Innovative Food Science and Emerging Technologies 38 (2016) 243–251

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

journal homepage: www.elsevier.com/locate/ifset

Effect of pulsed electric fields pre-treatment on mass transport during the osmotic dehydration of organic kiwifruit

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ARTICLE INFO

Article history:
Received 13 June 2016
Received in revised form 18 September 2016
Accepted 14 October 2016
Available online 15 October 2016

Keywords:
Kiwifruit
Pulsed electric fields
Osmotic dehydration
Mass transfer
Thermodynamics
Phenomenological coefficients

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 °Bx, 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.
Industrial relevance: This research develops a thermodynamic model able to describe mass transfer and kiwifruit deformation during OD and using PEF as a pre-treatment. Moreover, a deep analysis of active and passive mechanisms transports affected by PEF was done. The results of this research have demonstrated that PEF used as a pre-treatment of OD accelerated water mass transfer and removes part of the fruit natives electrolytes, affecting the functionality of the cell homeostasis system. Therefore, the present work represents an opportunity in the design of new candying products (less calories and sweetness).

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

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http://dx.doi.org/10.1016/j.ifset.2016.10.011
1466-8564/

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

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 Fig. 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, and Riemann (1976) applied voltage gradients in a simulated cell membrane. They reported values between 5 mV to 1 V at 20 °C and 1.2 V at 4 °C 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 20 °C and 3 MV/cm at 4 °C. However, some effects in chemical transport by using PEF at lower electric fields intensities used as pre-treatment of OD have been reported. Rastogi et al. (1999) have been able to accelerate the water mass transfer of carrots by applying electric fields between 0.22 and 1.6 kV/cm at 40 °C; Taiwo, Angersbach, Ade-Omowaye, and Knorr (2001) have increased the water loss with a minimal alteration of apples using an intensity electric field of 1.4 kV/cm at 40 °C. Finally, Tedjo, Taiwo, Eshtiaghi, and Knorr (2002), have obtained a moisture reduction without altering the taste of mangos by applying 1 to 3 kV/cm at 40 °C.

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 et al., 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 °C until their processing. The fruits were tempered at 25 °C, 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 °Bx.

2.2. Experimental procedure

The fresh samples were characterized according the following parameters: mass, volume, refractometric index (°Bx), 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 min. Due to the fact that the samples after treatments show concentration profiles, another batch of samples were reposed after the treatments at 4 °C during 24 h in decagon containers closed with parafilm® in order avoid the sample dehydration. Finally, mass, volume, °Bx, water activity and moisture were measured as final determinations for fresh, treated and reposed samples.