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Thermal intermittent drying of apples and its effects on energy consumption

Ana Paula Filippin[a], Lucídio Molina Filho[b], Valmir Fadel[c], and Maria Aparecida Mauro[a]

[a]Department of Food Engineering and Technology, Institute of Biosciences, Humanities and Exact Sciences (IBILCE), São Paulo State University (UNESP), São José do Rio Preto, SP, Brazil; [b]Department of Technology, State University of Maringá, Technology Center, Umuarama, PR, Brazil; [c]Department of Physics, Institute of Biosciences, Humanities and Exact Sciences (IBILCE), São Paulo State University (UNESP), São José do Rio Preto, SP, Brazil

ABSTRACT

This study investigated thermal intermittence in apple drying, conducted in two stages, and its effect on energy consumption, drying kinetics, color and chlorogenic acid retention. The energy consumption was measured using an energy analyzer and calculated through an energy balance. The results indicate intermittent drying advantages, such as an improvement in effective diffusivities and drying rates, a consequent reduction in the total processing time (35%) and no impairment of color parameters and chlorogenic acid retention. The consumption measures showed 17% energy savings, which could have been higher if insulation was improved, and a theoretical energy savings of up to 35% was obtained from calculations in adiabatic conditions.

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Chlorogenic acid; drying kinetics; effective diffusion coefficient; energy analyzer; energy balance

Introduction

Drying is widely applied to high moisture foods as a preservation technique. However, the energy demand of the drying operation is very high, accounting for up to 20–25% of the total energy consumed in a food processing factory.[1] An alternative to reduce energy consumption is intermittent drying, in which the operational conditions are changed with time. Conversely, such combinations are specific for each food, which implicates knowing the water diffusion behavior and the history of temperatures during its drying. These data are necessary to design intermittent drying processes for high moisture foods, and approaches are scarce in the literature, highlighting the need for further studies related to fruits and vegetables.

In addition, although drying is a well-established unit operation in the food industry, in general, dryers are not designed under the consideration of energy consumption; this is problematic because energy is an important operational cost, and its efficient use is a relevant factor in preserving the environment. Because of industrial and demographic expansion in emerging and developing economies, there has been a considerable increase in global energy consumption, which is becoming a concern, as is the limited amount of natural resources for its production. Furthermore, the increase in energy costs and more rigid environmental policies have intensified the search for new, more economical drying techniques.[2]

In this context, intermittent drying is presented as a promising technique for saving energy. Intermittency can be performed in various ways, by varying the operational conditions such as the drying temperature, humidity, pressure operation, airflow rate and the mode of heat transfer or using a tempering period, where the drying is interrupted by a period in which no heat is supplied.[1,3,4] Since the effects of different types of intermittency on product quality and energy efficiency depend on the drying method and the material properties, intermittency should be chosen based on the characteristics of each process and food type.[1] The thermal intermittence applied to high moisture level foods is advantageous in the sense that it can diminish the drying time and limit the food temperature to a pre-established maximum value. When using different temperatures during the process, the temperature changes should occur in such a way that a higher drying temperature is applied when the surface of the product is predominantly saturated and that a lower drying temperature is applied when the surface is partially unsaturated (from the critical moisture content). Thus, at the start of drying, the food surface temperature remains close to the wet bulb temperature, so that it does not reach elevated values.[5,6]

In the case of apples, one of the most consumed fruits in the world, the use of drying is becoming more and

CONTACT Ana Paula Filippin anafilippin1@hotmail.com Departament of Food Engineering and Technology, Institute of Biosciences, Humanities and Exact Sciences (IBILCE), São Paulo State University (UNESP), Rua Cristovão Colombo 2265, São José do Rio Preto, SP 15054-000, Brazil.
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more frequent, considering that dried apples are ingredients in various food preparations.[7] In addition, apples (*Malus domestica*) present considerable antioxidant activity, since they possess a great variety of phenolic compounds, which provides several health benefits.[8] Among the phenolics of the apple, chlorogenic acid, a hydroxycinnamic acid, has been highlighted for its anticarcinogenic,[9] antifungal,[10] anti-arthritic,[11] anti-obesity,[12] and antibacterial[13] properties. However, high temperatures and long drying times can degrade the antioxidant compounds, as well as cause undesirable changes in some important characteristics such as color, flavor and texture of plant foods.[7,14]

Regarding thermal intermittence, studies are scarce, since the majority of intermittent drying studies apply the tempering period to grains, during which the water diffuses to the grain surface, decreasing the moisture gradients. However, for high moisture foods, it is important to note that during the tempering period, while the moisture level is high, biochemical reactions can be strengthened by the rupture of cellular compartments and the consequent release of their substances, because mild temperatures, in general, are favorable to enzymatic activity.

In the studies on tempering-intermittent drying of high moisture foods, the authors achieved positive results with respect to saving energy, however, the studies were based on the reduction of heat supply time and the total drying time or on the increase of the drying rates provided by intermittence.[15–21] In a review dealing with recent progress and overall assessments of energy efficiency and product quality in intermittent drying, Kumar et al.[1] note that, although several studies have reported improvements in energy efficiency in comparison to continuous drying, no critical analysis of these processes and exact comparisons of the amount of energy savings have been reported in the literature. In fact, many intermittent drying studies focus on the quality of the dehydrated product, although some note the energy savings that this technique can provide.[22–27] In this way, the proposal of this study is to analyze intermittent drying from the standpoint of energy consumption.

A drying system can be characterized by various parameters; however, to evaluate the energy performance of a dryer, the parameters most used are energy efficiency and specific heat consumption. The latter parameter has an advantage over energy efficiency, since the adiabatic conditions can be used as a reference, whereas the use of energy efficiency requires knowledge of its maximum value, which depends on the material and the drying conditions.[28] Energy consumption during convective drying is frequently calculated from equations based on the energy provided by the heated-air,[29–34] on the rated power of the blowers and heaters as well as their performance duration,[35] or from the data obtained by consumption measuring equipment.[36,37] In this study, comparing the energy consumption obtained by enthalpy balances and by measurements from an energy analyzer is proposed. A comparison between the power requirements of enthalpy balance and of instrumental measurements could be a useful procedure for evaluating the performance of a drying system in different operational conditions, as well as an investigation into heat losses, therein, and their impact on process efficiency.

Considering the importance and the necessity of the drying operation in the food industry, the aims of this study are: to investigate the effects of applying thermal intermittence in the convective drying of apples on the drying kinetics and the corresponding energy consumption; to evaluate the potential for energy savings in the proposed system through the comparison between the real consumption, measured from energy analyzer equipment, and the theoretical consumption, obtained from the energy balance; and to evaluate the effects of the thermal intermittence on the retention of chlorogenic acid and the color in the dried apples.

Materials and methods

Dryers

The drying experiments were performed using two identical fixed bed dryers with forced heated air convection (Fig. 1), each equipped with a centrifugal fan (Ibran, Siroco VSI 195, Brazil), a 2.0 CV motor and the air velocity controlled by a frequency inverter (WEG, CWF10, Brazil). The air was heated by electrical resistances, and a proportional integral (PI) controller was used to control the drying air temperature. The drying chamber had a cross sectional area of $13.86 \times 10^{-2}\ m^2$, and the air flow was directed parallel to the samples. Each dryer had four PT100-type sensors and one moisture sensor (ImPac®, DO9861T- R, Italy) connected to the data acquisition system (ImPac®).

