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Determining the effective diffusion coefficient of water in banana (Prata variety) during osmotic dehydration and its use in predictive models

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ABSTRACT

The objective of this study was to develop a suitable method for determining the effective diffusion coefficient of water in banana (Prata variety) from experimental data of osmotic dehydration (OD) and using this coefficient for predicting dehydration of the same sample under other situations. Different methods were compared in order to determine the best coefficient to be used in the predictive models. The analytical solution of the diffusion equation allowed estimating averaged values of coefficients between the initial moisture and the average sample moisture at a given instant. The numerical method allowed estimating how the effective diffusion coefficient varies with the moisture. The models prediction ability were validated using a dehydration data set not used for estimating the diffusion coefficients. The use of the diffusive model with a coefficient that depends on the moisture content has the best predictive ability, because it takes into account that the coefficient decreases during the OD.

1. Introduction

Osmotic dehydration (OD) consists of partial removal of water from cellular tissues by the immersion of a food (vegetables, fruits, meat) in a hypertonic aqueous solution. During the osmotic process, the mass transfer (MT) in plant tissues is complex, being influenced by the cell wall structure. The driving force for the dehydration is the higher chemical potential of water in the food cells in relation to that in the osmotic solution (OS). In contrast, the chemical potential of the solute in the OS is higher than in the food cells. Thus, there are two simultaneous fluxes, i.e., water from the food to the solution, and solutes from the OS to the food. Since the cell membrane is not perfect, selective leaching of solutes from the cells to the OS can also occur (Torreggiani, 1993).

Despite being a technology extensively studied, there is still great interest in better understanding the phenomena and description of the involved mechanisms. Mathematical modeling can be a useful tool for understanding the kinetics of OD, as shown by the works of Yao and Le Maguer (1996, 1997a, 1997b). These authors present a conceptual model of plant cell structure and the corresponding mathematical model. Yet, they present a procedure for solving the models in order to determine the concentration profiles in the cell tissues undergoing OD. The parameters investigated included concentration of OS, molecular mass of solute, permeability of cell membrane, and the initial void ratio of plant tissue.

Literature presents mathematical models for OD based on thermodynamics of irreversible processes (Seguí et al., 2010, 2012) and on the Fick's law and histological observations of the cellular tissue (Spiazzi and Mascheroni, 1997). A microscopic view has the advantage of more accurate understanding of mass transfer phenomena that occur during the OD, since the properties of the heterogeneous tissue are considered. However, most of these models are complex and not easy to use, requiring the use of difficult to measure parameters such as cell characteristics, tensile modulus and void fraction in the cell wall, tortuosity, membrane permeability, among others. It is therefore common the use of macroscopic approaches to the development of models that are able to represent appropriately the mass transfer during OD in a simplified manner.

Most research assumes that the OD is macroscopically governed by Fick's Law, which is used for estimating average diffusion coefficients of water in the food through different methods (Hough et al., 1993; Ertekin and Sultanoglu, 2000; Rastogi and Raghavarao, 1997; Rastogi et al., 1997; Ferrari et al., 2005 among others). Hough et al. (1993) solved the diffusion equation numerically using Crank–Nicolson method, and developed a simplified model to describe the OD of apples. The value found for the effective diffusion coefficient of water in the fruit was approximately 2.0×10^{-10} m^2 s^{-1} for the different samples. The same method was used by Ertekin and Sultanoglu (2000) to investigate the OD of apples, using different temperatures, dehydrating agents, and solution concentrations. They estimated the equilibrium concentrations using the empirical model of Azuara (Azuara et al., 1992). The values found for the effective diffusion coefficient of water through the apple ranged between 10^{-11} and 10^{-10} m^2 s^{-1}, depending on the experimental conditions. Silva et al. (2012) estimated the diffu-

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Nomenclature

A	constant in D_X model ($m^2\ s^{-1}$)
aw	water activity
B	constant in D_X model ($m^2\ kg\ kg^{-1}\ s^{-1}$)
Bi	mass transfer Biot number
C	constant in D_X model ($m^2\ s^{-1}$)
D	constant in D_X model ($kg\ kg^{-1}$)
D	effective diffusion coefficient ($m^2\ s^{-1}$)
$\overline{D}$	average effective diffusion coefficient ($m^2\ s^{-1}$)
D_X	effective diffusion coefficient as a moisture content function ($m^2\ s^{-1}$)
$\overline{D}_X$	average effective diffusion coefficient between initial moisture content and moisture content at time t ($m^2\ s^{-1}$)
E	average error between experimental data and predicted values, in percentage
J_0	order zero Bessel function of the first kind
J_1	order one Bessel function of the first kind
L	half thickness of sample (m)
ML	mass loss ($kg\ kg^{-1}$), in percentage
MSE	Mean Square Error
MT	mass transfer
N	number of data
OD	osmotic dehydration
OS	osmotic solution
P	number of parameter
R	radial coordinate (m)
R	radius of the sample (m)
SG	solids gain ($kg\ kg^{-1}$), in percentage
T	time (s)
W	sample mass after osmotic dehydration (kg)
w_0	mass of non-treated sample (kg)
WL	water loss ($kg\ kg^{-1}$), in percentage
w_s	dry solids mass in the sample after osmotic dehydration (kg)
w_{s0}	dry solids mass in the non-treated sample (kg)
w_w	water content in the sample (kg)
w_{w0}	Water content of non-treated sample (kg)
X	axial coordinate (m)
X	moisture content in dry basis ($kg\ kg^{-1}$)
X_e	experimental moisture content in dry basis ($kg\ kg^{-1}$)
X_p	predicted moisture content in dry basis ($kg\ kg^{-1}$)

