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Study of three-stage intermittent drying of pears considering shrinkage and variable diffusion coefficient

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A B S T R A C T

An intermittent drying process of whole pears of *Rocha* variety was performed in order to reproduce the traditional sun drying of the Portuguese *São Bartolomeu* regional variety. This traditional drying originates a much appreciated product. The results show that the "*Rocha*" pear presents a similar kinetic behaviour with diffusion coefficients ranging from 2.5×10^{-9} m^2.s^{-1} to 6.0×10^{-11} m^2.s^{-1}, at 40 °C, and from 2.4×10^{-9} m^2.s^{-1} to 1.9×10^{-10} at 50 °C, considering shrinkage. A total time reduction of 28.7% was achieved when drying at 50 °C instead of 40 °C, thus concluding that the air temperature has a much greater influence on the drying kinetics than the airflow velocity. The intermittency of the process contributed to decrease the total time of convective drying, achieving a reduction of 26.2% when using three 14 h pauses in the set of tests performed at 50 °C with an airflow velocity of 2.7 m.s^{-1}. It was also verified that shorter pause periods are disadvantageous and lead to longer drying time, because the homogenization of the radial moisture distribution is incomplete before starting the next convective drying phase.

The methodology used in this study can be an alternative to traditional drying and be suitable to an industrial context, applying a correct strategy for the duration and number of pauses, with gains in productivity and energy savings.

1. Introduction

Drying of food products with the objective of their preservation as been used since ancestral times, recurring to sun as available energy source (Belessiotis and Delyannis, 2011). In recent years, new technologies emerged, with numerous solutions that seek to enhance quality, reduce energy consumption and environmental impact and improve the safety of foodstuffs (Jangam, 2011). Some examples are the technological advances in solar drying systems, the heat pump dryers, spray, rotary and freeze dryers, among other solutions, with the possibility of coupled technologies (like microwave or infrared drying) and/or pretreatments (Goh et al., 2011; Moses et al., 2014; Prakash and Kumar, 2013).

It is possible to find in the literature a huge number of dried food products including fruits, vegetables and grains, among others (Mujumdar, 2007).

Drying of whole pear is a practice in the central region of Portugal. The commonly used *São Bartolomeu* pear is a regional variety with low commercial viability when raw, but with a high market price when dried. The traditional proceeding is the outdoor sun drying. This process takes at least ten days in an intermittent mode that consists of several stages (Guiné, 2013), namely (*i*) *first drying*: after peeling, pears are sundried for a 5–6 day period, keeping the peduncle untouched; (*ii*) *barreling*, a two days stage where pears are taken out of the sun around the hottest hour of daytime and then muffled in baskets (supposedly to increase the elasticity of the final product); (*iii*) *pressing*, to give the pear a flat geometry; and (*iv*) *second drying*, repeating the sun drying for two or three days.

The traditional drying method requires long processing times and is strongly affected by several constraints, such as meteorological conditions and contamination by moulds or insects. These factors are incompatible with the current food safety demands. On

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Nomenclature

A	pears surface area [m]
C	water concentration [kg.m^{-3}]
C_{eq}	equilibrium water concentration [kg.m^{-3}]
C_i	initial water concentration [kg.m^{-3}]
C_s	surface water concentration [kg.m^{-3}]
d	pears diameter [m]
r	pears radius [m]
D	diffusion coefficient [m^2.s.$^{-1}$]
h_m	mass transfer coefficient at the surface [m.s^{-1}]
m_d	dry mass [kg]
m_i	initial mass [kg]
m_w	mass of water [kg]
$m_{w.i.}$	initial mass of water [kg]
M^*	normalized mass of water [-]
MAPE	mean absolute percentage error [%]
r	radius [m]
r_0	maximum radius [m]
$R.H.$	relative humidity [%]
T	temperature [°C]
T_c	chamber temperature [°C]
T_{int}	internal temperature of the pear near the centre [°C]
T_{surf}	temperature at the pear surface [°C]
t	time [h]
V	pear volume [m^3]
V_0	initial pear volume [m^3]

Symbols

X	water homogenization in pears [%]
ρ_w	water volumetric mass [kg.m^{-3}]
$\omega_{d.b}$	dry basis water content [kg H_2O/kg dry matter]

the other hand, the high interest in preserving this traditional product has motivated research in the last years, in order to adapt the traditional product to a large scale industrial operation, maintaining the high quality attributes of the sun dried product (Guiné, 2013; Guiné and Castro, 2002; Guiné et al., 2011). The present work is integrated in a research project whose main objective is the industrialization of the drying process of pear. This process can also be applied to other regional products from the central region of Portugal with high potential for commercialization as dried foodstuff.

