz) with near-rectangular shape monopolar pulses, a train of 60 pulses, a fixed pulse width of 100 ± 2 μs and a repetition time of 10.0 ± 0.1 ms.

2.4. Osmotic dehydration treatment

The OD was carried out by immersing the samples in 61.5 ºBrix sucrose solution prepared with commercial sugar and distilled water at 25 ºC and maintaining a relationship 1:4 (w/w) between the fruit and the OD solution in order to avoid changes in the solution concentration during the treatment time of 0, 10, 20, 30, 60 and 120 min.

2.5. Analytical determinations

Mass was determined by using a Kern balance ABS 320-4N (±0.0001) (KERN & SOHN GmbH, Germany), and a dew point Hygrometer Decagon (Aqualab®, series 3 TE) was used for measuring the water activity, with a precision ±0.003.

Volume was determined by an image analysis using Adobe© Photoshop© CS6 software (Adobe Systems Inc., San Jose, CA, USA) in order to get the diameter and the thickness of the samples.

The analysis of the moisture was accomplished following the AOAC Method 934.06, 2000. Sugar content was determined by measuring the refractometric index with a digital refractometer (KRÜSS Optronic© GmbH, Germany) calibrated with distilled water at 25ºC. Refractometric index was measured in both kiwifruit samples and agent solution after the treatment.

Analytical determinations described above were obtained by quadruplicate.

3. Results and discussion

During the osmotic treatments, kiwifruit suffers mass variations which involve the total mass, the water mass losses and the sucrose mass gain and they can be calculated using the following equations:

$$\Delta M = \frac{M_t - M_0}{M_0} \quad (1)$$

$$\Delta M_w = \frac{M_t x_{wt} - M_0 x_{w0}}{M_0} \quad (2)$$

$$\Delta M_s = \frac{M_t x_{st} - x_{s0} \cdot M_0}{M_0} \quad (3)$$

Where M represents the mass (g), x the mass fraction (g/g), the subscripts w represents the water, s the sucrose, t the treatment time and 0 the initial value.

Figure 2 shows the water and sucrose mass variation during the osmotic dehydration of the kiwifruit PEF pre-treated at different electric fields (0, 100, 250 and 400 V/cm). In the figure, water mass decreases due to high water losses for all the treatments, however, the water losses for samples that have not been pre-treated are considerably less than the PEF pre-treated samples. In addition, no differences in water losses between the samples pre-treated with 250 V/cm and 400 V/cm can be appreciated. Nevertheless, the sucrose mass gain is ordered in inverse sense of water losses; samples without PEF pre-treatment present the maximum sucrose mass gain.

Figure 3 shows the relationship between the overall mass variation and the water and sucrose mass variation. The line with a slope equal to 1 represents the mass balance $\Delta M = \Delta M_w + \Delta M_s$. No PEF samples are not fitted to the line which means that other flux is present in the process and it is not considered, probably a flux of other native solutes (sugar and electrolytes). However, the data of the samples pre-treated with PEF (all electric fields intensities) are located on the line, confirming that the kiwi mass variation is only due to the variation of water and sucrose (Castro-Giraldez, Fito, & Fito, 2010).

It is important to highlight that besides the water and sucrose mass variation, the native soluble solids present in the vegetal tissue should be considered, which can be estimated as follows:

$$\Delta M_i = \Delta M - (\Delta M_w + \Delta M_s) \quad (4)$$

Where ΔM_i represents the mass variation of native soluble solids leaving the fruit matrix to the osmotic solution.

Sugars present driving forces for mass gain as reported in Figure 2. However, as can be seen in Figure 4, samples without PEF pre-treatment lost up to 4 % of native soluble solids thus the nature of them has two characteristics: they are affected by the applied electric field and they play an important role in the transport of water and sugars. Therefore, these native compounds could be electrolytes. Throughout the traditional osmotic treatment, fruit tissue losses part of the native electrolytes (Peiró, Dias, Camacho, & Martínez-Navarrete, 2006), reducing the active transmembrane transport; however the samples pre-treated with PEF start the osmotic treatment with low amount of electrolytes.

In order to understand the different behaviors involved in the mass transfer, Figure 5 shows a scheme of a cellular system with the active and passive transports. Interface sucrose solution/surface fruit is defined in order to develop the transport models.

