Research article

Drying kinetics of two fruits Portuguese cultivars (*Bravo de Esmolfe* apple and Madeira banana): An experimental study

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ABSTRACT

Air convective dehydration was carried out at a laboratory scale using two fruits of cultivars produced in different regions of Portugal: *Bravo de Esmolfe* apple, from Beiras province, and Cavendish banana, from Madeira Island. Fresh fruits were dried in a tray drier with a hot airstream at different temperatures (35, 40, 45, and 50 °C) and velocity of 1.6 m s^{-1}. Drying rate curves were obtained using a simple mathematical approach applied to the moisture content curves adjusting linear and polynomial functions. Different drying rate stages were noticed in the experiments made with apples (one constant drying rate period followed by two falling drying rate periods), while in the case of the banana the constant drying rate period was not perceived, being dried entirely during a unique falling drying rate period. As expected, the constant drying rate value obtained at the beginning of the experiments with apples is higher when these were conducted at higher temperatures, changing from 8.103 to 14.474 g m^{-2} s^{-1} when the airstream temperature increases from 35 to 50 °C. The correspondent critical moisture contents in the *Bravo de Esmolfe* apples, at the instant the constant drying rate period stops and the drying rate starts to fall, slightly decreases from 4.800 to 4.134 kg$_{water}$/kg$_{dry\ solid}$.

This study explored for the first time the drying behavior of these two important fruits that have been increasingly used in the food industry in Portugal, giving important information for the industrialization of its production.

1. Introduction

The demand for fruit has increased considerably due to their content of vitamins, phenols and other antioxidants related to the prevention of various cancers and degenerative diseases (Guerreiro et al., 2017).

Although having an exceptional taste and notable health benefits, fresh fruits and vegetables are subject to degradation processes by microorganisms and chemical and enzymatic reactions, mainly due to their high water content. Food industries use several strategies to improve the fruits stability and availability being the direct dehydration to a dry form a commonly used method to increase the shelf-life of fresh fruit and to produce different healthy snacks. The dehydration process during which the water activity is reduced considerably defines the final fruit quality, such as nutritional value, color degradation, texture and rehydration capacity. In order to plan the dehydration process leading to a high quality dried fruit, it is essential to have a good understanding of the physico-chemical mechanisms that occur in the dehydration process.

Snack food products consumption has increased exponentially worldwide over recent decades, already representing a significant part of the daily intake of nutrients as they are consumed throughout the day between the traditional three meals to promote satiety and suppress overconsumption at the subsequent meals (Pires et al., 2021).

The present research is dedicated to the air-drying of two Portuguese original types of fruits: "*Bravo de Esmolfe*" apples, a Protected Designations of Origin (PDO) fruit growing in the enclosed region of north-central Portugal at Beiras traditional province, and banana from Madeira Island.

Apples are characterized by their variety and balanced composition, by a moderate energy value and by an adequate balance between sugar and acid contents, giving it a pleasant taste, being one of the most

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consumed fruits worldwide. In Portugal, in 2018 an average of 24.1 kg of apples per capita were consumed, being the most important consumed fruit, showing its importance in the Portuguese diet (Feliciano et al., 2010; FAOStat, 2020).

One of the most important commercialized apples are the *Bravo de Esmolfe* apple, a small to medium size Portuguese apple variety with pale-yellow skin, white interior and an intense aroma, highly valued by consumers. This apple recognised as a PDO product is a high added value product with impact in the local and national economy, having an higher price when compared to others varieties, like Starking and Golden (Feliciano et al., 2010; Pires et al., 2018; Rocha et al., 2004). Its production corresponding to 200,000 kg per year, have a growing commercial demand, owing to its pleasing sensory characteristics, mainly taste and sweetness (Pires et al., 2018; Reis et al., 2009).

Bravo de Esmolfe apple is harvested in the middle of September and its commercialization last no longer than May, being more intensive between December and February (Rocha et al., 2004). The commercialization of dehydrated and snack fruit would be an important way to increase the longevity of this fruit on the market, increasing the environmental and economic sustainability of this important Portuguese fruit production sector.

The other fruit studied is the Cavendish banana from Madeira Island, a small, sweet and tasty fruit. Bananas are cultivated in over 130 countries and grow over a harvested area of approximately 10 million hectares (Villaverde et al., 2013; Vilela et al., 2014). The banana fruit has a relevant nutritional value, providing a significant consumption of carbohydrates, fiber, vitamins, and minerals, as well of phytochemicals, including unsaturated fatty acids and sterols (Pontes et al., 2012; Vilela et al., 2014).

The banana plant is a very important crop in the Madeira Island economy. The sub-tropical climatic conditions of Madeira Island allowed the successful introduction of this crop in the middle of the sixteenth century (Oliveira et al., 2005). According to official statistics, the banana plantations produce annually about 30,000 tonnes of fruit, representing 20% of the agricultural production and about 30% of the exportations from the Island (Oliveira et al., 2006; Vilela et al., 2014; DREM, 2020). "Dwarf Cavendish" (*Musa acuminata* Colla var cavendish) specie is economically the most important cultivar in Madeira Island, and is also the most relevant in productivity (ca. 50–60% of the total banana production) and occupied area (Oliveira et al., 2005; Vilela et al., 2014).

The application of a drying step in the manufacture of foodstuffs, and in particular, of vegetables and fruits has the following advantages: i) to increase the product stability in terms of conservation and consequently the rise of its expiration dates due to its lower water activity; ii) to prevent the development of microorganisms; iii) to facilitate the manipulation of the dried food by the customer; iv) to reduce the solid weight, facilitating the transport and v) to reduce costs of dehydration compared with other drying processes such as freeze drying (Mujumdar, 2006).

Moisture content of a solid is usually expressed in a dry basis, mass of water per mass of dry solid, and is designated by X. The drying curve of a specific material is the plot of X versus t, representing the moisture content evolution in the solid along the drying process. Very often, by inspection of that curve, different behaviors in the solid drying are observed due to the influence of the product internal structure in the mass transfer phenomena. Frequently, after a transitory period, at the beginning, where the solid temperature adjusts to the air drying conditions, there is an initial period where drying is controlled by the external moisture transport through the airstream, after evaporation at the solid surface, being the solid dried at the maximum drying rate. Afterwards, the drying rate starts to decrease when the moisture internal transport becomes the dominant mechanism and is conditioned by the nature of the product being dried. In this phase one, or two, periods with different behaviors in the drying curve is observed.

The instantaneous drying rate at which the moisture is removed from the solid can be obtained from drying curves (X versus t) as the slope dX/dt. If R represents the drying rate at any time t, thus:

$$R = -\frac{W_s}{A}\frac{dX}{dt} \tag{1}$$

where A stands for the drying area (the area exposed to the drying agent), W_s is the weight of the solid completely dry and t is the time.

If the solid surface is saturated with water, the evaporation rate depends on the airstream conditions (external mass transfer controlling) and X decreases linearly with t. During this period, the drying rate is constant, R_c. Some products do not exhibit a constant drying rate period (CDRP), particularly when dealing with food and agricultural products (Doran, 2013; Guiné et al., 2014; Aghilinategh et al., 2015).

When a solid surface starts to present dry zones, the mechanisms of moisture transport through the internal structure of the solid control the drying rate (internal mass transfer controlling) and moisture migration to the surface is not enough to maintain the maximum drying rate. The solid moisture content at this instant is designated by critical moisture content (X_c) and the drying rate decrease as the process continues. A falling drying rate period (FDRP) starts and several phenomena are responsible for moisture migration limitations through the solid. Moisture transport due to capillary forces, induced by pressure gradients and liquid or vapor diffusion are some of them, with their magnitudes depending on the solid structural nature and drying operation conditions.

Some solids may display more than one critical moisture content. In general, this is observed when the principal phenomena associated with moisture migration changes due to structural/chemical modifications occurring in the solid (May and Parré, 2002). This behavior is reflected in the drying rate curve with a change of shape. Experiments of drying kinetics are of crucial importance for X_c determination as it is not only a solid property but it depends also on drying rate conditions.