Greek letters

P	concentration of water in the sample ($kg\ m^{-3}$)
ρ_i	Initial concentration of water in the sample ($kg\ m^{-3}$)
ρ_s	water concentration in the surface of the samples in equilibrium with the osmotic solution ($kg\ m^{-3}$)
$\bar{\rho}$	average concentration of water in the sample ($kg\ m^{-3}$)
γ_n	nth root

sion coefficient of West Indian cherry during OD by the inverse method, using average moisture contents. The optimization method of Levenberg–Marquardt and the differential evolution algorithms were used for estimating the diffusion coefficient, which values ranged from $1.558 \times 10^{-10}\ m^2\ s^{-1}$ to $1.771 \times 10^{-10}\ m^2\ s^{-1}$.

Rastogi and Raghavarao (1997) investigated the OD of carrots under different conditions and observed the dependence of the water diffusion coefficient with the temperature and OS concentration. This dependency was represented empirically by an Arrhenius type equation. The water diffusion coefficient ranged between 3.0×10^{-10} and $7.0 \times 10^{-10}\ m^2\ s^{-1}$, depending on the temperature and sucrose concentration. Similarly, Rastogi et al. (1997) found values of diffusion coefficients of water in banana (Cavendish) between 2.43×10^{-10} and $8.50 \times 10^{-10}\ m^2\ s^{-1}$. Although the diffusion equation do not represent the complexity of the different mass transfer mechanisms during OD of a food, it has been very useful to modeling this process (Schmidt et al., 2009).

Other empirical models have been used to describe the mass transfer during OD processes, such as the model proposed by Azuara et al. (1992). This model is based on a simple mass balance and allows estimating a pseudo-equilibrium concentration of a solute in the interface solid–liquid solution. The probabilistic model based on the Weibull distribution was also used as an equation suitable for describing the loss of water during the OD of apples (Cunha et al., 2001).

Literature data of the diffusion coefficients for a same product are generally averaged (mean values), and exhibit considerable differences among them, even for comparable experimental conditions. The use of effective (apparent) diffusion coefficients reduces all structural effects and physical mechanisms to a single parameter. In this way, to improve the fit of the model to the data, it is recommended expressing the diffusion coefficient as a function of the sample moisture (Aguilera et al., 2003).

This paper compares different mathematical approaches to determine the behavior of the effective diffusion coefficient of water in banana fruit subjected to osmotic dehydration. The influence of fruit moisture content on the water diffusion coefficient was investigated, as well as the predictive ability of the diffusion model, using the 'different' water diffusion coefficients determined from a data set of OD experiments. The models were validated using a new data set, obtained from different experiments, which were not used for estimating the model diffusion coefficients.

2. Materials and methods

2.1. Banana samples and osmotic solution

Banana (*Musa Sapientum* L., Prata variety) was purchased in a local market (Florianópolis, SC, Brazil). The fruits were selected based on their appearance and state of ripeness, which was evaluated from soluble solids content using a digital refractometer (AR200 Reichert, USA) and from the resistance to penetration using a penetrometer (Effegi, model FT 327-8mm, Italy). The soluble solids content were 23.1 ± 1.4 °Brix (average ± standard deviation). Selected fruits were peeled manually before use and sliced to 5 mm and 10 mm of thickness with a diameter of approximately 30 mm.

Osmotic solutions were prepared with commercial sucrose and distilled water. A mass ratio of 1:30 between fruit samples and OS was used in all experiments, in order to avoid significant changes on sugar solution concentration during the experiments.

2.2. Experimental device

Experiments of OD of banana samples were performed with the device sketched in Fig. 1. This device consisted of a container (internal volume of $14.14\ dm^3$) with the temperature controlled by a thermostatic bath (Quimis, Model Q214M2, Brazil) that circulated water at a constant temperature in its jacket. The osmotic