Drying trials

Sample preparation

The Fuji cv. apples (*M. domestica*) were produced by Sanjo in São Joaquim (Santa Catarina, Brazil) and purchased from the São José do Rio Preto Fruit and Vegetable Wholesales (CEAGESP, São Paulo, Brazil). The apples had a diameter of 6.9 ± 0.3 cm and an initial moisture level of $86 \pm 0.3\ kg \cdot 100\ kg^{-1}$. They

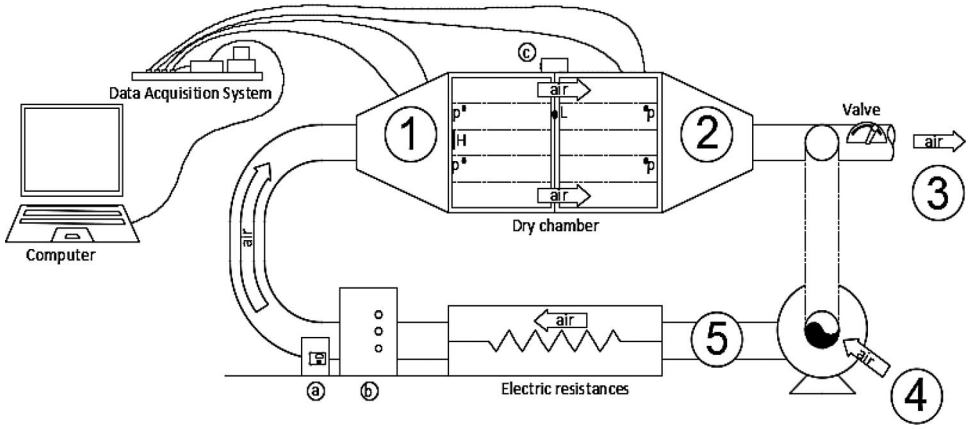

Figure 1. Schematic diagram of the dryer (a) frequency inverter; (b) main switch and electric resistance switches; (c) temperature controller; p, PT 100; H, hygrometer; L, thermocouple.

were sanitized in running water and then sliced with the skin (5.1 ± 0.3 mm thick), using a slicer (ECO, Brazil). The slices were immersed in distilled water for a maximum of 5 min to avoid enzymatic browning and then placed on absorbent paper towels to remove the excess water, before being placed between two metallic screens to avoid deformation during drying. In each drying, three trays were used with 16 slices of apple on each (255.3 ± 10.6 g of sample). Therefore, three drying curves were determined. The central condition was repeated (85°C/45 min/60°C) and showed reproducibility for the drying trials, which was attributed to the homogeneous raw material and the accuracy of the PI temperature controller installed in the dryers.

Intermittent and continuous drying

To determine the drying time of the stage 1 intermittent drying phase, trials were performed where the surface temperature of the samples was registered using *T*-type thermocouples (1.5 mm diameter hem), which were carefully inserted into the surface of an apple slice during the drying procedures that were performed at 75, 85, and 95°C. The treatments are presented in Table 1.

The intermittent drying trials were performed using two identical convective dryers. During the first drying period, the trays were placed in dryer 1. After completing the first stage, the trays were removed from dryer 1 and immediately inserted into dryer 2, where they remained until the samples reached their final moisture content between 4 and 5 kg · 100 kg^{-1}. In both dryers, the drying air velocity was 2 m · s^{-1}. The samples were weighed successively during drying using a semi-analytical balance (Gehaka, BK 4000, Brazil). The continuous drying trials were performed in the dryer used in the second stage of intermittent drying, until the samples reached the same final moisture content as in intermittent drying.

Drying kinetics

The drying can be described by the falling-rate period, where the liquid diffusion is the principal flow mechanism. This period can be described by Fick's second law, presented in Eq. (1) in its modified form, in terms of the mass fractions on a dry weight basis, considering the concentration of the solids to be constant.

$$\frac{\partial X_w}{\partial t} = D_{eff} \nabla^2 X_w \tag{1}$$

where X_w is the mass fraction of water on a dry weight basis (kg · kg^{-1}), D_{eff} represents the effective diffusion coefficient (m^2 · s^{-1}), and t is the time (s).

Assuming the approximation of the apple slices to the geometry of an infinite plate with dimensions $-l < z < l$ and considering that water migration only occurred in the direction z and that external resistance to moisture transference was insignificant, Eq. (1) would be subjected to the following conditions:

$$t = 0, \text{ for the whole of } z, \; X_w = X_w^0 \tag{2}$$

Table 1. Time/temperature conditions for intermittent and continuous drying.

Intermittent drying			
Treatment	Stage 1 temperature (°C)	Stage 1 time (min)	Stage 2 temperature (°C)
T1	75	45	60
T2	85	45	60
T3	95	45	60
T4	85	45	50
T5	85	45	70
T6	85	30	60
T7	85	60	60
Continuous drying			
Treatment		Temperature (°C)	
T8		50	
T9		60	
T10		70	

$$t > 0, \quad \left.\frac{\partial X_w}{\partial z}\right|_{z=0} = 0 \tag{3}$$

$$t > 0, \quad z = \pm l, \quad X_w = X_w^{eq} \tag{4}$$

where X_w^0 and X_w^{eq} represent the water content on a dry weight basis ($kg \cdot kg^{-1}$) at the initial moment ($t = 0$) and at equilibrium (eq), and l is the half-thickness of the samples (m).

The effective diffusion coefficients were obtained based on Fick's second law, using the analytical solution for an infinite plate integrated at a distance of twelve terms in the series, according to Eq. (5).[38]

$$MR = \frac{\bar{X}_w - X_w^{eq}}{X_w^0 - X_w^{eq}} = \frac{8}{\pi^2}\sum \frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2 \cdot \pi^2 \cdot D_{eff} \cdot t}{4l^2}\right] \tag{5}$$

where MR (moisture ratio) is the nondimensional aspect of the water concentration, $\bar{X}_w$ represents the mean mass fraction of the water on a dry weight basis ($kg \cdot kg^{-1}$) in a time t (s), and n is the number of terms in the series.

Although Eq. (5) was integrated with respect to slice thickness, an approximate method was used to consider the shrinkage of the solid, which was the insertion of a variable thickness, determined as a linear function with the moisture content of the sample on a dry weight basis.[39] The thickness of the fresh apple slices was obtained from the mean of the slices chosen at random from the batch prepared for each drying procedure, and subsequently discarded. The thickness was also measured at the end of each trial, and all the measurements were made using a micrometer screw (Mitutoyo, MDC-25SB, Japan).

The determination of the drying coefficients was performed for each of the stages, separately. In the first stage, for the determination of the conditions of Eq. (1), the initial moisture was taken from the fresh apple, while at the second stage, the initial moisture was considered as the final moisture of the first stage.

Equation (1) that is applied to the first drying step is an approximation, because the apple surface remains partially saturated during a part of this period. However, it was assumed that the equilibrium moistures were considered those measured at the end of the corresponding second drying stages.

The diffusion coefficients were determined according to the fit of Eq. (5) to the experimental data, based on the Levenberg–Marquardt algorithm used in the estimation of the nonlinear parameters by the least squares method.[40]

Drying rates

The drying rates were calculated from the drying curves according to Eq. (6)

$$\dot{E} = \frac{m_s \Delta X_w}{\Delta t} \tag{6}$$

where $\dot{E}$ is the drying rate (kg water $\cdot s^{-1}$), m_s represents the mass of the dry solids of the apple (kg dry matter) and $\Delta X_w/\Delta t$ represents the variation in moisture (kg water $\cdot kg^{-1}$ dry matter $\cdot s^{-1}$).

Energy balance

Energy balances were calculated considering adiabatic drying and a perfect equilibrium between the mass of air removed from the dryer and the mass of air returning into the equipment. Thus, mass and energy balances were written in terms of the rate of dry air, which allows one to ignore the effect of air density due to the temperature and the relative humidity.[41] The environmental and heated air properties were determined by a psychrometric chart considering the altitude of São José do Rio Preto, Brazil (498 m).

The wet volume was calculated according to Eq. (7)[6]

$$\upsilon_i = (0.00287 + 0.00462 \times Y) \times (T + 273) \tag{7}$$

where υ is the wet volume (m^3 of mixture $\cdot kg^{-1}$ dry air), Y is the absolute moisture content of the air (kg steam $\times kg^{-1}$ dry air), T is the temperature (°C), and i represents the position inside the dryer, as shown in Fig. 1.

$$\dot{m}_1 = \frac{v \cdot S}{\upsilon_1} = \frac{\dot{Q}_1}{\upsilon_1} \tag{8}$$

where $\dot{m}_1$ is the flow rate of dry air at position (1) of the dryer (kg dry air $\cdot s^{-1}$), and $\dot{Q}_1$ the flow rate of the moist air ($m^3 \cdot s^{-1}$).