Each chemical specie involved in the osmotic dehydration treatment has different driving forces to move into the cell system. Particularly, water fluxes can be generated by passive and active transports. Passive transport is driven by water chemical potential gradients and it could be produced outside the cells by the apoplastic pathways (Steudle & Frensch, 1996) and through transmembrane protein channels by the aquaporins (Agre et al., 1998; Shiratake & Martinoia, 2007). On the other hand, active transmembrane transport requires energy as ATP and is driven by Ca^{2+} pump. In case of high water stress, the homeostatic cell system counteracts the water losses by the aquaporins introducing water in cell by calcium pump (Moraga,

Moraga, Fito, & Martínez-Navarrete, 2009). Regarding the sucrose fluxes, they are driven by passive transport in the apoplastic ways and by active transport throughout the membrane, by the sodium pump (Zeuthen, 2010).

Electrolytes transmembrane transport is produced by the sodium/potassium pump (Jaitovich & Bertorello, 2006); however, the rest of active transports depend on the pass of some electrolytes such as Ca^{2+}, Na^{+}, K^{+} or Mg^{2+} throughout this pump.

In order to understand and quantify the passive transport, a non-equilibrium thermodynamic model based in Gibbs free energy has been developed (Talens, Castro-Giraldez, & Fito, 2016):

$$dG = -SdT + VdP + Fdl + \psi de + \sum_i \mu_i dn_i|_{P,T,n_i} \quad (5)$$

Where SdT corresponds to the thermic term, VdP and Fdl are the mechanical energies, ψde the electric term and finally $\sum_i \mu_i dn_i$ is the activity term and represents the addition of the chemical potentials of all the compounds in the system considering pressure and temperature constants, and without molecular interactions. Developing the chemical potential for i compound affected by j compounds, by using the equation 5, next equation is obtained:

$$d\mu_i = \frac{dG}{dn_i} = -s_i dT + v_i dP + F_i dl + \psi_i de + RTln\, a_i + \sum_j RTln\, a_j \frac{dn_j}{dn_i} \quad (6)$$

During the PEF treatment, cellular tissue was immersed in a water bath with two poles, inducing an electric field throughout the samples. Taking into account the interface tap water/fruit surface, the chemical fluxes were defined. In case of water and sugars only the activity terms induce chemical potential gradients to produce

transports, because internal pressure and temperature are constant (no deformations appear and the system is tempered). Nevertheless, electrolytes (chemical species with high charge) are also affected by the external electric field, producing high gradients of chemical potential and therefore ion fluxes leaving the tissue. Taking into account only the PEF pre-treatment, the ion chemical potential throughout the interface water/tissue can be defined as follows (Velázquez-Varela, Fito, & Castro-Giráldez, 2014):

$$\Delta\mu_i = \sum_i z_i F E \, \Delta n_i + \sum_j RT \, ln \frac{a_j^{ext}}{a_j^{int}} \, \Delta n_j \qquad (7)$$

Where z is the valence of each electrolyte (with sign), F is the Faraday constant (96485.3415 C/mol), E is the Electric field applied (V/m), Δn_i is the variation of each ion and the subscripts i and j represent the electrolytic and chemical species, respectively. The first term of the equation represents the electric term and the second one is the activity term. Considering that the electric fields applied are moderately high (100 to 400 V/cm) and the electrolytes concentrations are low (low activity of each chemical specie) the driving force that governs the ion transport is the electric term. Therefore, during the PEF pre-treatment electrolyte fluxes are induced, leaving the tissue. Final quantity of electrolytes that will remain in the tissue depends on the electric field strength. Depending on the amount of electrolytes with physiological activity in the tissue, the water and sucrose transmembrane active transport, during the osmotic treatment, will be affected.

In order to quantify the effect of the reduction of the amount of electrolytes, the driving forces during the osmotic dehydration treatment must be defined by using equation 6, fixing the interface between osmotic solution and fruit surface.

In the osmotic dehydration treatment, equation 6 could be transformed according to the research developed by Castro-Giráldez, Fito, & Fito, (2011b) and Tylewicz, Fito, Castro-Giráldez, Fito, & Dalla Rosa (2011). For this treatment, the thermal (SdT) and electric (ψde) terms can be neglected because it is an isothermal process and the amount of native ions is low. Therefore it is possible to obtain the water chemical potential as follows:

$$\Delta\mu_w = \frac{\Delta G}{\Delta n_w} = v_w \Delta P + F_w \Delta l + RTln\frac{a_w^S}{a_w^{OD}} + RTln\frac{a_s^S}{a_s^{OD}}\frac{J_s}{J_w} \quad (8)$$

Where the superscript OD represents the osmotic dehydration solution (sucrose solution), and superscript S represents the properties of fruit surface.