The aim of this study was to adapt the traditional sun drying of the Portuguese *São Bartolomeu* pear to the demands of the current market, on the basis of an intermittent convective drying strategy, trying to approach as close as possible the unique organoleptic properties of this traditional product. Therefore, the stages of traditional sun-drying of this regional variety were reproduced with the main purpose of studying the drying kinetics of *São Bartolomeu* pear and reducing the process time. However, due to the unavailability of *São Bartolomeu* pear along the year, the experimental campaigns were conducted with another Portuguese variety (*Rocha*) with similar size. The absence of solar radiation in this drying methodology will certainly influence the organoleptic properties of the product, but this will be analyzed in subsequent studies.

2. Materials and methods

2.1. Experimental setup

In order to simulate the stages of traditional sun drying, a set of laboratorial tests was performed. The methodology is based on a cyclic sequence of three distinct stages, namely (*i*) a convective drying period (C) at high air temperature ($T = 40–50$ °C) and low relative humidity (RH) (15%), reproducing the first and second drying phases of the traditional process; (*ii*) a "hot humid" pause (P1) at $T = 40–50$ °C and RH = 80%, simulating the barreling stage; and (*iii*) a "cold humid" pause (P2) at $T = 17$ °C and RH = 80%, simulating the night period of the traditional solar drying.

To allow the analytic approach of the kinetic behaviour considering an almost spherical sample, the pressing of pears was not performed.

The intermittency of the process, guaranteed by the cyclic repetition of the sequence of stages C-P1-P2, aims at achieving the particular textural and colorimetric properties of the sundried product, despite the absence of solar radiation. As stated by several authors, intermittent drying procedures improve the organoleptic characteristics and also reduce the energy costs of the process, through an overall reduction of the convective time (Kowalski and Szadzínska, 2014; Kumar et al., 2014; Silva et al., 2014; da Silva et al., 2015).

Due to the unavailability of *São Bartolomeu* pear along the year, another Portuguese variety (*Rocha*) was tested. The characterization of the drying process (in continuous and intermittent mode), considering the fruit shrinkage, and the determination of the main parameters of the process are presented, highlighting the similarities of both fruit varieties.

A programmable climatic chamber *Fito clima 300 EDTU* with dimensions of 0.640 m × 0.780 m × 0.575 m was used as drying chamber to simulate the different stages of the intermittent process. An extruded polyethylene box with dimensions 0.380 m × 0.380 m × 0.380 m was positioned inside the climatic chamber (Fig. 1). It works as a drying tunnel along which the airflow is guaranteed by the chamber fan that promotes the air extraction through a perforated section at the centre of the rear wall, for a continuous air circulation during operation. The area of the box rear section is modifiable using removable plates that assure different configurations for achieving different levels of air velocity at the centre of the box, where the sample tray will stand, hanged from a balance. In the present work, two plates (0.380 m × 0.125 m × 0.030 m) were used for the convective stages (C) in tests 1 to 4 and in tests 6 to 8 (see Fig. 2a). In the other tests, no plates were applied on the rear section (Fig. 2b)). For the pause periods (P1 and P2), the rear section of the test box is sealed, while the front section area was reduced to about ¾ by applying a small plate on its bottom and covered with a plastic mesh with 0.005 m hole aperture (Fig. 2c). This configuration assured very low airflow velocity ($U < 0.2$ m.s^{-1}) and the T and RH conditions specified for the P1 and P2 periods inside the test box.

In the pause periods of all tests and in the convective stages of the tests with $U = 1.28$ m.s^{-1}, the distance between the box and chamber ventilator was fixed at 0.09 m. In stages C of test 5 and of tests 9 to 12, this distance was null.

In the middle of the test box, a perforated square tray with 0.0225 m^2 is suspended from a balance for continuous mass measurement as described in 2.3.

At the beginning of each test, three approximately spherical pears, representative of each available lot in use, were peeled and disposed on the sampling tray keeping the peduncle intact.