Since the mass of dry air that arrives at the trays is the same as that leaving the trays, then

$$\dot{m}_1 = \dot{m}_2 \tag{9}$$

The absolute moisture content of the air leaving the trays (position 2) was determined as follows:

$$Y_2 = Y_1 + \frac{\dot{E}}{\dot{m}_1} \tag{10}$$

where Y is the absolute moisture content of the air (kg steam $\cdot kg^{-1}$ dry air), and $\dot{E}$ represents the amount of water evaporated (kg steam $\cdot s^{-1}$), calculated from the experimental drying curves (Eq. (6)). Drying rates ($\dot{E}$) were assumed as constant means within the corresponding intervals of drying time, as in a stationary state.

The mass of dry air leaving the dryer (position 3) can be determined using Eq. (11), the result of a simple mass balance

$$\dot{m}_3 = \dot{m}_1 \cdot \frac{Y_2 - Y_1}{Y_2 - Y_4} \tag{11}$$

The mass of fresh air entering the dryer (position 4) is equivalent to the mass leaving the dryer (position 3), hence

$$\dot{m}_3 = \dot{m}_4 \tag{12}$$

Equation (13) defines the percentage of air recycled in relation to the air leaving the dryer

$$\text{Recycle } (\%) = \frac{(\dot{Q}_1 - \dot{Q}_3)}{\dot{Q}_1} \cdot 100 = \frac{(\dot{m}_1 \upsilon_1 - \dot{m}_3 \upsilon_3)}{\dot{m}_1 \upsilon_1} \cdot 100 \tag{13}$$

where $\dot{Q}$ is the flow rate of moist air ($m^3 \cdot s^{-1}$), and the lower-case index represents the position in the dryer. An elevated air recycling value was used, with a percentage varying from 95 to 97%. This was estimated from the values of dry air mass and wet volume previously determined and confirmed by way of the flow rate measurements made directly in the dryers.

Considering adiabatic drying, the enthalpy of the air passing over the resistances can be calculated as follows:

$$H_5 = \frac{(\dot{m}_1 - \dot{m}_3)H_1 + \dot{m}_4 H_4}{(\dot{m}_1 - \dot{m}_3) + \dot{m}_4} \tag{14}$$

where H is the enthalpy of the heated air ($kJ \cdot kg^{-1}$ dry air), and the lower-case indexes refer to the positions in the dryer. Thus, the amount of energy required to heat the air can be calculated from the difference between energy after and before the resistances

$$\dot{q} = \dot{m}_1 H_1 - \dot{m}_1 H_5 \tag{15}$$

The energy consumed throughout the whole drying procedure was calculated according to the sum of the energy consumption estimated for each time interval corresponding to the ranges for the drying rates ($\dot{E}$) calculation.

Measure of energy consumption

The energy consumption was measured using a portable energy analyzer (Embrasul, RE 7000/Pt, Brazil). The first stage of intermittent drying was measured for the entire stage, during the 45 min at each temperature (75, 85, and 95°C). For the second stage, drying procedures were performed at temperatures of 50, 60, and 70°C, during which time the analyzer registered the values for energy consumption for 6, 4, and 4 h, respectively. These registered values were used to determine the equations written as a function of the drying time and used to calculate the energy consumptions for the complete drying, both intermittent and continuous. When necessary, the equations were extrapolated.

Analytical methods

The total solids content of the fresh and dried apple slices were gravimetrically determined in triplicate by drying them in a vacuum oven at 60°C and 10 kPa to constant weight.[42] The color measurements, performed before and after drying the samples, were evaluated in eight replicates using a Colorflex spectrophotometer (HunterLab; ColorFlex 45/0, USA), version 4.10 of the Universal software with the following settings: illuminant D65, observer at 10°, and reading the absolute values of L^* (lightness or darkness), a^* (redness or greenness), and b^* (yellowness or blueness), C^* (chroma), which indicates the purity or saturation of the color and the hue angle (h^*), which expresses the color change.

Extraction of chlorogenic acid

After drying, the apples were crushed in a food microprocessor (Black and Decker, HC31, Brazil). 3 g of the powder was weighed in triplicate, and 15 mL of methanol and HCl solution (1%, v/v) was added at room temperature.[43] The solution was stored in a refrigerator (2°C) for 12 h. It was then sonicated (Maxiclean 750, Unique, Brazil) for 30 min, and the pH was measured (pH ~ 0.81) (Tecnopon pH-meter, MA 210, Brazil). The solutions were then centrifuged (9000 rpm/15 min/25°C), and the supernatant was separated and centrifuged again (15000 rpm/20 min/−4°C). The 9 mL of supernatant was then added to 0.1 mL of a 5 mM DSS solution in deuterated water.

NMR spectroscopy

The NMR samples were prepared in 600 µL of supernatant/D_2O/DSS mixture containing a fixed concentration of 0.522 mM DSS. The NMR experiments were recorded on a Bruker Avance III spectrometer equipped with a TCI cryoprobe and operating a ^1H frequency of 600 MHz. All spectra were recorded at 293 K with double presaturation on water and methanol resonances over a spectral width of 20 ppm. The spectra were processed, the chlorogenic acid resonances were assigned with the Chenomix program and the concentration of chlorogenic acid was measured taking the DSS concentration as reference.

Calculation of chlorogenic acid retention

The retention of the chlorogenic acid in the dried samples was calculated through Eq. (16), considering the propagation of division operations errors.

$$R(\%) = \left(\frac{X^{D}_{ACG} \pm \Delta X^{D}_{ACG}}{X^{F}_{ACG} \pm \Delta X^{F}_{ACG}}\right) \cdot 100 = \left(\frac{X^{D}_{ACG}}{X^{F}_{ACG}} \pm \frac{X^{D}_{ACG} \cdot \Delta X^{F}_{ACG} + X^{F}_{ACG} \cdot \Delta X^{D}_{ACG}}{\left(X^{F}_{ACG}\right)^{2}}\right) \cdot 100 \quad (16)$$

where $R(\%)$ is the retention of chlorogenic acid, X^{D}_{ACG} and X^{F}_{ACG} represent the fraction of chlorogenic acid concentration in the dry and fresh samples (kg chlorogenic acid $\cdot$ kg^{-1} dry solids), respectively, and ΔX^{D}_{ACG} and ΔX^{F}_{ACG} represent the standard deviations of the concentrations of dry and fresh samples.

Statistical methods

The goodness of fit was based on the coefficient of determination of the fit (R^2), the mean relative error $P(\%)$ as described by Eq. (17) and the root mean square error (RMSE) as defined by Eq. (18).

$$P(\%) = \frac{100}{N}\sum_{1}^{n}\frac{\left|X^{exp} - X^{calc}\right|}{X^{exp}} \quad (17)$$

$$RMSE = \left[\frac{1}{N}\sum_{1}^{n}\left(MR^{calc} - MR^{exp}\right)^{2}\right]^{1/2} \quad (18)$$

where X^{calc} represents the water content on a dry basis, X^{exp} is the experimental value, MR^{exp} is the experimental moisture ratio, MR^{calc} is the calculated moisture ratio, and N represents the number of observations or residuals. The data were analyzed using a analysis of variance and Tukey's test at a 5% significance level.

Results and discussion

Evolution of surface temperature at the first stage

The surface temperature of any food that passes through a drying process is important to know, since until a certain point of drying, it remains close to the wet bulb temperature, such that the air temperature, even when high, has less influence on the food. However, when the surface becomes partially unsaturated, the surface temperature increases, which may cause degradation of the compounds of interest or cause damage, which will affect product quality parameters. Therefore, especially in the case of intermittent drying, it is necessary to focus on the time the food is exposed to the drying conditions in the first stage, in which the dryer operates at the highest temperatures. Figure 2 shows the mean surface temperatures measured during drying at 75, 85, and 95°C as a function of the time, where the surface temperature at the end of the first stage of all the intermittent drying configurations does not exceed the second stage drying temperatures.