There are several models proposed in the literature to describe drying kinetics. Some were developed from theoretical considerations and others are entirely supported by experimental results.

Page model is a popular and successful model in describing the drying behavior of fruits and legumes. It is a semi-theoretical model approved by ASABE (American Society of Agricultural and Biological Engineers) for modelling thin-layer drying of crops (ANSI/ASAE, 2014) and is represented by an exponential function with two parameters (k and n),

$$\frac{X - X_e}{X_i - X_e} = \exp(-k\,t^n) \tag{2}$$

where, X_i is the initial solid moisture content (dry basis) and X_e is the equilibrium solid moisture content.

In a recent review study (Onwude et al., 2016), the thin-layer theories, models, and applications, particularly to fruits and legumes drying behavior, were presented. In this study, Page model (Equation 2) is referred to as one of the most suitable models to describe the drying kinetics of the fruits and legumes, particularly to represent the banana drying. In the study carried out by Kaleta et al. (2013), the drying characteristics of apple cubes (variety Ligol) were evaluated in a fluidized bed drier, and Page model (Equation 2) was considered as one of the most appropriate models.

Empirical models are also widely used to obtain the relationship between moisture content and the drying time and they adequately describe the drying kinetics of various products, and some fruits and legumes in particular (Onwude et al., 2016). The model of Wang and Singh (1978) considers a quadratic equation and was originally proposed to fit the data registered in a thin-layer of medium-grain rough rice drying experiment,

$$\frac{X - X_e}{X_i - X_e} = 1 + a\,t + b\,t^2 \tag{3}$$

where a and b are constants.

This empirical model is referred by Onwude and coauthors (2016) to explain adequately the drying behavior of bananas, supported in the conclusions made by Omolola et al. (2014) and Fadhel et al. (2011).

Among the models tested by Omolola et al. (2014), the quadratic equation (Equation 3) proposed by Wang and Singh was the one to be suitable in describing the microwave drying kinetics of a thin-layer of Mabonde banana variety. Fadhel and coauthors (2011) found the same conclusion when essayed to describe the thin-layer behavior of banana in a forced convection indirect solar drier. Among the eight models tested, the Wang and Singh model presented the higher values of the correlation parameters.

Kemp et al. (2001) proposed some methods for processing drying kinetics raw data, but a simple and expeditious approach has been applying by the authors with success. This approach was presented in detail using the cork powder drying as a case study (Castro and Pinheiro, 2016) and afterwards, was used in processing drying data recorded in experiments with granular cork products with different sizes (Madaleno et al., 2017) and foodstuffs as courgette (Pinheiro et al., 2015) and potatoes (Madaleno et al., 2018). The data acquired during experiments, after being expressed in terms of moisture content is fitted using appropriate functions. A linear function is firstly essayed to fit data corresponding to the process beginning (after neglecting the initial transitory instants)

$$X = a\,t + b \tag{4}$$

and a second-degree (or higher) polynomial function is used to fit the remaining data,

$$X = c\,t^2 + d\,t + e \quad \text{or} \quad X = f\,t^3 + g\,t^2 + h\,t + i \tag{5}$$

where a, b, c, d, e, f, g, h and i are constants.

Therefore, the drying rates correspondent to CDRP and FDRP according to Castro and Pinheiro (2016) are obtained differentiating the functions fitted (Equation 4 and Equation 5), as described by Eq. (1). The procedure is repeated with new iterations until continuous functions of drying rate are attained when the transition between the two periods occurs. Hence, at this step, the critical moisture content is determined. The proposed methodology could be also useful in detecting more than one falling drying rate period if present. For more details of the methodology implemented, the description in Castro and Pinheiro (2016) is recommended.

Although several studies have been reported on the drying process of various food products, there is still a lack of information regarding the kinetics of the drying process of the two Portuguese fruits used in the present study. The typical aroma and texture of a fruit is characterized by the presence of a wide range of volatile metabolites, with different volatilities and concentrations that can vary among the different cultivars from different regions (Pontes et al., 2012). Thus, the specificity of the characteristics of the two studied fruits also determines their behavior during the drying process. Given the importance that these two fruits present and the relevance that dehydrated and snack fruit assume in the diet of modern societies, the increase in the knowledge of the drying process of these typical Portuguese fruits is essential to allow the development of the food industry that improves the fruit sector supply chain and consequently the sustainability of this important economic activity in Portugal.

Two studies (Guiné and Barroca, 2014; Guiné et al., 2015) were published on the topic of convective drying using the same Portuguese variety of banana with origin in Madeira Island, but with different objectives of the present study. Guiné and Barroca (2014) dried the banana with hot air at different temperatures to evaluate the kinetics of colour change during the drying process. Guiné et al. (2015) dried the banana with hot air at 50 °C and 70 °C in order to investigate the impact on the phenolic content and antioxidant activity. The present work constitutes, to our knowledge, the first complete study concerning the experimental characterization of the drying kinetics behavior at different temperatures, of *Bravo de Esmolfe* apples and banana from Madeira Island.

2. Materials and methods

2.1. Materials and samples preparation

Bravo de Esmolfe PDO apples, a fruit of the cultivar derived from the species *Malus domestica Borkh,* growing in the enclosed region of north-central of Portugal at Beiras traditional province, and Cavendish banana cultivar from Madeira Island were selected to be studied in the drying experiments. Both fruits were obtained fresh, in a local supermarket and immediately dried or stored in a fresh local for a short period. Care was taken to choose apples and bananas with the indication of products marketed under-protected designations of origin and with the same category and caliber.

Apples and bananas were peeled and cut into 3 mm thickness slices. Each slice was cut in a (almost) square shape and placed in one tray dryer to obtain a uniform single layer covering all the tray surface (Figure 1). A clean metallic tray with dimensions 0.276 m × 0.184 m × 0.015 m was used. To prevent enzymatic browning reactions in the fruits, this phase of sample preparation and disposal in the tray was made as rapidly as possible (as recommended by Guiné and Barroca (2014) for this banana cultivar).

2.2. Convective hot air-drying experiments

A laboratory tray dryer (Armfield Ltd, model UOP8) equipped with an axial flow fan and heating elements near the tunnel entrance was used to perform the hot air convective drying kinetics experiments. In all the experiments, the fan speed was maintained to obtain nearly the same hot airstream flow rate passing through the dryer tunnel. The heater power was modified to change the air temperature downstream of the drying chamber from 35 to 50 °C.

A humidity/temperature sensor (HigroClip2 from Rotronic) connected to an external probe of the data logger HygroLog HL-NT3 was used to measure the temperature of the airstream downstream and upstream the drying compartment. The airstream velocity at the outlet of the tunnel was measured with an anemometer from Airflow Developments (LCA6000).

One stainless steel tray with the fruit sample was placed in a metallic structure connected to a digital balance OHAUS, Adventurer Pro AV8101 (accuracy ±0.1 g). The solid weight reduction was recorded in a computer with an acquisition frequency of 0.025 Hz using the HyperTerminal software. When the weight recorded remains approximately constant, revealing that the equilibrium with the air humidity prevailing in the air-drying stream is achieved, the experiment was interrupted.

During the drying experiment, the airstream conditions were periodically verified by measuring temperature, humidity, and velocity. The parameters used to characterize the drying conditions were determined averaging the values registered during the experiments and are summarized in Table 1 with the corresponding standard deviation. Although the humidity in the airstream was measured downstream of the drying compartment, the equipment used does not allow humidity control, and the humidity in the inlet air is the one from the laboratory environment. In the experiments performed with apple samples, the average value of the relative humidity in ambient air ranged from 49 to 56%, and for the experiments with bananas, the variation was similar (43–51%).

At the end of the experiments, the initial moisture content of the humid solid was determined by putting the entire contents of dried fruit in an oven at (104 ± 1) °C and weighting until constant weight in a high precision digital balance (Mettler Toledo PB3002, accuracy ±0.0001 g).