In order to understand the transports, it is necessary to calculate the water molar flux with the following equation:

$$J_w = \frac{\Delta M_w \,.\, M_0}{\Delta t \,.S\,.Mr_w} \quad (9)$$

Where J_w is the water flux (mol/s m^2), ΔM_w represents the water mass variation (dimensionless), M_0 is the initial mass of the sample (g), Δt is the process time (s), S corresponds to the surface of the sample during the treatment (m^2) and Mr_w is the molecular weight of water (18 g/mol).

Figure 6 shows the maximum water flux ordered by the PEF pre-treatment intensity. The electric field applied before the osmotic treatment increases the water flux because the pre-treatment removes a part of the basic electrolytes, reducing the homeostatic cell system based on the Ca^{2+} pump.

Applying the first relation of Onsager (Traffano-Schiffo, Castro-Giráldez, Fito, & Balaguer, 2014), the molar fluxes are related to the chemical potential, as a driving force of the transport of the component i, by the phenomenological coefficient (L_i) (equation 10).

$$J_i = L_i \, . \Delta\mu_i \tag{10}$$

Where the component *i* represents the water or the sucrose. The phenomenological coefficient is the physical property than explains the overall transport of each chemical specie. Nevertheless, the chemical potential is needed in its estimation where mechanical forces induced by the tissue deformations increase the complexity in the calculation. Tissue deformation is produced by the plasmolysis cell process, thus, this effect is punctual and it affects in determined periods of the osmotic treatment. Therefore, it is necessary to analyze the tissue deformation in order to determine the periods without mechanical effects, in order to estimate the phenomenological coefficient.

In order to analyze the tissue deformation, volume and surface variation were calculated by using the following equations:

$$\Delta V = \frac{V_t - V_0}{V_0} \tag{11}$$

$$\Delta S = \frac{S_t - S_0}{S_0} \tag{12}$$

Where V corresponds to the volume (m^3), S is the surface (m^2) and the subscripts t and 0 correspond to the treatment time and the initial value (0 minutes), respectively.

In Figure 7, it is possible to observe the volume deformation during the osmotic treatment, where a shrinkage/swelling process occurs in two phases divided by the plasmolysis process of the different tissues as was explained by (Castro-Giráldez, Tylewicz, Fito, Dalla Rosa, & Fito, 2011c) where activity terms are predominant in the shrinkage periods and mechanical terms are predominant in swelling periods (equation 8). The samples pre-treated by PEF show the critical point of plasmolysis before than the no pre-treated samples. This phenomenon could be accelerated, in the pre-treated samples, by higher water fluxes, and therefore higher intracellular shrinkage. The initial shrinkage is ordered according to the pre-treatment intensity. Consequently, at the initial shrinkage (10 min of OD), mechanical term could be considered neglected, therefore, the chemical potential could be estimated as follows:

$$\Delta\mu_w = RTln\frac{a_w^S}{a_w^{OD}} + RTln\frac{a_s^S}{a_s^{OD}}\frac{J_s}{J_w} \quad (13)$$

And for sucrose chemical potential:

$$\Delta\mu_S = RTln\frac{a_w^S}{a_w^{OD}}\frac{J_w}{J_S} + RTln\frac{a_s^S}{a_s^{OD}} \quad (14)$$

Applying equations 13 and 14, the phenomenological coefficients of water and sucrose were obtained (Table 1). The phenomenological coefficient has a physical

meaning which describes the contribution of driving forces of the compounds according to the fluxes (Ferrando & Spiess, 2003). From literature, similar phenomenological coefficients values were reported for water transport; Castro-Giráldez et al., (2011c) obtained a value of $2.46 \cdot 10^{-5}$ mol^2/J s m^2 for OD of kiwifruit at 30ºC and using a 65% w/w sucrose solution; Segui, Fito, & Fito, (2012) obtained $L_w = 0.9 \pm 0.3 \cdot 10^{-4}$ mol^2/J s m^2 for apple isolated cells during OD at 30ºC using a 45% (w/w) sucrose solution, also Segui, Fito & Fito, (2013) obtained $L_w = 1.3 \pm 0.3 \cdot 10^{-4}$ mol^2/J s m^2 for apple isolated cells during rehydration. In contrast, few data are available for sucrose phenomenological coefficients (L_s).

In Table 1, it is possible to observe the increase of water phenomenological coefficient according to the electric field intensity applied as pre-treatment. Water transmembrane transport works with active and passive transport. The homeostatic cellular system, in case of water stress, induces the activity of Ca^{2+} pump in opposite way of aquaporins (passive transport). However, before the osmotic treatment, the PEF pre-treatment removes the electrolytes, reducing the activity of Ca^{2+} pump, affecting to the osmotic treatment and increasing the kinetics of the dehydration, as the values of Table 1 show. The case of sucrose is the opposite; sucrose transmembrane transport works by the Na^+ pump, therefore any reduction of the overall quantity of the electrolytes reduces the sucrose transmembrane transport maintaining the sucrose transport in the apoplastic ways.