Drying kinetics and diffusivities

Figure 3 shows the continuous and intermittent experimental drying curves, as well as the curves created using the values predicted according to Eq. (1). The intermittent drying curves showed discontinuity between the first and second stages as indicated by the dashed lines. A comparison between the intermittent and continuous drying curves shows the considerable contribution of the thermal intermittence in the moisture reduction profile. Figure 3a shows the rapid reduction in moisture content with the two highest first stage temperatures (95 and 85°C), whose curves were relatively similar to each other and readily distinguishable from the curves of the first stage temperature of 75°C and even more so from the curves of the continuous dryings.

In Fig. 3b, it can be observed that the change from 30 to 60 min had virtually no effect on the drying curves. Figure 3c shows little difference between treatment T5 (85°C/45 min/70°C) and the corresponding continuous drying (70°C). On the other hand, Fig. 3d emphasizes the positive effects of intermittent drying performed at 85°C for 45 min, followed by drying at 50°C.

Table 2 shows the values for diffusivity and the determination coefficients (R^2), relative errors ($P(\%)$), and RMSE for the drying trials.

The R^2 indicated a good fit for Eq. (1), since all the values were above 0.99. The values for $P(\%)$ were low for the first stages of intermittent drying but were above 10% for the second stages and for the continuous

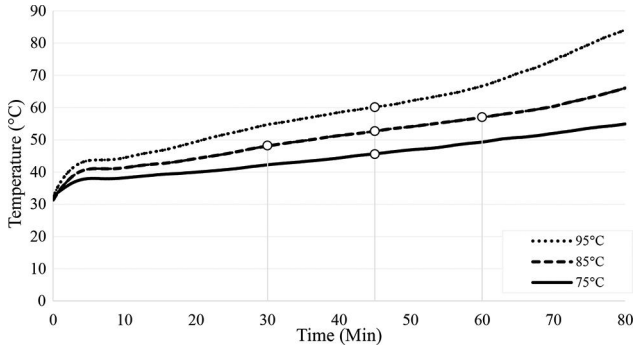

Figure 2. Mean surface temperature of sliced apples as a function of time, when exposed to drying air temperatures of 75, 85, and 95°C, at 2 m $\cdot$ s^{-1}.

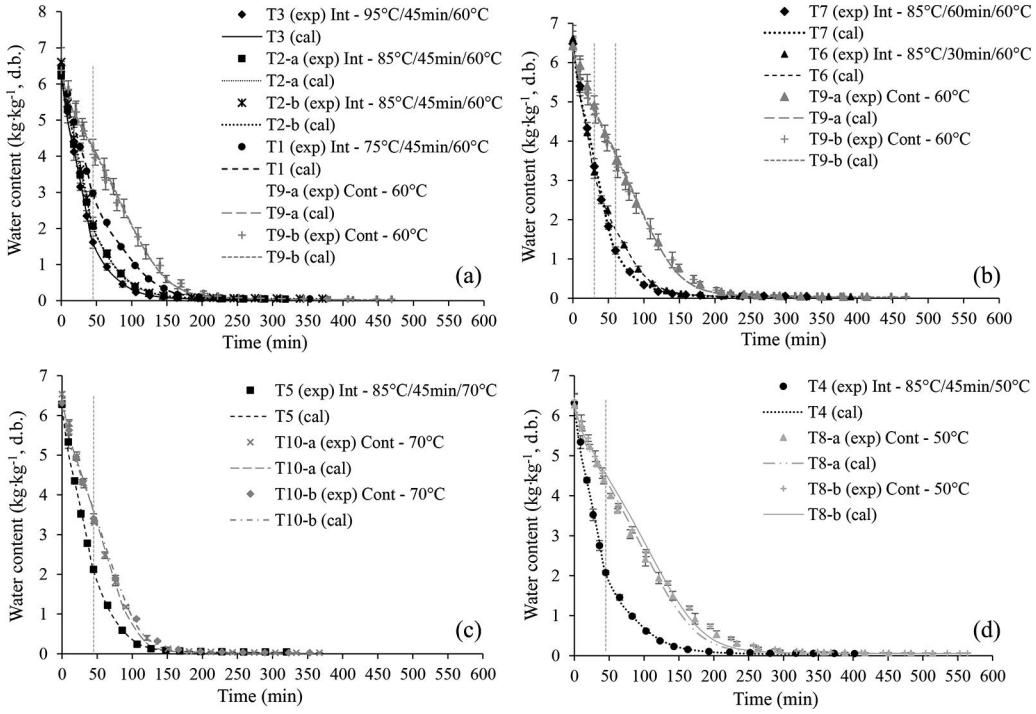

Figure 3. Experimental (exp) and predicted (calc) values for the water content (d.w.b.) as a function of drying time, for intermittent (Int) and continuous (Cont) drying runs. Dashed lines represent the duration time of the first stage of the intermittent drying: 30 min, 45 min and 60 min.

drying, which is the reference value for the fit to be considered satisfactory.[44] However, since the $P(\%)$ is a relative measurement, as drying advances, the value for the moisture content becomes very small, and since it is the denominator of Eq. (17), it amplifies the errors. In evaluating the fit of the equation using the statistical parameter of RMSE, which is not relative, very low values were found for both the first and the second intermittent drying stages and for the continuous dryings, signifying that the fit was satisfactory.

Although the diffusion coefficients were considered constants in Eqs. (5) and (6), they are dependent on the concentration.[45] Thus, a mean coefficient was determined for the process. If the drying curves were segmented, then the diffusion coefficients would represent a mean for each drying stage. The dependence of these coefficients on temperature can be observed through the diffusion coefficients for the first stage of drying based on the increase that occurred while the temperature increased from 75 to 95°C (T1, T2, T3, Table 2), when performed for 45 min. The temperature in the first stage of drying trials also affected the diffusion coefficients of the second stage, which increased from 1.3 to $1.9 \times 10^{-10}\,m^2 \cdot s^{-1}$. Thus,

Table 2. Effective diffusion coefficients for the continuous and intermittent dryings.

				Effective diffusion coefficients × 10^{10} ($m^2 \cdot s^{-1}$)											
				Intermittent - stage 1				Intermittent - stage 2				Continuous			
Treatment	Process conditions	Rep.	Drying time (min)	D_{eff} (stage 1)	R^2	P (%)	RMSE	D_{eff} (stage 2)	R^2	P (%)	RMSE	D_{eff}	R^2	P (%)	RMSE
T1	75°C/45 min/60°C	a	353	2.1	0.990	2.5	0.026	1.3	0.999	10.1	0.012	–	–	–	–
T2	85°C/45 min/60°C	a	318	2.9	0.995	2.6	0.023	1.7	0.999	14.9	0.013	–	–	–	–
		b	335	2.9	0.998	2.4	0.017	1.7	0.998	13.3	0.016	–	–	–	–
T3	95°C/45 min/60°C	a	283	3.3	0.997	2.6	0.021	1.9	0.998	19.5	0.014	–	–	–	–
T4	85°C/45 min/50°C	a	402	3.0	0.996	2.5	0.021	1.4	0.998	17.5	0.015	–	–	–	–
T5	85°C/45 min/70°C	a	320	2.9	0.996	2.5	0.022	2.1	0.999	17.2	0.010	–	–	–	–
T6	85°C/30 min/60°C	a	391	3.1	0.995	2.2	0.021	1.7	0.999	13.4	0.008	–	–	–	–
T7	85°C/60 min/60°C	a	329	2.8	0.996	3.2	0.022	1.7	0.996	20.7	0.017	–	–	–	–
T8	Continuous 50°C	a	514	–	–	–	–	–	–	–	–	1.0	0.998	19.2	0.024
		b	564	–	–	–	–	–	–	–	–	1.0	0.998	23.6	0.023
T9	Continuous 60°C	a	414	–	–	–	–	–	–	–	–	1.3	0.998	17.5	0.021
		b	469	–	–	–	–	–	–	–	–	1.3	0.998	20.9	0.019
T10	Continuous 70°C	a	367	–	–	–	–	–	–	–	–	1.9	0.999	25.7	0.018
		b	353	–	–	–	–	–	–	–	–	1.8	0.999	24.8	0.018

RMSE, root mean square error.

although the second stage temperatures were the same (60°C), the temperatures of the first stage exerted an influence on the second stage's diffusivity, which varied proportionally with its increase, probably because it affected the vegetable structure, making the subsequent drying easier.