2.3. Drying kinetics data processing

Monitoring the moisture content evolution during the drying process of both fruits and further application of the mathematical approach proposed by Castro and Pinheiro (2016) allowed to determine some
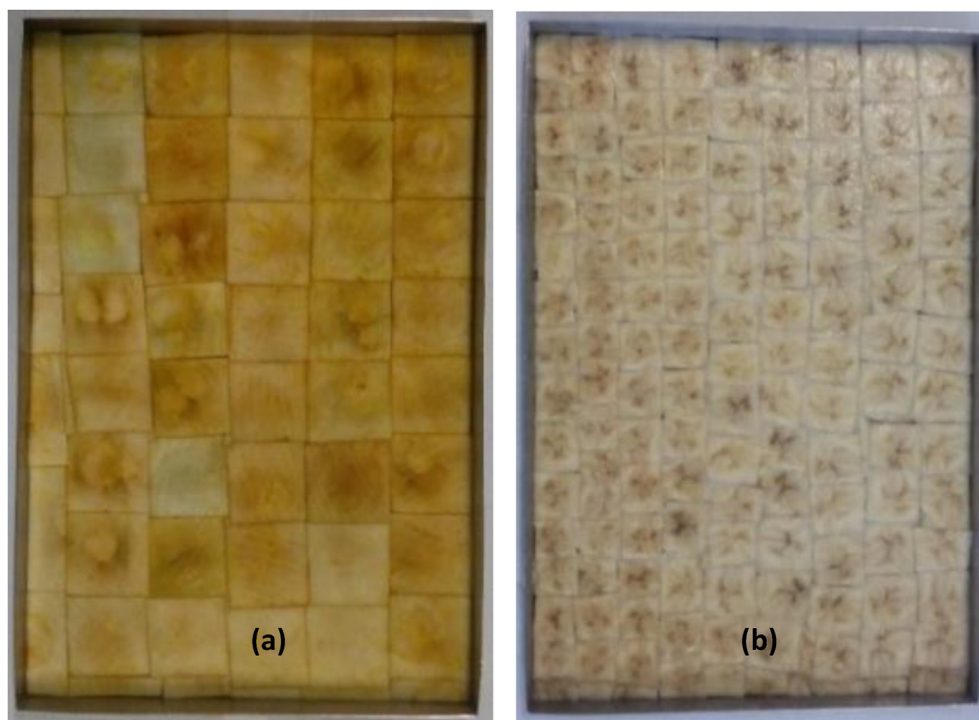
Figure 1. Fruit samples arrangement in the tray before drying in the dryer: (a) apple samples and (b) banana samples.

Table 1. Hot air conditions used in drying experiments performed at different temperatures with apple and banana. The mean values of the airstream temperature and velocity followed by the associated standard deviation are depicted.

apple		banana	
temperature (°C)	velocity (m s^{-1})	temperature (°C)	velocity (m s^{-1})
35.13 ± 0.05	1.60 ± 0.00	35.0 ± 0.2	1.59 ± 0.02
40.01 ± 0.08	1.59 ± 0.01	40.0 ± 0.1	1.59 ± 0.01
45.0 ± 0.2	1.60 ± 0.01	45.1 ± 0.1	1.59 ± 0.01
50.1 ± 0.2	1.61 ± 0.01	49.9 ± 0.4	1.62 ± 0.00

important aspects to be accounted for in potential industrial-scale operations.

As discussed before, Page model is widely used in describing the dehydration behavior of fruit and legumes. Empirical models, like the quadratic equation proposed by Wang and Singh, are also successfully essayed relating moisture content in foodstuffs and drying times as already enhanced. Moreover, in the literature, some studies concerning the kinetics of convective drying of apples suggest the existence of two FDRP (Feng et al., 2000; Velić et al., 2004; Nowak and Lewicki, 2005; Golestani et al., 2013; Guiné et al., 2014). For example, Velić et al. (2004) refer two well-defined FDRP and a short CDRP when drying Jonagold apples in a convection tray dryer at 60 °C and airflow rate velocities of 0.64 and 1.00 m s^{-1}. The authors used an exponential model (like Page model) for an approximation of data and drying curves calculation. Nowak and Lewicki (2005) using infrared energy and convective drying referred that apple slices dried in most cases in the FDRP. Only at the lowest air velocity (0.5 m s^{-1}) a CDRP was observed.

To understand the best option in processing the data obtained in the experiments performed in the present study, three different equation types to model drying kinetics of *Bravo de Esmolfe* apples were tested:

i) a linear equation ($X = a\,t + b$) followed by two different functions, a quadratic ($X = c\,t^2 + d\,t + e$) and a cubic equation ($X = f\,t^3 + g\,t^2 + h\,t + i$);

ii) a linear equation ($X = a\,t + b$) followed by a third-degree polynomial function ($X = f\,t^3 + g\,t^2 + h\,t + i$);

iii) a linear equation ($X = a\,t + b$) followed by an exponential function ($X = X_i \exp(-k\,t^n)$, Page model type).

The linear function in the three scenarios tested was used to represent the CDRP and the exponential and polynomial functions to represent the unique FDRP or the two FDRP. The methodology proposed by Castro and Pinheiro (2016) was used to detect the transition between the different drying rate periods.

Concerning the processing of data obtained from the banana drying experiments, the Page model and an empirical model were used as options to describe the fruit dehydration behavior, according to the state of the art presented in the Introduction. Hence, the two options tested were:

i) a linear equation ($X = a\,t + b$) followed by a third-degree polynomial function ($X = f\,t^3 + g\,t^2 + h\,t + i$);

ii) a linear equation ($X = a\,t + b$) followed by an exponential function ($X = X_i \exp(-k\,t^n)$, Page model type).

Also in the banana drying modelling case, the linear function in the two scenarios tested was used to represent the CDRP. According to the bibliography, evidence exists for a unique FDRP when drying banana that is represented by the polynomial and exponential functions in the two possibilities tested.

The methodology proposed by Castro and Pinheiro (2016) was used to detect the transition between the different drying rate periods when the functions indicated are used. The correlation performance in describing data was evaluated by statistical analysis for each scenario tested in both fruits, and the best fit was used to obtain the drying rate curves at the different temperatures used in the experiments.

In general, a unique drying rate curve can be used for a specific material dried at different air conditions over a narrow range (Mujumdar, 2006). This curve is designated by characteristic drying curve (or normalized drying curve) and is obtained plotting R/R_c as a function of the characteristic moisture ratio. The characteristic moisture ratio is a dimensionless parameter calculated as the ratio of the free moisture

content at the instant t, $(X - X_e)$, and the free moisture content at the critical time t_c, $(X_c - X_e)$.

Applying this approach to food products is not always straightforward as in some cases the constant drying rate period is absent and it is not available the value of the critical moisture content. When the existence of a constant drying rate is not clear, Baini and Langrish (2007) and Jannot et al. (2004) suggested that X_c can be replaced by X_i (the initial value of X) and R_c can be taken as the higher value of R.