Sorption isotherms describe the relationship between the surface water activity of the samples and its moisture (in dry basis) (Traffano-Schiffo, Castro-Giraldez, Colom, & Fito, 2015). Figure 8 shows the sorption isotherms after treatment (Fig. 8a) and after

reposed 24 h (Fig. 8b) at 4ºC for all the dehydrated samples at each PEF treatment condition. Moreover, data of a pure solution of water and sucrose is shown (Starzak & Mathlouthi, 2006). Surface water activity is a punctual value and moisture is an average value, thus the distance between surface data and line of pure sucrose solution explains the concentration profile inside sample (Castro-Giráldez et al., 2011b). Samples fitted in pure sucrose solution line represent equilibrated samples (no concentration profile), thus it is possible to rename this line to "equilibrated sample line". The relations between both isotherms permit to predict the internal transport, strongly driven by the symplastic ways (Fisher & Oparka, 1996).

After osmotic treatment, samples are close the equilibrium line depending on the pre-treatment intensity (see figure 8a). However, in Figure 8b it is possible to observe that the no pre-treated samples and samples pre-treated at low electric field intensity reach the equilibrium line at 24h, nevertheless the samples pre-treated with PEF are far from the equilibrated sample line. It could be explained because sucrose molecules, in samples without Na^+ pump working (affected by PEF pre-treatment), equilibrate the sucrose content by the apoplastic ways. The symplastic transport of sucrose, without active transport, does not work because symplastic transport needs first a transmembrane transport. Therefore, samples pre-treated by PEF, increase the water transport but reduce the sucrose transport.

Therefore, PEF pre-treatment opens an opportunity in osmotic dehydration treatments in fruits, accelerating the water losses, but reducing the sugar gained in fruit (less calories and sweetness).

4. Conclusions

The application of pulsed electric fields as a pre-treatment of the osmotic dehydration in kiwifruit increase the water mass transfer and reduces the final sugar concentration comparing with samples that have not been pre-treated. The water phenomenological coefficient, in osmotic treatment, increases according to the electric fields applied in the pre-treatment. Thus because, the application of electric field prior to the osmotic treatment removes the electrolytes, reducing the activity of Ca^{2+} pump, and leaving alone the aquaporins as a main protein channel of water transmembrane transport and therefore affecting to the regular functionality of cell homeostasis system. However, the sucrose phenomenological coefficient, in osmotic treatment, decrease according to the electric field applied, because the sucrose transmembrane transport is made by the Na^{+} pump, therefore, any reduction of the overall quantity of the electrolytes reduces the sucrose content. PEF pre-treatment opens an amazing opportunity in the design of new products of candying fruits with high dehydration and less sugar content.