An important point to note was that the effective diffusion coefficients of the second stage of intermittent drying were higher than those of the corresponding continuous drying, except for treatment T1 (75°C/45 min/60°C). For treatment T2 (85°C/45 min/60°C), the diffusion coefficient of the second stage was 24% greater than that of the corresponding continuous drying stage, and for T3 (95°C/45 min/60°C), the diffusivity of the second stage was 31% greater. These results suggest that the application of the first stage at temperatures of 95 and 85°C, in addition to accelerating the first stage of drying, favored the efficiency of the lower temperature stage, both contributing to a reduction in the total drying time. However, the temperature of 75°C (T1) did not result in gains in the efficiency of the second stage.

With respect to the first stage, when the treatments presented the same drying temperature and time (T2, T4, and T5), the coefficients showed great correlation, with a mean and standard deviation of $2.9 \times 10^{-10}\ m^2 \cdot s^{-1} \pm 0.1 \times 10^{-10}$. This correlation was also observed in the diffusion coefficients of the second stage for treatments T2, T6 (85°C/30 min/60°C) and T7 (85°C/60 min/60°C), showing that the duration of the first stage did not influence the value of the diffusivity in the second stage, which was always approximately $1.7 \times 10^{-10}\ m^2 \cdot s^{-1}$.

On the other hand, despite the slight deviations in the values for the diffusivities in the treatments T6 and T7, they remained close to the mean for the temperature ($2.9 \times 10^{-10}\ m^2 \cdot s^{-1}$). In the first stage, a time influence on diffusivity is expected if there is a predominant period of a constant drying rate. However, the trials in which the surface temperature of the samples was registered (Fig. 2) showed that the apple slices did not show a constant drying rate period at the air-drying temperatures (75, 85, and 95°C), as the surface temperatures increased constantly with the drying time.

The drying rates (Fig. 4) also confirm the lack of a constant drying period. However, the existence of an eventual period of constant drying could not be detected, because the measurements were taken in over short periods of 9 or 10 min. In addition, there is a period of sample adaptation, during which the rates are generally low,[5] impeding interpretation of the mechanism in the first few minutes of drying.

The drying rates in the first stages of intermittent drying were higher than those in the second stages because of the drying air temperature. However, the

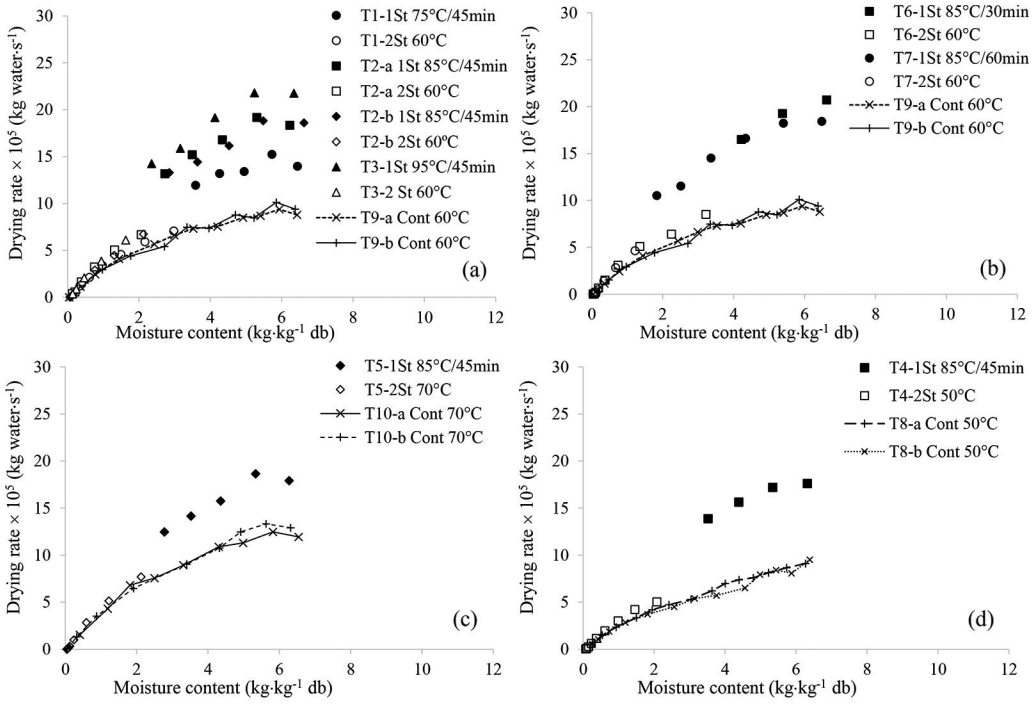

Figure 4. Drying rates as a function of moisture for the first stage (1St) and the second stage (2St) of intermittent drying and for continuous (Cont) drying: (a) effect of the first stage temperature on drying rates of the second stage at 60°C; (b) effect of the first stage time of intermittent drying; (c) e; and (d) effect of the second stage temperature on drying rates.

intermittent drying rates in the second stages were higher than the continuous drying rates at the same temperature, showing that the high temperatures (85 and 95°C) in the first stage of intermittent drying modified the drying kinetics in the second stage, improving the drying efficiency, in accordance with the effective diffusion coefficients (Table 2). Thermal intermittency provided a considerable reduction in the duration of all the intermittent drying trials. Treatments T5 (85°C/45 min/70°C) and T6 (85°C/30 min/60°C) showed the lowest reductions in the total operational time with an average reduction of 11%, but the reduction reached 35% (150 min) in treatment T3 (95°C/45 min/60°C). The reduction in drying time caused by intermittency has also been reported by other authors, but in these cases, the intermittency was established by periods of tempering.[20,21,23,25,46] It is worth noting that tempering-intermittent drying shortens the effective drying time required for the drying process to achieve the desired final moisture content but prolongs the total process time, which can have consequences for compounds more sensitive to drying time than to drying temperature.[23]

Energy analyzer consumption data

To estimate the energy consumption of the dryer resistances during the total time of each drying, the energy consumption profiles were evaluated, with the data taken at 10 min intervals as seen in Fig. 5. The continuous dryings performed at 50, 60, and 70°C showed a linear behavior but were better described by two separate linear equations.

For the same temperature, the difference between the equations was due to the water content of the apple slices, which was high at the start of drying and therefore demanded more from the dryer electrical resistances. As drying continued, the moisture content decreased and affected the energy consumption less. Hence, to determine the consumption and power values at each time interval of the continuous dryings, two linear equations were established, with one describing the consumption during the drying to a moisture content of approximately 75% (w.w.b.) and the other describing the consumption from this point to the completion of drying. The equations used to determine the energy consumption for the continuous drying are shown in Fig. 5.

In the intermittent dryings, the consumption measured in the first stages also showed a linear behavior as described in Fig. 6.

In the second stages, the apple slices started drying with lower moisture contents, as a function of the time and temperature in the first stage. Therefore, the energy consumption equations of the second stages were determined by the consumption data shown in Fig. 5, considering only the moisture ranges of each treatment.

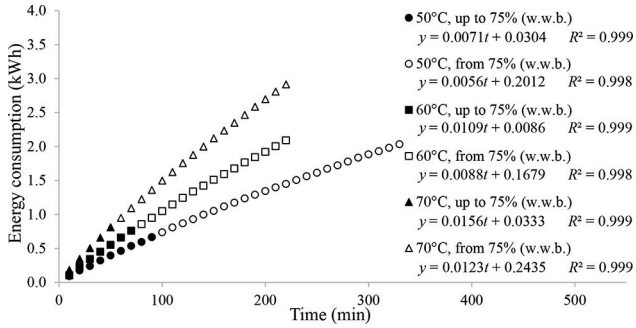

Figure 5. Energy consumption equations as a function of drying time for continuous drying considering two different intervals, from the initial moisture to 75% (w.w.b.) and from 75% (w.w.b.) to the final moisture.