3. Results and discussion

A set of experiments were planned to study the effect of the airstream temperature on the drying performance of *Bravo de Esmolfe* apple and Madeira banana. The airstream flowing tangentially over the tray surface with the wet (continuous) fruit layer was forced to pass with virtually the same velocity and its temperature was modified from 35 to 50 °C, with
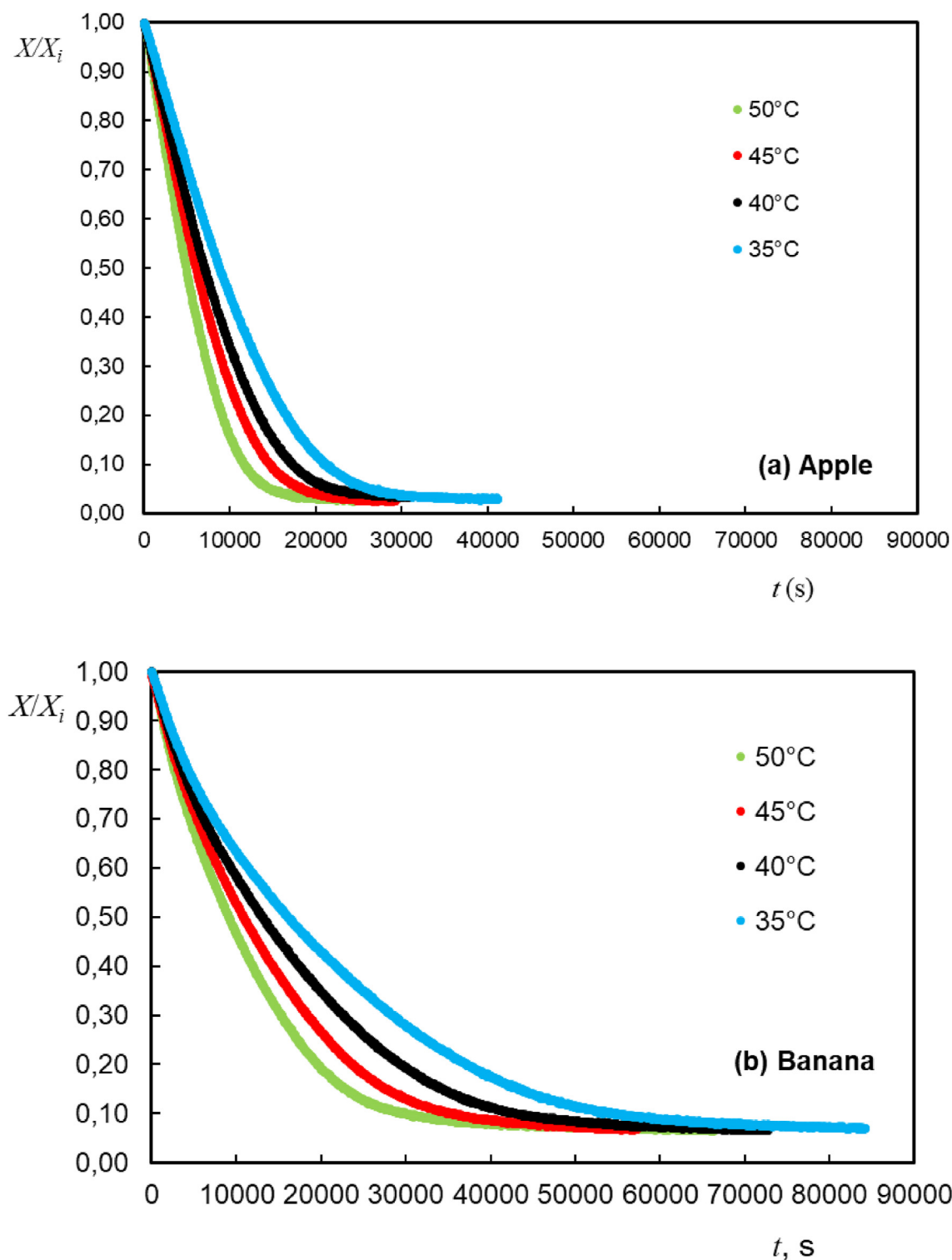

Figure 2. Dimensionless moisture content evolution during drying carried out with the air-drying stream (1.6 m s^{-1}) at different temperatures for: (a) *Bravo de Esmolfe* apple samples and (b) Madeira banana samples.

increments of 5 °C. A resume of the operating conditions used in the experiments can be seen in Table 1.

3.1. Drying curves

Figure 2a shows the evolution of the *Bravo de Esmolfe* apples moisture content during the drying experiments carried out at the different temperatures. An equivalent representation is shown in Figure 2b for Madeira banana. The moisture content of the fruits was divided by the correspondent X_i, and is represented as a dimensionless parameter (X/X_i) to avoid the effect introduced by the variability in X_i at the used samples.

An evident influence of the airstream temperature on the solid moisture reduction can be observed from Figure 2, being the rate of moisture depletion more intense when the air temperature is higher. Consequently, the equilibrium conditions between the solid and the drying agent were reached faster for the highest temperature used. For apples, the equilibrium was reached in ≈390 min (23 400 s) and ≈600 min (36 000 s) when the drying was at 50 and 35 °C, respectively. The same trend was observed for Madeira banana, although the moisture reduction with time is shallower than in the apples drying, and to achieve a certain (dimensionless) moisture content the time required is greater.

The nature of the fruit conditioned the drying kinetics, the initial moisture content, and also the value of residual moisture when equilibrium was reached with the drying air conditions. Information about initial and equilibrium moisture contents in the fresh fruit samples used in all the drying experiments is given in Table 2. The average value obtained for the initial moisture content in apples was (6.0 ± 0.6) kg/kg dry solid and for bananas was (3.2 ± 0.2) kg/kg dry solid.

Initial moisture contents found in the literature for fresh bananas are similar to the average value encountered for Madeira bananas in this study (see Table 2). For example, Baini and Langrish (2007) performed experiments where peeled ripe bananas were dried continuously for 72 h at temperatures of 60 and 80 °C in a pilot-scale kiln dryer. The initial moisture content obtained in four different banana samples shown a coefficient of variation of 4.8%, being the average value of 3.617 kg/kg (dry basis). A reference of the initial moisture content of banana fruits from Madeira Island was found in the work of Barroca and Guiné (2013). The value indicated by the authors is 2.06 kg/kg (dry basis), which is lower than the value encountered in this study for the Cavendish banana from Madeira Island. It should be noted that the banana moisture content depends on the ripe stage (Corrêa et al., 2012) as on the harvesting season of the fruit (Nguyen and Price, 2007).

Concerning the value of moisture content for *Bravo de Esmolfe* apples, it seems to be slightly higher than other cultivars as Golden Delicious and Granny Smith, when comparing to values published for these fruit varieties. Product quality before and after convective drying, for those species of apples, was evaluated by Cruz et al. (2015) for several temperature conditions, in drying experiments with a halogen moisture analyzer. Regarding the moisture of fresh apples, the authors reported values that correspond to 4.56 kg/kg and 5.25 kg/kg (dry basis) for apples from cultivar Golden Delicious and Granny Smith, respectively, that are somewhat lower than the initial moisture content determined for *Bravo de Esmolfe* in the present study.

The moisture content in bananas when equilibrium with air-drying conditions was reached (X_e) does not change significantly (less than 9.5%) in the experiments performed at different temperatures (Table 2). In opposition, in the drying experiments carried out with apples, the residual moisture at higher temperatures (45 and 50 °C) is about 25% less than the values obtained in the experiments at 35 and 40 °C.

3.2. Drying rate curves

Understanding the migration of water through the cellular structure of food, and particularly in fruits like apples and bananas, is a complex issue. Water can be found in different locations within the food tissue in different proportions: in the intracellular spaces; in the spaces between cells (intercellular) and in the cell walls (Khan et al., 2018). In opposition to the water residing inside the cells, the intercellular water behaves like free water, and frequently is designated by capillary water. In its turn, the water in the cell wall is bounded more strongly than intracellular water (Khan and Karim, 2017).

Apples and bananas present different microstructural characteristics, the former with high porous tissue (Khan et al., 2016a) and the latter with a high starch content and similar to the low porous tissue of potato. This diversity in microstructure definitely will be associated with different behaviors in cell level water transport, certainly visible in the drying rate curves.