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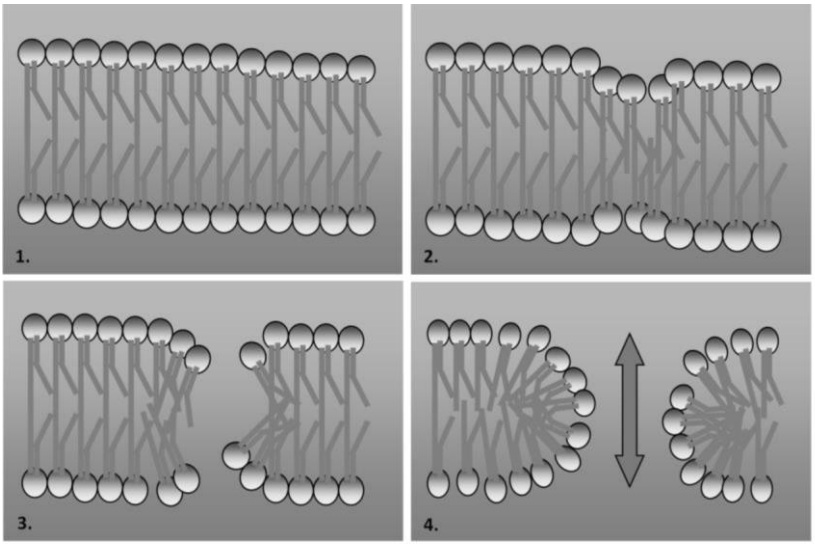
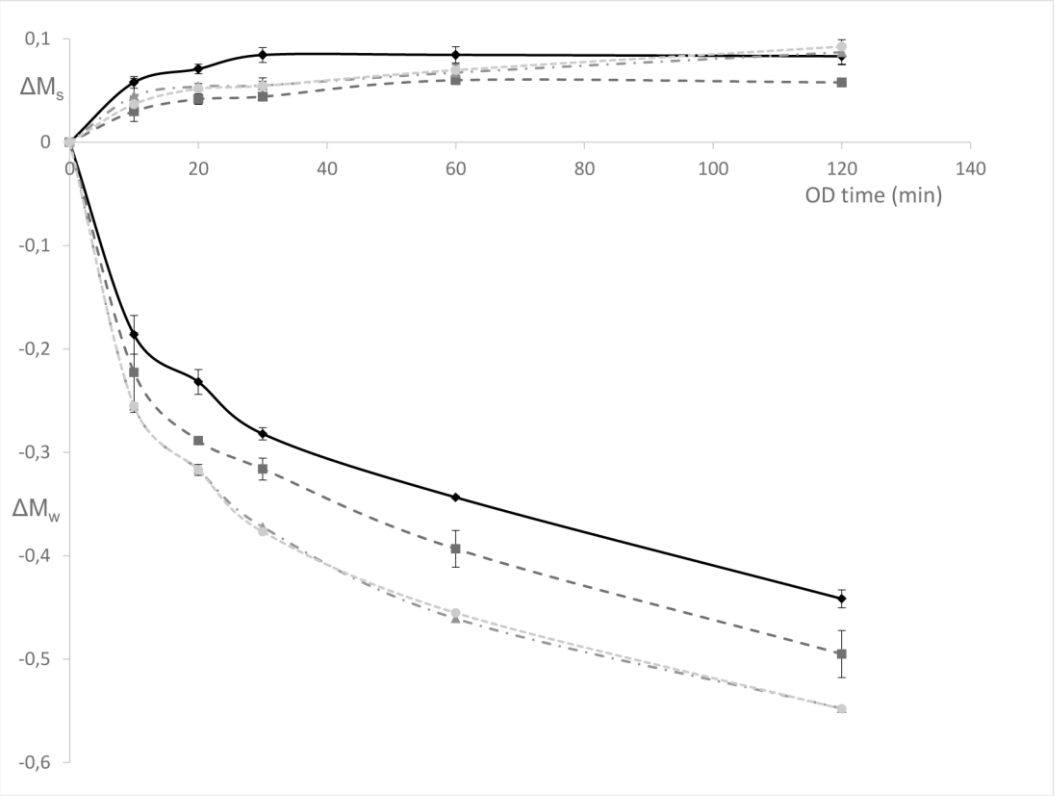


Figure 1.



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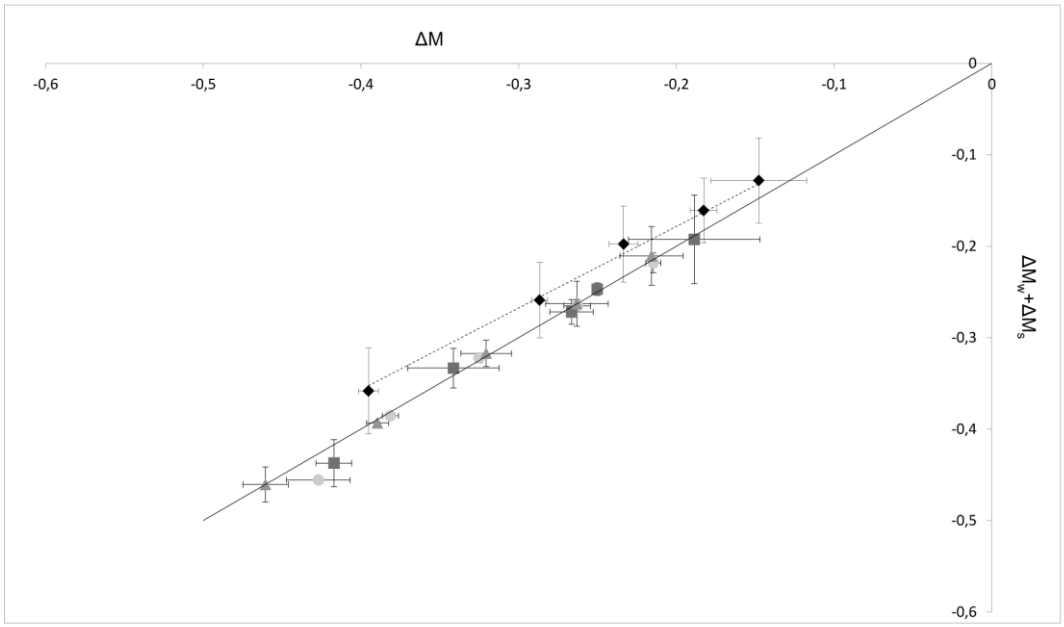