Energy consumption analysis of the continuous and intermittent dryings

The differences between the measurements obtained using the analyzer and the energy balances showed how much energy the drying system consumed and how much it could consume assuming an adiabatic system. This signifies that all the heat provided by the heated air is used in the drying operation, without any loss of heat. With this information, one could evaluate the potential of the drying conditions proposed and the conditions under which the heat losses to the environment were significant.

Although the energy demand on the resistances increased with an increase in temperature, the energy balance calculations and the mean consumption measured by the analyzer showed that there was a reduction in energy consumption, when intermittent drying was compared with continuous drying, as shown in Fig. 7.

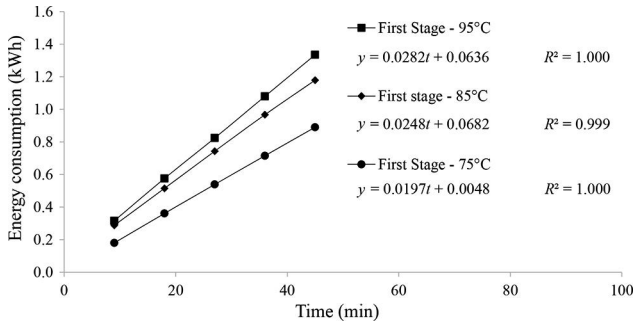

Figure 6. Energy consumption profile in the first stages of intermittent drying as a function of drying time.

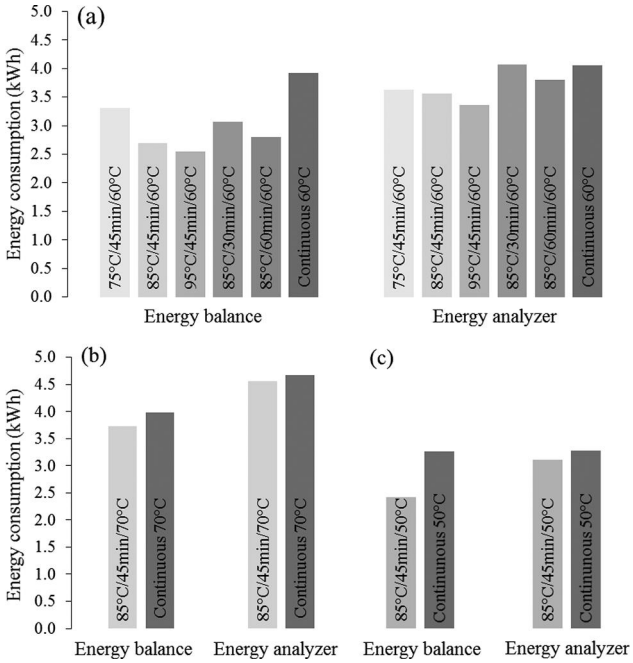

Figure 7. Energy consumption (kWh) determined by the energy analyzer and by the energy balance for the continuous and intermittent drying treatments: (a) Comparison of the consumption during the second stage of intermittent drying at 60°C with continuous drying at 60°C; (b) Comparison of the consumption during the second stage of intermittent drying at 70°C with continuous drying at 70°C; (c) Comparison of the consumption during the second stage of intermittent drying at 50°C with continuous drying at 50°C." by "Energy consumption (kWh) determined by the energy analyzer and by the energy balance for the continuous and intermittent drying treatments: (a) Comparison of intermittent drying with second stage at 60°C and continuous drying at 60°C; (b) Comparison of intermittent drying with second stage at 70°C and continuous drying at 70°C; (c) Comparison of intermittent drying with second stage at 50°C and continuous drying at 50°C.

It can be seen from Fig. 7 that according to the energy balance, all the intermittent dryings consumed less energy than the continuous dryings performed at the temperature of the second stage of intermittent drying. This event, although with less discrepancies, was also reproduced by the energy analyzer, except for treatments T6 (85°C/30 min/60°C) and T7 (85°C/60 min/60°C), where the measurements were similar to those of the corresponding continuous dryings (Table 3).

Table 3 shows the values for the power and consumption of the continuous and intermittent dryings calculated from the energy balance (E.B.) and measured by the energy analyzer (E.A.).

Both the analyzer data and the energy balance equations showed that the greatest reduction in energy consumption occurred in treatment T3 (95°C/45 min/60°C), even though the power required for the dryer to operate at 95°C is almost three times that required at 60°C. According to the analyzer, under these conditions, thermal intermittence results in an economy of approximately 17% in relation to continuous drying, corresponding to a reduction of approximately 0.7 kWh in consumption. However, based on the energy balance, which considers the system to be adiabatic, the savings could be approximately 35%. The second highest energy reduction, as indicated by both measurement methods, was treatment T2 (85°C/45 min/60°C), which allowed for a savings of approximately 11%, according to the energy analyzer, and 28%, according to the energy balances.

A comparison of the consumption of treatments T2 (85°C/45 min/60°C), T6 (85°C/60 min/60°C), and T7 (85°C/30 min/60°C), with the continuous drying consumption at 60°C, showed that increasing the first stage time reduced the energy savings by half (approximately 6.2%), when measured by the analyzer. On the other hand, when the duration of the first stage decreased, according to the analyzer, there was no difference in energy consumption between the intermittent drying and corresponding continuous drying, although the energy balance showed an energy savings of approximately 25%.

When the temperature in the second stage of the T2 treatment (85°C/45 min/60°C), which provided the second largest gain in energy savings, was modified, either to 50°C (T4) or to 70°C (T5), no substantial energy gain was observed. In the T4 treatment, the energy savings in relation to the continuous drying at the same temperature were only 2.3%, according to the analyzer, and 6.3%, according to the energy balance, and in the T5 treatment, the savings were 5.2% according to the analyzer. In this specific case, the intermittent drying was performed on a very dry day (Table 3), whereas for the continuous drying, the relative humidity was higher. Consequently, the energy balance expressed a high savings value of approximately 26%.

With respect to the energy losses from the dryer to the environment, it was shown that the values for energy consumption measured by the analyzer during the continuous dryings at 50 and 60°C were close to those calculated by the energy balance (Fig. 6), varying by a maximum of 5%. This reflects low heat losses from the system when the temperature gradients between the inside and outside of the dryer did not exceed 30°C. However, when the drying was performed at 70°C, the difference between the measured and the calculated energy consumption was relevant (approximately 17%). Moreover, for intermittent drying, the differences between energy consumption values obtained from the balances and the analyzer measurements were higher than for the corresponding continuous dryings, because heat losses were more intense during the first stage, when the highest temperatures were applied. These heat

Table 3. Mean power and consumption of the continuous and intermittent drying treatments as calculated by the energy balance (E.B.) and measured by the energy analyzer (E.A.).