In order to select the best functions to adjust the moisture content evolution in the fruits during drying and obtain the correspondent drying rate curves, some correlation parameters were calculated to evaluate the description performance of data by the functions tested. The root mean square error (RMSE), the determination coefficient (r^2), and the chi-square test (χ^2) were used as correlation indicators of the functions tested. Those criteria are traditionally accepted to assess model robustness and the equations for their calculation can be found easily in the bibliography (Lee and Kim, 2009; Roberts et al., 2008; Vega-Gálvez et al., 2009). The values obtained for the functions tested to represent all the experiments performed with apples are shown in Table 3. Values of r^2 near the unity, and values of χ^2 and RMSE approaching zero indicate that the prediction is close to the experimental data. Analyzing those popular parameters, it can be concluded that the best fit was obtained when a linear equation followed by two polynomial functions (i.e., considering the existence of two FDRP) are used in data approximation, once this scenario presented the smallest values of RMSE and χ^2, and the highest value of r^2. For that, this option was considered the most appropriated to fit drying kinetics data for *Bravo de Esmolfe* apple. However, it should be enhanced that when a unique FDRP was assumed a good fit to data was also obtained, probably due to a weak changing behavior between the two FDRP. In opposition, when Page model was used the correlation indicators are clearly worse, as can be observed in Figure 3. In fact, considering the histograms of the deviations (Figure 4) it is evident that in Page model the frequency of occurrence of high deviations is significant and in the other two options, the occurrence of deviations is concentrated in the small ranges.

When applying the methodology proposed by Castro and Pinheiro (2016) to detect the transition between the different drying rate periods in both options considered for processing data from drying experiments with banana, no convergence of the method had been attained, indicating the inexistence of a CDRP in this case. As was found in the literature, drying kinetic studies with bananas do not show the evidence of such a period in the drying rate curve, referring to a unique FDRP. For that reason, in Table 3, only the model constants *f*, *g*, *h* and *i*, and *k* and *n*

Table 2. Moisture content in both fruits (*Bravo de Esmolfe* apple and Madeira banana) for fresh samples (before drying) and equilibrium conditions with the airstream used in the experiments performed with different temperatures. For the apple, the values obtained at the constant drying rate period and the moisture content at the transitions to the falling drying rate periods (X_c) are also depicted.

	T (°C)	35	40	45	50
Bravo de Esmolfe apple	X_i (kg$_{water}$/kg$_{dry\ solid}$)	6.838	6.045	5.682	5.239
	X_e (kg$_{water}$/kg$_{dry\ solid}$)	0.196	0.201	0.147	0.146
	R_c (g$_{water}$ m^{-2} min^{-1})	8.103	10.088	11.845	14.474
	X_c* (kg$_{water}$/kg$_{dry\ solid}$)	4.800	4.258	4.155	4.134
		1.426	1.140	2.025	2.018
	t_c* (min)	85.26	67.20	53.51	34.32
		271.39	229.37	137.82	104.53
Madeira banana	X_i (kg$_{water}$/kg$_{dry\ solid}$)	3.039	3.023	3.535	3.255
	X_e (kg$_{water}$/kg$_{dry\ solid}$)	0.210	0.199	0.240	0.214

* transition between constant and first falling drying rate periods/transition between first and second drying rate periods.

Table 3. Model constants and parameters used as criteria for selecting the best model to define drying curves for *Bravo de Esmolfe* apples and banana from Madeira Island: root mean square error (RMSE), determination coefficient (r^2) and, reduced chi-square (χ^2). The parameters determining the best quality of the fit are in bold.

apple		35 °C			40 °C		
		linear + empirical model (two FDRP*)	linear + empirical model (one FDRP*)	linear + Page model	linear + empirical model (two FDRP*)	linear + empirical model (one FDRP*)	linear + Page model
model constants	$a \times 10^2$	-2.436407	-2.402638	-2.421454	-2.688558	-2.640009	-2.666309
	b	6.877598	6.864049	6.872123	6.064842	6.049799	6.058570
	$c \times 10^5$	3.333160	-	-	4.663870	-	-
	$d \times 10^2$	-3.004796	-	-	-3.315373	-	-
	e	7.126061	-	-	6.290342	-	-
	$f \times 10^8$	-4.610000	-3.610000	-	-7.700000	-5.977264	-
	$g \times 10^5$	7.787260	6.462290	-	10.46253	8.618384	-
	$h \times 10^2$	-4.403784	-3.842411	-	-4.760146	-4.133162	-
	i	8.554439	7.803983	-	7.479953	6.808940	-
	$k \times 10^6$	-	-	4.983710	-	-	6.922362
	n	-	-	1.304615	-	-	1.296889
correlation parameters	RMSE	**0.01094**	0.01971	0.06481	**0.00874**	0.01640	0.06726
	r^2	**0.99997**	0.99990	0.99888	**0.99997**	0.99991	0.99840
	χ^2	**0.0001201**	0.0003899	0.0042085	**0.0000768**	0.0002704	0.0045352

apple		45 °C			50 °C		
		linear + empirical model (two FDRP*)	linear + empirical model (one FDRP*)	linear + Page model	linear + empirical model (two FDRP*)	linear + empirical model (one FDRP*)	linear + Page model
model constants	$a \times 10^2$	-2.996639	2.945945	-2.978738	-3.508272	-3,349337	-3.399622
	b	5.758742	5.744749	5.754283	5.337561	5.304671	5.317321
	$c \times 10^5$	5.487220	-	-	6.669760	-	-
	$d \times 10^2$	-3.583882	-	-	-3.966049	-	-
	e	5.921480	-	-	5.434810	-	-
	$f \times 10^8$	-9.690000	-9.150000	-	-18.02000	-17.19502	-
	$g \times 10^5$	11.75382	11.23324	-	17.48122	16.82145	-
	$h \times 10^2$	-4.759035	-4.601809	-	-5.635577	-5.471018	-
	i	6.604801	6.458611	-	6.211207	6.083763	-
	$k \times 10^6$	-	-	8.881999	-	-	9.418408
	n	-	-	1.294241	-	-	1.319492
correlation parameters	RMSE	**0.01173**	0.01401	0.05582	**0.01363**	0.01562	0.06331
	r^2	**0.99994**	0.99992	0.99874	**0.99991**	0.99988	0.99806
	χ^2	**0.0001385**	0.0001973	0.0031245	**0.0001870**	0.0002457	0.0040212

banana		35 °C			40 °C		
		linear + empirical model (one FDRP*)		linear + Page model	linear + empirical model (one FDRP*)		linear + Page model
model constants	$f \times 10^9$	-1.370608		-	-2.646832		-
	$g \times 10^6$	5.027515		-	7.884100		-
	$h \times 10^3$	-6.261850		-	-7.904981		-
	i	2.875060		-	2.892177		-
	$k \times 10^5$	-		9.475404	-		10.55466
	n	-		0.921827	-		0.931220
correlation parameters	RMSE	**0.03822**		0.04330	**0.03675**		0.05230
	r^2	**0.99724**		0.99646	**0.99741**		0.99476
	χ^2	**0.0014638**		0.0018764	**0.0013536**		0.0027380

| *banana*		45 °C			50 °C		
		linear + empirical model (one FDRP*)	linear + Page model		linear + empirical model (one FDRP*)		linear + Page model
model constants	$f \times 10^9$	-5.967737	-		-8.528760		-
	$g \times 10^6$	14.33405	-		18.07846		-
	$h \times 10^3$	-11.60724	-		-12.61829		-
	i	3.429281	-		3.155837		-
	$k \times 10^5$	-	9.846221		-		16.73897
	n	-	0.957166		-		0.918859
correlation parameters	RMSE	**0.01797**	0.06263		**0.02326**		0.08700
	r^2	**0.99956**	0.99465		**0.99905**		0.98673
	χ^2	**0.0003237**	0.0039284		**0.0005424**		0.0075795