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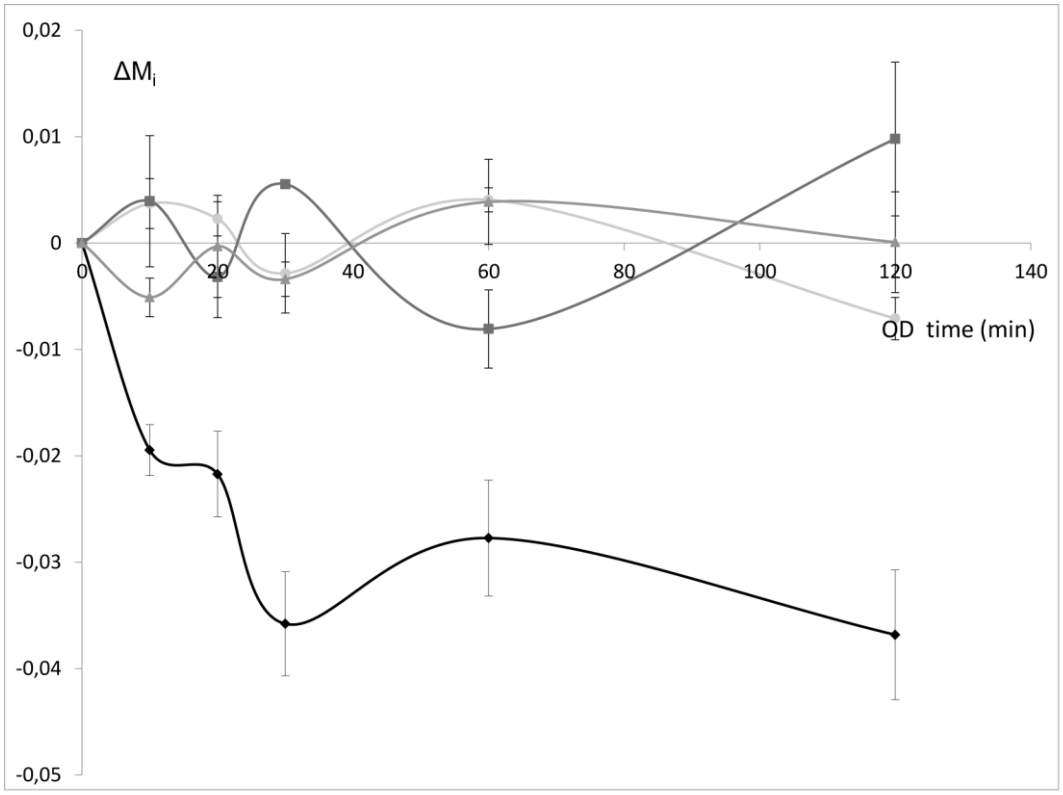

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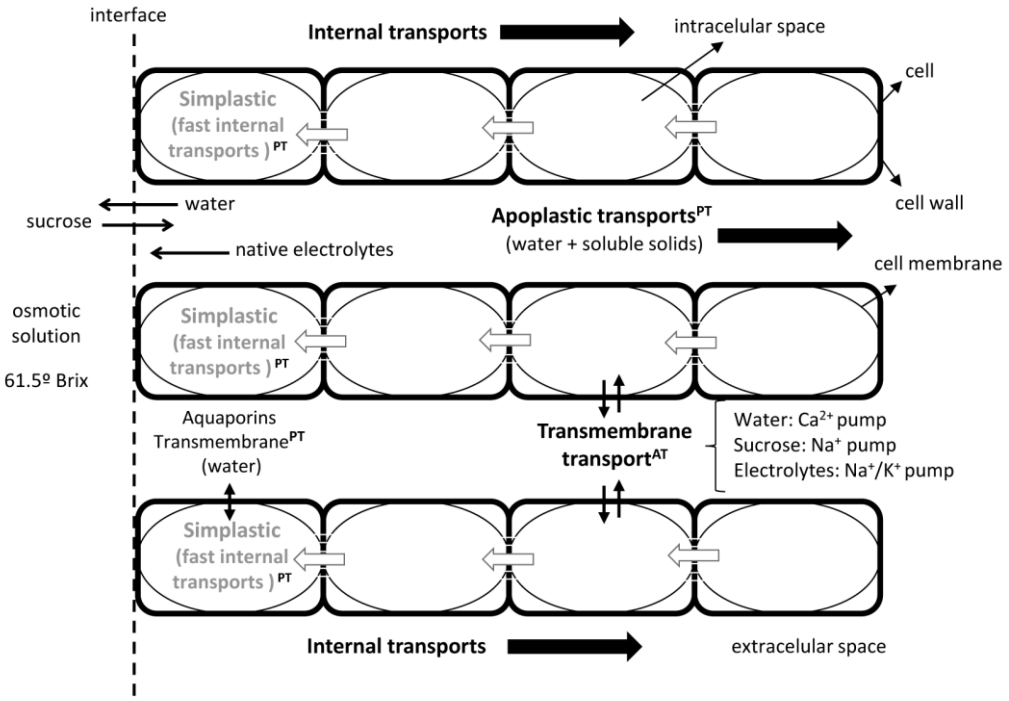