Treatment	Process conditions	Mean temperature in the dryers	RH% in the dryers	Total time (min)	Mean power (kW)		Mean consumption (kWh)			
					E.B.	E.A.	E.B.	E.A.	E.B. (total)	E.A. (total)
Intermittent drying										
T1	75°C/45 min	78.29 ± 0.67	6.52 ± 0.26	353	0.822	1.187	0.616	0.890	3.309	3.635
	60°C	60.24 ± 0.29	10.65 ± 0.47		0.528	0.554	2.693	2.745		
T2	85°C/45 min	85.23 ± 0.56	6.27 ± 0.14	318	1.126	1.572	0.845	1.179	2.688	3.562
	60°C	60.67 ± 0.25	7.63 ± 0.32		0.408	0.516	1.843	2.383		
T3	95°C/45 min	96.37 ± 0.69	5.32 ± 0.25	283	1.143	1.780	0.857	1.335	2.543	3.358
	60°C	60.57 ± 0.25	8.08 ± 0.07		0.427	0.524	1.685	2.023		
T4	85°C/45 min	86.96 ± 1.45	5.69 ± 0.36	402	1.038	1.572	0.779	1.179	2.434	3.124
	50°C	50.55 ± 0.32	10.36 ± 0.31		0.281	0.336	1.656	1.945		
T5	85°C/45 min	86.92 ± 0.77	6.52 ± 0.16	320	0.980	1.572	0.735	1.179	3.767	4.564
	70°C	70.48 ± 0.37	7.11 ± 0.30		0.663	0.771	3.032	3.385		
T6	85°C/30 min	85.56 ± 1.19	6.32 ± 0.21	391	1.241	1.738	0.621	0.812	3.069	4.073
	60°C	60.61 ± 0.03	7.74 ± 0.17		0.411	0.566	2.448	3.261		
T7	85°C/60 min	85.76 ± 1.18	6.22 ± 0.18	329	1.056	1.655	0.880	1.556	2.797	3.803
	60°C	60.51 ± 0.25	7.56 ± 0.22		0.430	0.510	1.918	2.247		
Continuous drying										
T8	50°C	50.56 ± 0.65	13.57 ± 0.79	514	0.379	0.425	3.067	3.150	3.067	3.150
	50°C	49.66 ± 0.40	14.54 ± 0.95	564	0.375	0.418	3.497	3.440	3.497	3.440
T9	60°C	61.00 ± 0.88	10.60 ± 0.49	414	0.548	0.610	3.620	3.811	3.620	3.811
	60°C	60.88 ± 0.52	11.02 ± 0.53	448	0.561	0.603	4.235	4.295	4.235	4.295
T10	70°C	70.42 ± 1.43	7.50 ± 0.49	367	0.671	0.888	3.907	4.758	3.907	4.758
	70°C	70.49 ± 1.25	7.91 ± 0.44	353	0.712	0.885	4.055	4.585	4.055	4.585

losses, in turn, were not evaluated in the energy balance, which considers the adiabatic system. For instance, in treatment T3 (95°C/45 min/60°C), the values measured by the analyzer were 24% higher than those found from the energy balance (Table 3).

Investigating the two stages of this treatment separately, it was verified that the greatest divergence between the methods occurred in the first stage of drying, in which the analyzer presented an energy consumption approximately 36% higher than the one calculated by the energy balance, while in the second stage, the consumption measured by the analyzer was approximately 16% higher.

The second stages of the intermittent dryings had closer values for the two methods for measuring energy consumption, but in general, the differences were higher than those observed for the continuous dryings. Since the energy demands were lower in the second stage due to the samples having a lower moisture content, the differences between the analyzer and energy balance had proportionally more discrepancies. This was attributed to the power required to compensate for the heat losses from the system into the environment, which remained approximately constant throughout drying, whereas that required to evaporate the water decreased as drying advanced.

The two energy consumption methods, when compared, allowed one to evaluate the heat losses from the system and the potential for energy savings resulting from the thermal intermittency application. In this way, the differences between the energy analyzer measurements and the energy balances results highlight the importance of efficient insulation for reducing heat losses from the external dryer surfaces.

It can also be observed that in the second stage, as the drying proceeded, the energy demand to compensate for the heat losses were proportionally more significant than the energy demand for evaporation, when the moisture contents were low. This result underlined the elevated energy consumption needed to dehydrate products to very low moisture contents, encouraging the investigation of combined methods that make use of a vacuum in the final drying stages.

The T3 treatment (95°C/45 min/60°C), despite having a 7.5% higher energy consumption than the T4 treatment (85°C/45 min/50°C), provided a 30% reduction in the total drying time, which corresponded to 150 min of operation time. Moreover, even though energy consumption for the insufflation of the dry air was not evaluated in the present study, it is considerable and directly related to the drying time, which reinforces the importance of reducing the length of the drying period.

Retention of chlorogenic acid

Detection and quantification of chlorogenic acid peaks by ^{1}H NMR

The generated spectra appear in Fig. 8. The dried apple spectrum can be divided into three regions: the high field (0–2.5 ppm), the center field (2.5–5.8 ppm) and the low field (5.8–8.5 ppm). The signs of the predominant compounds (glucose, fructose and sucrose) appear in the central region.[47] However, the chlorogenic acid signs, as well as the other phenolic compounds, are found in the

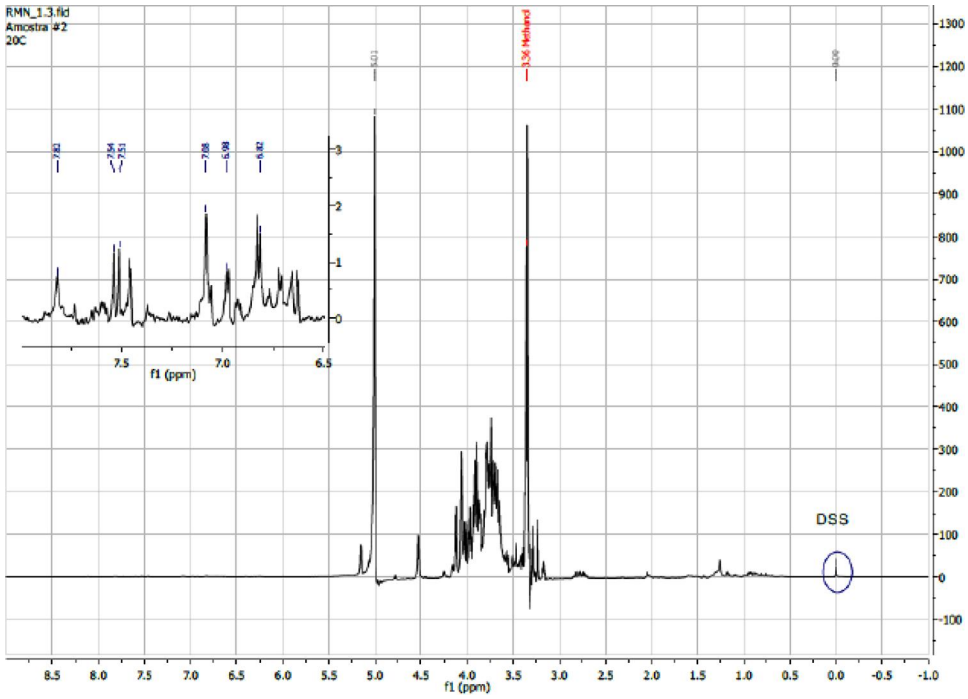

Figure 8. ^{1}H NMR spectrum of dried apple.

low field region (expanded scale of the vertical axis, Fig. 8). It was possible to detect the signal of four hydrogen nuclei of chlorogenic acid that were present in the regions of 7.52, 7.08, 6.97, and 6.82 ppm. Berrigi et al.[48] reported peaks for this same compound in the same region.

Table 4 shows the chlorogenic acid retention that was calculated for each treatment based on the mean retention of fresh samples.

According to the data in Table 4, all the dryings exhibited high retention that, in some cases, reached 100%. However, the standard deviations of the retentions were high, with variance coefficients up to 21%, which implies a similarity between the retentions of all the treatments. In terms of retention, the high values of the standard deviations expressed in all the drying treatments can be related to the low concentration of the specific compound being tested in the samples, which results in small peaks in the spectrum; therefore, the specific compound concentration is affected by the signal/noise ratio and acquisition artifacts. In this sense, although ^{1}H NMR is recognized as a reliable technique for the quantification of organic compounds,[49] it was used qualitatively in this work, which ensured that the use of an initial drying stage at a higher temperature did not affect the chlorogenic acid concentration of the dried Fuji apples compared to conventional (continuous) drying and that this compound did not have significant losses in the drying conditions tested. In this sense, similar results were found by Joshi et al.,[50] who verified that in the drying conditions tested, the chlorogenic acid concentration in the apples was not significantly affected compared to the concentration in the fresh sample. In addition, although chlorogenic acid also appears in the pulp of the Fuji apple cultivar,[51] it is found mainly in their peel,[52] which, because of the peel's low permeability, makes it difficult for O_2 to access chlorogenic acid.

Table 4. Retention of chlorogenic acid in Fuji apple samples dried in different drying configurations.