* Falling Drying Rate Period.
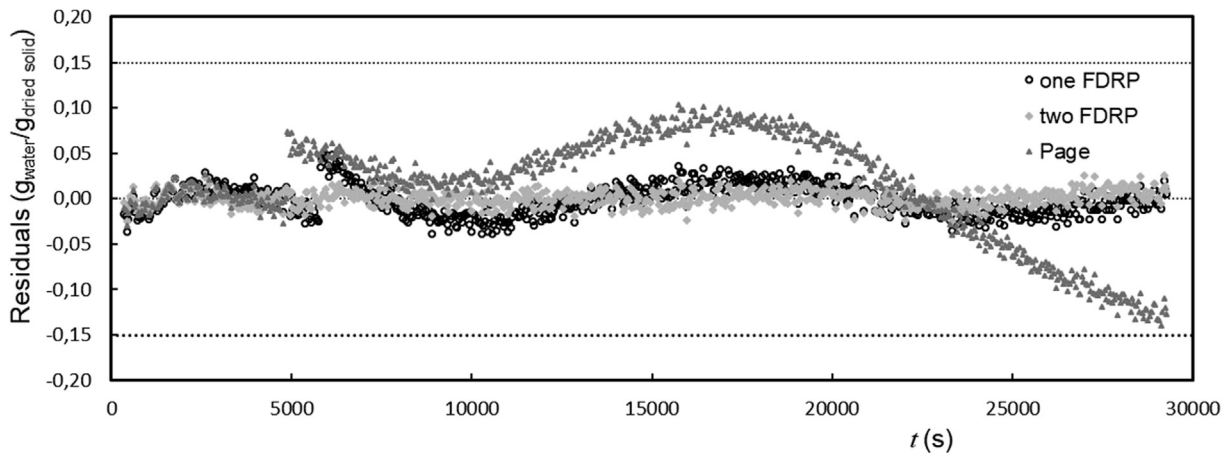
Figure 3. Deviations between experimental data and predictions obtained with the tested models (linear + empirical model) with one FDRP and two FDRP, and (linear + Page model) for *Bravo de Esmolfe* apples dried at 40 °C.
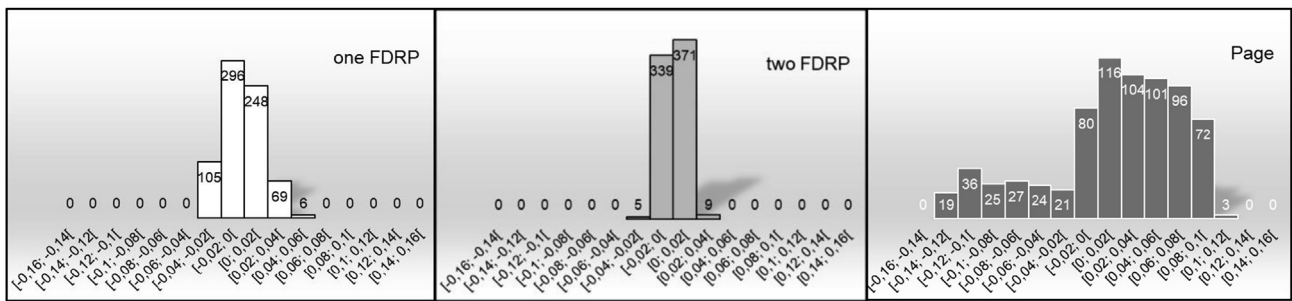

Figure 4. Histogram for deviations between experimental data and predictions obtained with the tested models (linear + empiric model) with one FDRP and two FDRP, and (linear + Page model) for *Bravo de Esmolfe* apples dried at 40 °C.

are indicated, corresponding to the third-degree polynomial function and the exponential function used to describe the FDRP.

The parameters used to evaluate the model's statistical fitness in the case of banana are presented in Table 3 and it can be concluded that the best fit was obtained when the polynomial function was used to represent the FDRP. Therefore, this option was considered the most appropriated to fit drying kinetics data for the banana. However, it should be noted that although a good statistical performance was obtained, when comparing with the apples results the correlation parameters point out for a poor correlation of data. In fact, deviations between predictions and data for

banana dehydration are higher for both tested models, as illustrated in Figure 5.

The drying rate curves obtained from the best fitting functions referred before, for both fruits, are shown in Figure 6 for the different hot airstream temperatures used in the experiments.

During the apple drying, the moisture evaporation rate is constant for higher moisture contents in the fruit and is observed a CDRP for all the used temperatures (Figure 6a), followed by a period where the drying rate decreases continuously (FDRP) until the apple equilibrium moisture content is reached. In opposition, Madeira banana does not exhibit an
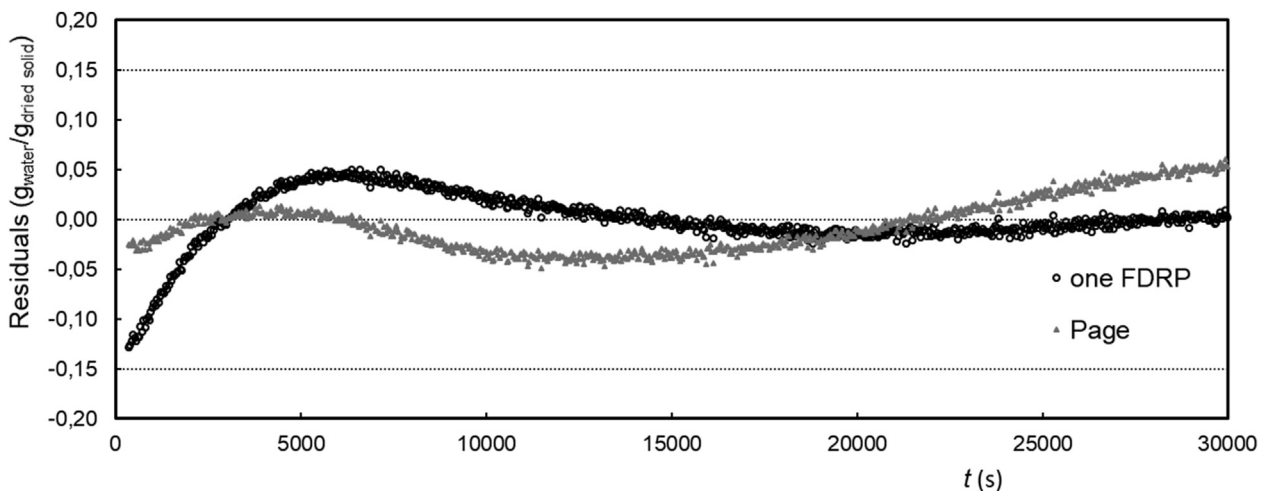

Figure 5. Deviations between experimental data and predictions obtained with the tested models (linear + empirical model and linear + Page model) for Madeira Island bananas dried at 40 °C.

initial CDRP in all the conditions used. A unique FDRP was observed until the end of the drying process (Figure 6b). The difference in drying behaviors of the two fruits probably can be indorsed to the dissimilarity in cellular structure.

The structure of apple tissue is highly porous and amorphous. Khan et al. (2016b) referred that about 80–90% of the water within the apple structure is inside the cells. Therefore, it is expected that during drying the moisture migration within apple tissue occurs essentially from the intracellular environment, which is a slow process unless the cell membranes rupture occurs. This cellular level mechanism of water transport is frequently