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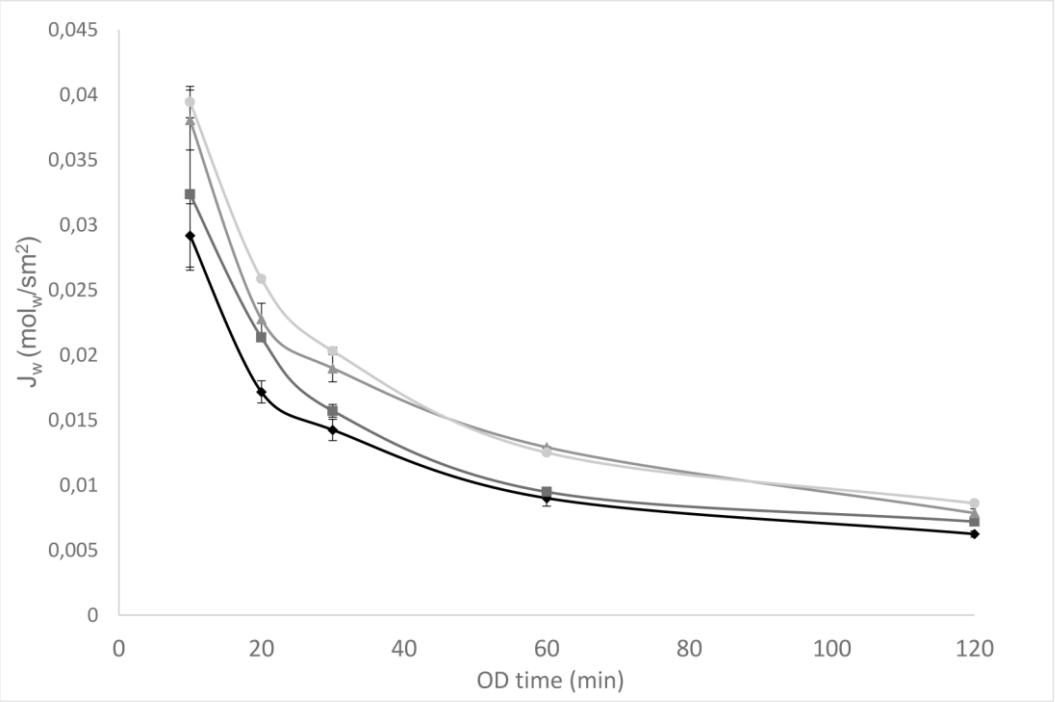

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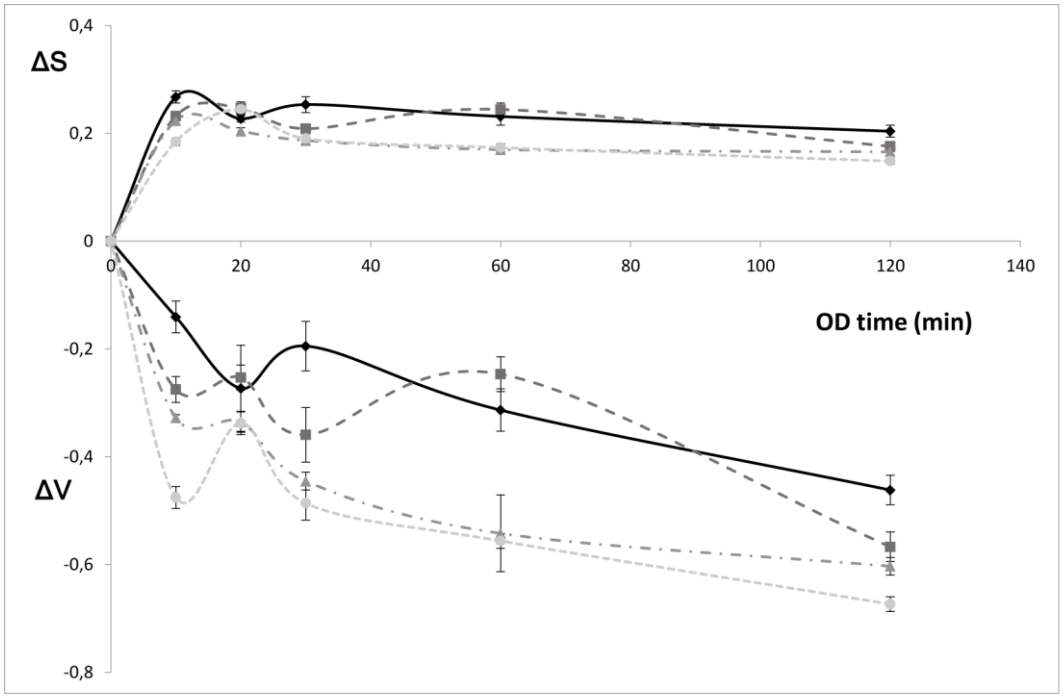