Treatment	Process conditions	X^{D}_{ACG} (kg · kg^{-1})	Retention	CV (%)
T1	75°C/60 min/60°C	0.000614	0.8 ± 0.1	17
T2	85°C/45 min/60°C	0.000608	0.8 ± 0.1	15
T3	95°C/45 min/60°C	0.000630	0.9 ± 0.1	17
T4	85°C/60 min/50°C	0.000675	0.9 ± 0.1	13
T5	85°C/45 min/70°C	0.000738	1.0 ± 0.2	15
T6	85°C/30 min/60°C	0.000821	1.0 ± 0.1	10
T7	85°C/60 min/60°C	0.000645	0.9 ± 0.2	18
T8	Continuous 50°C	0.000568	0.8 ± 0.1	14
T9	Continuous 60°C	0.000644	0.9 ± 0.2	17
T10	Continuous 70°C	0.000554	0.8 ± 0.2	21

Color

The color parameter values of the fresh and dried apples are presented in Table 5.

The parameters a^*, b^*, and C^* in the dry samples are presented in increments in relation to the fresh parameters. This may be related to the moisture loss caused by drying and the consequent pigment concentrations,[53]

Table 5. Color parameters in the CIELAB system for dried apple slices (cv. Fuji) by continuous drying and different intermittent drying treatments.

Treatment	Process conditions	L^*	a^*	b^*	C^*	h^*
Natura		$74.08^{d} \pm 1.63$	$0.78^{f} \pm 0.34$	$26.72^{c} \pm 0.90$	$26.74^{c} \pm 0.91$	$88.52^{d} \pm 0.76$
T1	75°C/60 min/60°C	$80.20^{b} \pm 0.92$	$3.21^{cde} \pm 0.50$	$33.21^{b} \pm 2.18$	$33.37^{a} \pm 2.21$	$84.57^{ab} \pm 0.61$
T2	85°C/45 min/60°C	$77.69^{abc} \pm 1.08$	$2.10^{abc} \pm 0.74$	$31.98^{ab} \pm 1.04$	$32.07^{ab} \pm 1.06$	$86.35^{bc} \pm 1.21$
T3	95°C/45 min/60°C	$76.36^{acd} \pm 1.64$	$2.60^{abcd} \pm 0.58$	$31.86^{ab} \pm 1.47$	$31.98^{ab} \pm 148$	$85.44^{abc} \pm 0.96$
T4	85°C/60 min/50°C	$77.82^{abc} \pm 1.13$	$1.84^{abf} \pm 0.80$	$31.42^{ab} \pm 0.71$	$31.49^{ab} \pm 0.71$	$86.72^{bcd} \pm 1.48$
T5	85°C/45 min/70°C	$76.08^{acd} \pm 1.67$	$2.95^{bcde} \pm 1.17$	$32.08^{ab} \pm 2.41$	$32.24^{ab} \pm 2.42$	$84.89^{ab} \pm 2.09$
T6	85°C/60 min/60°C	$75.18^{cd} \pm 2.99$	$2.16^{abc} \pm 0.83$	$31.26^{ab} \pm 1.58$	$31.37^{ab} \pm 1.60$	$86.24^{bc} \pm 1.34$
T7	85°C/30 min/60°C	$77.71^{abc} \pm 2.3$	$1.58^{af} \pm 0.96$	$30.71^{a} \pm 1.07$	$30.77^{b} \pm 1.11$	$87.19^{de} \pm 1.66$
T8	Continuous 50°C	$78.74^{ab} \pm 0.99$	$3.92^{e} \pm 0.70$	$32.53^{ab} \pm 0.96$	$32.69^{ab} \pm 0.96$	$83.27^{a} \pm 1.12$
T9	Continuous 60°C	$78.71^{ab} \pm 1.33$	$3.73^{de} \pm 1.07$	$33.04^{ab} \pm 1.57$	$33.28^{a} \pm 1.68$	$83.72^{a} \pm 1.54$
T10	Continuous 70°C	$78.80^{ab} \pm 0.85$	$3.68^{de} \pm 0.76$	$31.69^{ab} \pm 0.96$	$31.94^{ab} \pm 1.02$	$83.54^{a} \pm 1.28$

Values in the same column having the same letter for each parameter are not significantly different at a confidence level of 95%.

or even, to enzymatic and nonenzymatic browning, with the latter resulting from the Maillard reactions.[7,53] Long dryings at low temperatures could promote color changes associated with browning product formation in the apples.[7,54] However, there was no significant difference in the color parameters between continuous dryings at 50, 60, and 70°C (T8, T9, and T10). Conversely, a comparison between treatments revealed that the a^* parameters after the intermittent dryings were lower than after the continuous dryings, and some of them showed significant differences, specifically, the T2, T4, T6, and T7 treatments. All samples from intermittent dryings presented the lowest a^* values and, consequently, shifted the color of these samples from the reddish to the yellowish region, leading to the highest h^* values. As phenolic compounds in the apple flesh can be oxidized by the polyphenoloxidase (PPO) enzyme, low red chromaticity suggests that the fast, initial drying during the first stage of the intermittent treatments may have minimized the brown compounds formation by the inhibition of the enzymatic reactions. However, the small differences between red chromaticity were not reflected by the L^* parameters. The compounds found in at substantial quantities in the apple Fuji pulp, such as chlorogenic acid, epicatechin, and phloridzin,[52] may be associated with the browning reaction. According to Oleszek et al.,[55] these compounds are substrates for the PPO and contribute to different browning rates; phloridzin, particularly, contributed drastically to the browning rate.

Conclusion

Thermal intermittence, in addition to accelerating drying in the first stage, provided an increase in the diffusivity and drying rates of the second stage, allowing a considerable reduction in the total process time. Moreover, in the best studied condition (treatment T3), it was possible to achieve an energy savings of 17%, which according to energy balances, could be higher if insulation was improved, and a savings of 35% with the adiabatic condition. The use of the first stage at the studied temperatures and times did not affect the chlorogenic acid retention and color.

This work will be useful for guiding new studies with respect to procedures for establishing time and temperature conditions in the initial drying stages, as well as for evaluating heat losses and insulation efficiency by comparing direct measurements with theoretical heat balances.

It was concluded that the application of thermal intermittence in the convective drying of Fuji apples is advantageous in terms of total drying time and energy consumption, showing a promising technique from an economic and sustainability perspective.

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Nomenclature

D_{eff}	effective diffusion coefficient of moisture ($m^2 \cdot s^{-1}$)
$\dot{E}$	water evaporation rate (kg water $\cdot s^{-1}$)
H	enthalpy of the dry-air (kJ $\cdot$ kg^{-1} dry air)
l	half-thickness of samples (m)
MR	fractional or residual moisture, d.w.b (dimensionless)
$\dot{m}$	rate of airflow (kg dry air $\cdot s^{-1}$)
m_s	mass of dry solids of the apple (kg dry matter)
N	number of observations or residuals
n	number of terms of the series
P(%)	P value
$\dot{q}$	energy required to heat the air (kW)

$\dot{Q}$	volumetric flow ($m^3 \cdot s^{-1}$)
$R(\%)$	retention of chlorogenic acid
RMSE	root mean square error
S	transversal area of the bed (m^2)
T	temperature (°C)
t	time (s)
v	air velocity ($m \cdot s^{-1}$)
d.w.b.	dry weight basis
w.w.b.	wet weight basis
X_w	fraction of the moisture (kg water $\cdot$ kg^{-1} dry solids)
X^D_{ACG}	fraction of chlorogenic acid concentration in the dry apple (kg chlorogenic acid $\cdot$ kg^{-1} dry solids)
X^F_{ACG}	fraction of chlorogenic acid concentration in the fresh apple (kg chlorogenic acid $\cdot$ kg^{-1} dry solids)
$\bar{X}_w$	mean fraction of the water mass (kg water $\cdot$ kg^{-1} dry solids)
Y	absolute humidity (kg water $\cdot$ kg^{-1} dry air)
υ_1	humid volume ($m^3 \cdot kg^{-1}$ dry air)
$\Delta X/\Delta t$	variation in moisture (kg water $\cdot$ kg^{-1} dry matter $\cdot$ s^{-1})
ΔX^D_{ACG}	standard deviation of X^D_{ACG}
ΔX^F_{ACG}	standard deviation of X^F_{ACG}

Subscripts and superscripts

0	initial state
eq	equilibrium
calc	calculated
exp	experimental
I	position in the dryer

References

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