modelled as a Fickian diffusion problem through micro-channels. The free moisture (10–20% of water is in an intercellular environment) probably migrates to the surface by capillarity at the early drying stage, where evaporates to the airstream passing over the upper surface of the thin-layer of apple in the tray. Until this evaporation rate is compensated by the flow rate of (free) water coming by capillarity from the solid interior, heat transfer in the airstream governs the drying process and a CDRP is observed. As the driving force for heat transfer in the hot airstream passing tangentially to the solid surface is higher when the temperature of the airstream increases, greater water evaporation rates from apple surface exposed to
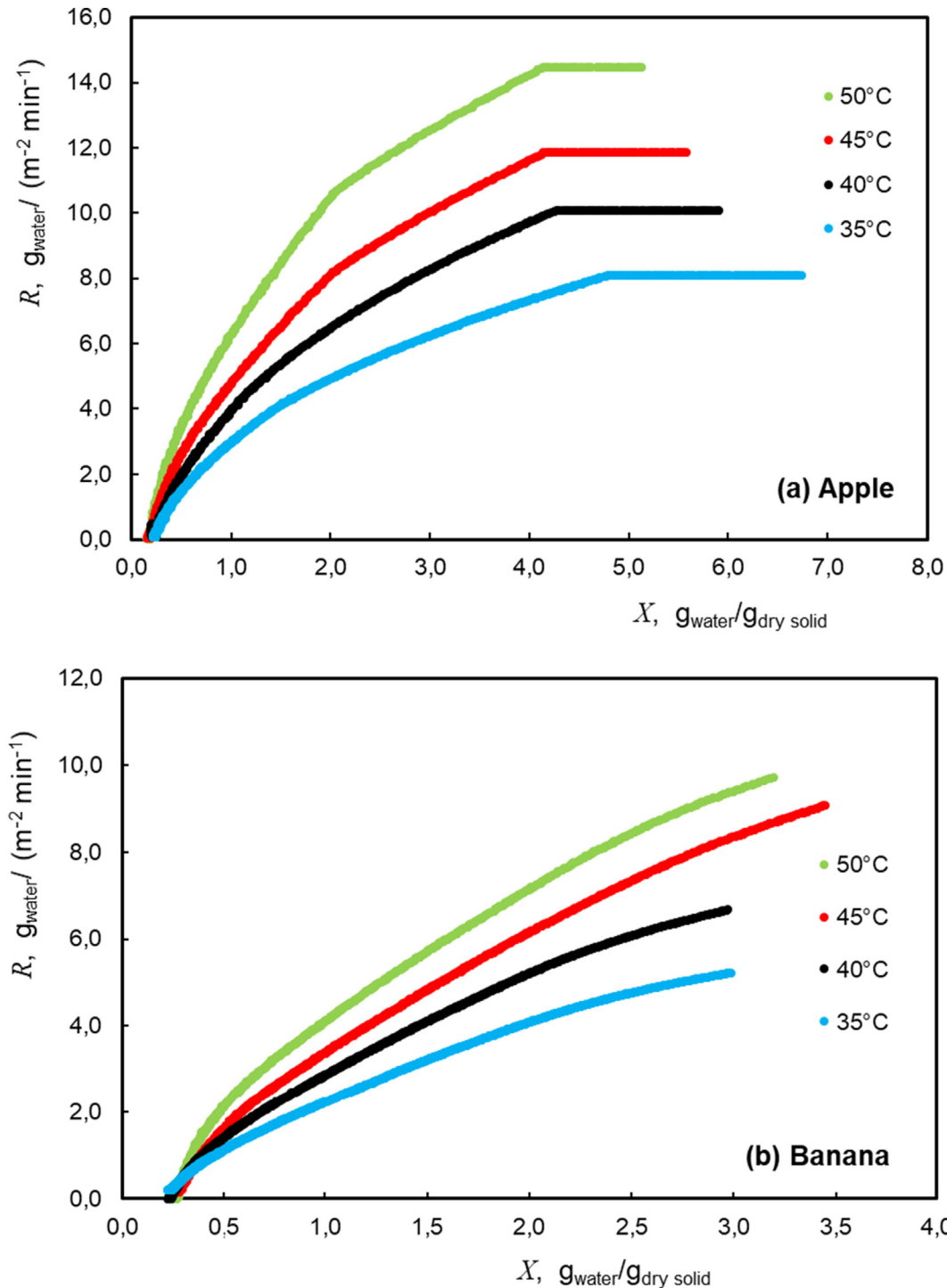

Figure 6. Drying rate curves obtained with the air-drying stream (1.6 m s^{-1}) at different temperatures for: (a) *Bravo de Esmolfe* apple samples and (b) Madeira banana samples.

drying agent are obtained for the experiments conducted at higher temperatures (Figure 6a). As can be seen in Table 2, the value of R_c increases from 8.10 to 14.47 g m^{-2} min^{-1} when the apple was dried at 35 and 50 °C, respectively. When the water in the intercellular environment becomes scarce, the drying process starts to be governed by the migration of moisture located at intracellular spaces, and the drying rate decreases as the moisture content in the apple drops and an FDRP initiates.

As in the early stage the moisture removed from *Bravo de Esmolfe* apples is unbound moisture, theoretically, the drying process is not influenced by the solid. The external conditions of the airstream (temperature, humidity, and flow rate) control the water evaporation rate. For the sake of confirmation, an experiment with similar airstream conditions but with the tray filled with water instead of apple samples was performed. In such an experiment, for an airstream at 40.0 ± 0.5 °C and 1.64 ± 0.02 m s^{-1} passing over the tray filled with water, the free water evaporation rate, per unit of the exposed area, was 10.59 g m^{-2} min^{-1}. This value compares very well with the R_c value obtained in similar air-drying conditions (10.09 g m^{-2} min^{-1}, see Table 2), being only 5% less, confirming that unbound moisture is removed from the apples at the CDRP.

Like the majority of the cells from mature plant tissues, in banana tissue, the cells are characterized to have a large central vacuole within the cytoplasm besides the presence of several organelles and the cell wall. Starch granules also exist in banana cells in a large number at the early ripening stages. When a banana presents a green peel, starch granules occupy a considerable fraction of the volume cell, representing about 20% of its weight (Lii et al., 1982). Banana ripening is accompanied by chemical composition modifications with starch being rapidly converted to soluble sugars.

Proton relaxation times measurements have been used to characterize water distribution within plant tissues and food at a cellular level (Snaar and Van As, 1992; Hills and Remigereau, 1997). Raffo and coauthors (2005) used transverse relaxation times of water protons and self-diffusion coefficients NMR measurements to monitor the ripening of bananas. Banana (Musa sp.) at a premature ripening stage was used in the work of Raffo et al. (2005). From the results obtained with samples of the same banana during seven days, the water present in the different sub-cellular environments was evaluated. The shortest relaxation time was attributed to the water in the cell walls and within starch granules and represented the smallest contribution to the overall banana moisture content. The intermediate relaxation time was associated mainly with the water resident in the cytoplasm and the highest time relaxation component was related to the water resident in the vacuole. The vacuolar water represented during all the banana ripening period more than 50% of the banana moisture content. The authors concluded that no significant changes occurred in the water distribution inside the cells during banana ripening but no reference is made to the water in the intercellular environment. However, banana is a low porous food and similar characteristics in water distribution at a cellular level to identical tissues are expected. Madiouli et al. (2011) determined the apparent volume of a banana during convective drying (26.7 °C) using a non-intrusive stereovision technique, which allows the 3D shape measurements from the images recorded. The banana shrinkage coupled with the information of banana's weight loss allowed the porosity calculation. The authors referred to an initial value of 5% for banana porosity, which remains almost constant until its moisture content decrease ca. 70%. Potato, also a low porous food, has mostly intracellular water at low temperatures (when cell membranes are not damaged), and only ca. 2% of water is in the intercellular spaces (capillaries) (Halder et al., 2011). Probably similar characteristics can be attributed to the banana. Following this idea, the absence of a CDRP, as observed in Figure 6b, is expectable since the capillary water contribution to banana moisture content is not significant. In the literature, several studies corroborate that trend. Demirel and Turhan (2003) studied the air-drying behavior of two varieties of banana (Dwarf Cavendish and Gros Michel) and concluded that the

drying of untreated samples carried out at temperature conditions ranging from 40 to 70 °C, were controlled by the internal resistance of moisture transfer during the entire process. Doymaz (2010) when drying thin-layer banana (Cavendish variety) slices in a hot air dryer at temperatures varying from 50 to 80 °C also reported the non-existence of a CDRP. Baini and Langrish (2007) pointed out that it is not clear the existence of an unhindered drying period for bananas.

The moisture distribution in the food tissue changes if the cell membranes are damaged or suffer a rupture during the drying process. Halder et al. (2011) dried potato and eggplant samples in an oven at different temperatures and regularly measured the intercellular water content by bio-electrical impedance analysis. The authors observed that at ca. 52 °C the intercellular water content sharply decreased indicating cell membranes rupture at one single stage. However, Khan et al. (2017) found a contradictory behavior and referred to the cell membrane collapsing at different stages within potato tissue when drying occurs at 60 °C. The authors used an NMR method to identify the type of water at a cellular level. Khan et al. (2018) extended the previous work, concerning the water transport at a cellular level in low porous food tissues, as is the case of potato tissue, to food products highly porous as apples. They used Granny Smith apple samples in drying experiments carried out in a cabinet dryer at different temperatures. They observed one period where the amount of intracellular water remains almost constant until the apple surface rose to 52–53 °C, followed by a period with a rapid decrease. Once more, the authors argue that cell membrane rupture occurs at different stages. According to the studies referred, it is expected that damage/rupture of cell membranes do not occur, at least significantly, as the highest airstream temperature used in the experiments is lower than the cell rupture conditions identified.