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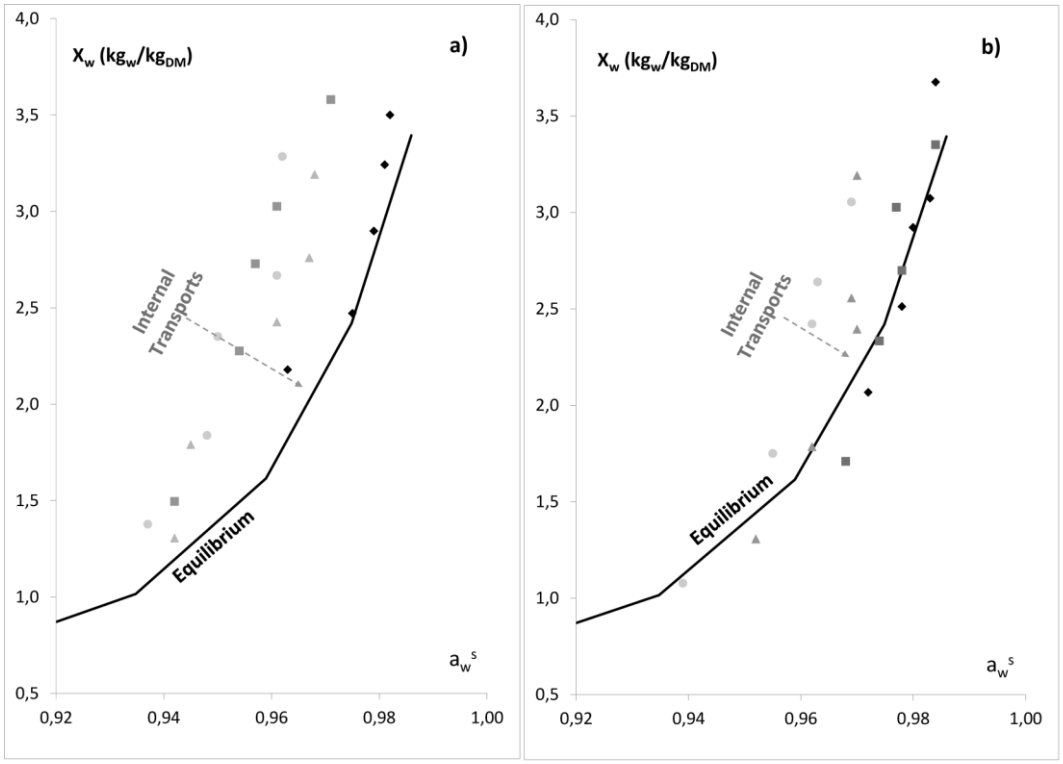

Figure 8.

Table 1

PEF (V/cm)	**L_w (10^{-4})** ($mol^2/J\ s\ m^2$)			**L_S (10^{-8})** ($mol^2/J\ s\ m^2$)		
0	1.7	±	0.4	8.5	±	3.8
100	1.83	±	0.15	1.5	±	0.5
250	2.04	±	0.7	2.9	±	1.7
400	2.4	±	0.5	1.75	±	0.5

RESEARCH HIGHLIGHTS

> The usefulness of PEF as pre-treatment of OD of kiwifruit has been demonstrated.

> A thermodynamic approach able to analyze tissue deformation has been developed.

> The phenomenological coefficients of water and sucrose have been obtained.

> Samples pre-treated with PEF show higher water losses and less sugar gain.

> PEF removes part of the native electrolytes, reducing the activity of proteins pumps.