Observing Figure 6a) and Table 2, it can be seen that the solid critical moisture content (X_c) slightly decreases with increasing drying temperature (only visible for apples, since experiments with bananas did not present a CDRP as already referred). This probably is due to the mass transfer intensification within the fruit layer in the tray towards the surface when the temperature is higher that easily maintains a continuous water film on the solid surface. As a result, the FDRP starts at slightly lower (critical) solid moisture content values for higher temperatures. The X_c value decreases gradually from 4.800 to 4.134 kg$_{water}$/kg$_{dry\ solid}$ when the air drying temperature in the experiments performed with the *Bravo de Esmolfe* apples changed from 35 to 50 °C.

3.3. Normalization of drying rate curves

Drying rates for a specific product depend on complex phenomena as capillarity, diffusion, and heat transfer. Thus, the reduction to one normalized drying curve presenting a good performance in capturing the influence of the temperature of the drying agent on drying rates is a very useful method. If the method can properly explain this dependency probably exists a proportionality between the influence of drying agent temperature on the drying rate period governed by moisture diffusion within the solid (the FDRP) and the influence of drying agent temperature on the drying rate period governed by the external conditions (the CDRP) (Suherman and Tsotsas, 2007).

Figure 7 presents the normalized drying rate curves for both fruits. As referred before, there is no CDRP in the banana experiment and, as by Baini and Langrish (2007) and Jannot et al. (2004), X_c was replaced by X_i and R_c by the highest value of R to obtain the normalized curve for Madeira banana.

Observing Figure 7, a unique curve appears to describe data obtained from drying experiments for the studied temperature range. This result indicates that the shape of drying curves for *Bravo de Esmolfe* apples and Madeira bananas does not differ significantly for the airstream temperatures used in the experiments. However, for higher temperatures a difference starts to be perceptible in the transition region between the two FDRP.
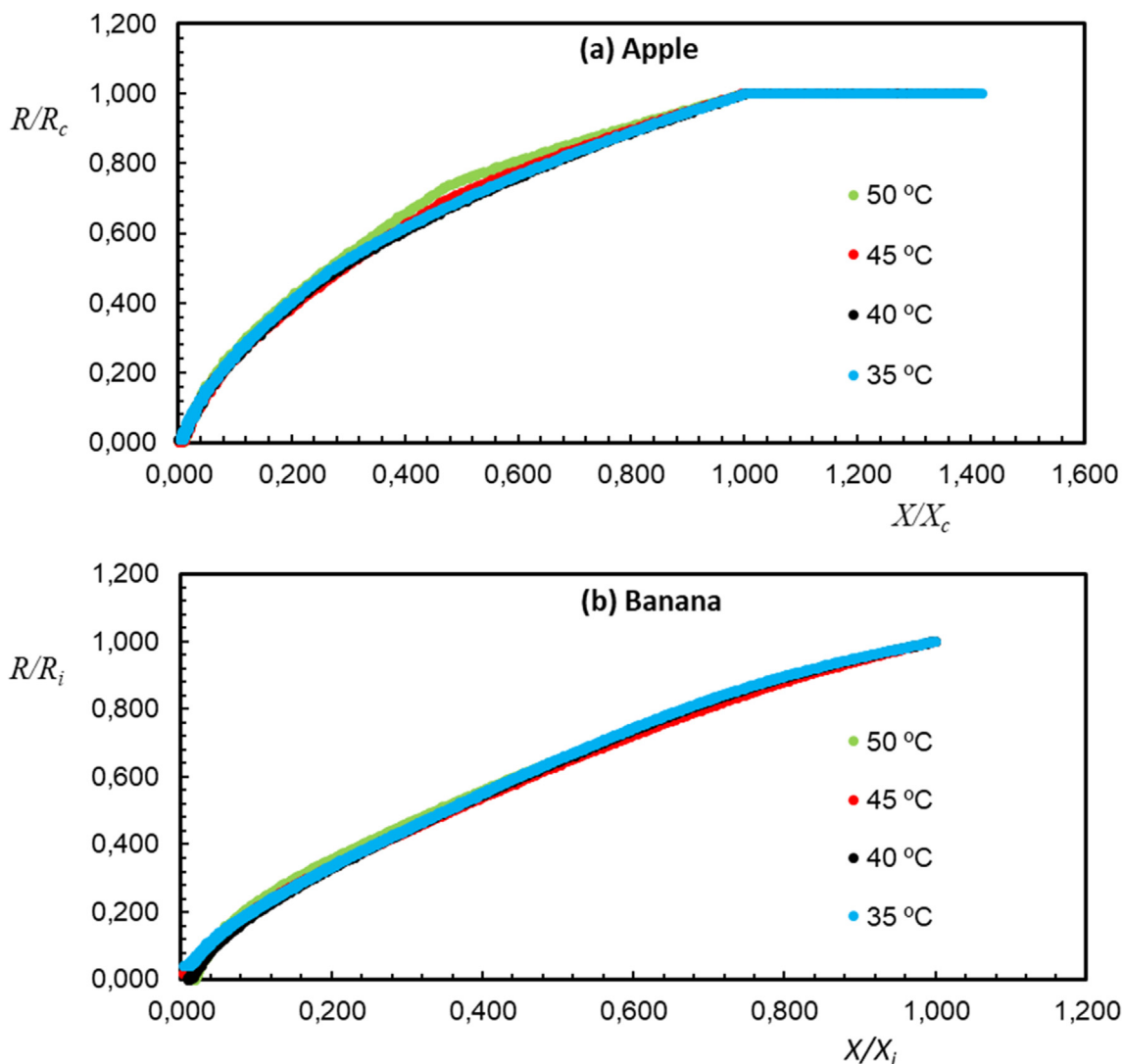
Figure 7. Normalized drying rate curves obtained from the experiments performed with different temperatures of the air-drying stream for: (a) *Bravo de Esmolfe* apple samples and (b) Madeira banana samples.

4. Conclusions

Using a simple mathematical approach, different adjusting functions were essayed to represent the moisture content evolution with time during drying of *Bravo de Esmolfe* apple, from Beiras province of Portugal, and Cavendish banana, from Madeira Island. The best fitting was obtained with a linear function followed by two polynomial functions for the case of *Bravo de Esmolfe* apples, indicating the existence of a constant drying rate period and the presence of two falling drying rate periods. As expected, the constant drying rate value is higher when the apples were dried at higher temperatures, changing from 8.103 to 14.474 g m^{-2} s^{-1}, and the critical moisture content, at the instant the constant drying rate period changes to a falling drying rate period, slightly decreases from 4.800 to 4.134 kg$_{water}$/kg$_{dry\ solid}$, when the drying temperature increases from 35 to 50 °C.

For the case of Madeira banana a unique polynomial function was the best fitting model, showing that the constant drying rate period was not perceived. A falling drying rate period during all drying process exists. A possible reason for the different dehydration behavior, supported in the different structural nature of the fruits based on published information, was presented and discussed. However, an effort to get a deep comprehension of the phenomena involved must pursuit.

A unique curve was obtained when the drying rate curves at different temperatures were normalized, indicating that the airstream temperature have an effect directly proportional on the resulting drying rate magnitude.

As far as the authors know, it was not available in the literature similar information for both studied fruits of the Portuguese cultivars. Thus, this paper contributes to reducing the lack of information regarding the kinetics of the drying process of these two fruits and gives relevant information to support the industrialization of healthy snacks production that have been showing an increasing acceptance for commercial purposes.

Declarations

Author contribution statement

M. N. Coelho Pinheiro, Luis M. M. N. Castro: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

R. O. Madaleno: Performed the experiments; Analyzed and interpreted the data.

Funding statement

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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