Drying and Rehydration Kinetics of Peeled and Unpeeled Green Apple Slices (Granny Smith CV)

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Abstract

Dried fruit consumption is increasing due to its nutritional and healthy properties. Apples are an important source of essential nutritional compounds such as antioxidants, vitamins, minerals, and fibers. In this work, the kinetics of drying and rehydration of green apple slices peeled and unpeeled (Granny Smith cv) were studied. The apple slices were dried at 50, 60, and 70 ºC, and after that, rehydrated at ambient (T_a) and boiling temperature (T_b). The drying kinetics were adjusted with the Dincer and Dost model, giving a good fit (R^2 > 0.98). Effective diffusivity (D_{eff}) and the convective mass transfer coefficient (h_m) were also determined, both coefficients increase with drying temperature, being $1.25×10^{-9}$ $m^2.s^{-1}$ and $9.53×10^{-7}$ $m^2.s^{-1}$ the highest values obtained for the peeled apple slices respectively. Subsequently, Peleg and Weibull models were adjusted to the rehydration experimental data obtaining a good fit (R^2 > 0.99). D_{eff} values increase significantly with rehydration temperature but take similar values between peeled and unpeeled samples. Equivalent diameter, pH, acidity, soluble solids, and moisture content were determined to compare the fresh apple slices with those after dehydration and post rehydration process. The apple slices rehydrated at boiling temperature better preserved the characteristics of fresh samples due to the short immersion times in water, no significant differences were observed between peeled and unpeeled apples. According to the obtained results, it is convenient to dry the apple slices unpeeled at 70 °C and rehydrate them at T_b.

Statement Of Novelty

The drying and rehydration of peeled and unpeeled apple slices (Granny Smith cv.) were studied. The drying was carried out at 50, 60, and 70°C, and the rehydration process at ambient temperature (T_a) and boiling temperature (T_b). Moreover, the fresh and rehydrated samples were characterized considering: pH, acidity, equivalent diameter, soluble solids, and moisture content; characteristics that affect directly the flavor and texture of apples. No reports of the drying and rehydration kinetics simultaneously evaluated of Granny Smith apple slices were found and it is also novel to make a comparison between peeled and unpeeled samples. There are no published works where the effect of drying and subsequently rehydration processes on the characteristics of fresh apple slices is considered.

1. Introduction

Apples, *Pyrus malus* L. (*Rosaceae* family) are one of the most cultivated fruits around the world, its production worldwide is about $4.10×10^7$ tons [1], being China the main producer. Argentina is one of the principal producers in Latin America, with $5.63×10^5$ tons and a productive area of $5.00×10^4$ ha [2]. The apple-producing areas are mainly in the provinces of Río Negro, Neuquén, Mendoza, and San Juan, being the major cultivars of Red Delicious, Gala, and Granny Smith.

Apples are generally eaten fresh, although they can also be consumed like juice, or dehydrated as a snack in breakfast preparations, salads, and other culinary recipes [3]. Apples are a vital source of many essential nutritional compounds: vitamins (A, B1, B2, B3, B5, B6, C, and E in minor amounts), minerals, fibers, and also are rich in antioxidants [3 – 6]. Granny Smith variety, widely grown in Argentina, is the most representative variety of the group of green apples. It is characterized by an intense and uniform green color, medium size compared with other varieties, also it is juicy and slightly acidic. Moreover, this variety contains more fibers and antioxidants than others [7].

According to Global Industry Analysis [8], dehydrated fruit is becoming a potential product. The study indicates that, during 2020, the consumption of dehydrated fruit was close to $4×10^6$ tons. China is the largest exporter of dried fruits, followed by Germany, the United Kingdom, the United States of America, and Russia, exporting 150, 46, 41, 36, and 35 thousand tons respectively [9]. The increasing consumption of dehydrated fruit is related to the global trend of consuming nutritious and healthy foods as well as avoiding wasting fruit [8].

To obtain dried products, conventional air drying is the most widely used drying operation due it is a simple process [10]. This unit operation comprises the water content reduction through simultaneous mass and heat transfers [11]. The water remotion is carried out through evaporation, consuming important energy quantities, for that, drying is denominated as an energy-intensive process [12]. This unit operation reduces the cost of packaging, transportation, storage, and preservation.

The drying kinetics of foods are greatly affected by air temperature, moisture content, and material structure, observing contraction and changes in physical properties [13]. According to Shrestha et al. [14], the drying temperature of apples must be between 40 and 80°C to avoid the decomposition of heat-sensitive biological compounds. Several authors recently investigated the drying of apples and their peel: Kidon and Grabowska [15] studied the effect on the bioactive compounds, antioxidant activity, color, and sensory attributes of red apple cubes by three different drying methods (convective, vacuum-microwave pretreatment with convective, and freeze-drying). Raponi et al. [16] real-time monitored the hot-air drying of apple cylinders using computer vision. Ma et al. [17] studied the effects of different methods (hot-air, heat-pump, and vacuum freeze drying) on the drying kinetics, color, phenolic stability, and antioxidant capacity of apple peel, and Chen et al. [18] analyzed the high-power microwave drying of apple slices to better understand the moisture kinetics and microstructure evolution.

It is important to remark that food drying is a very broad area of study, there are many experimental and theoretical reports to determine and estimate moisture transfer parameters for food drying [3, 19–21]. Heat and mass transfer models are applied to simulate drying curves under different conditions, thereby improving operational control of the process, being the most researched theoretical drying model of Fick's second law of diffusion. [22–24]. This law can be used for various forms of regular shape, such as rectangular, cylindrical, and spherical products, and commonly postulates that one-dimensional moisture movement occurs with constant diffusivity, uniform initial moisture distribution, negligible external resistance, and no change in volume [25].

Dincer et al. [26] developed and verified analytical techniques to characterize mass transfer in geometric and irregularly shaped objects (using a form factor) during drying. New drying parameters were defined, such as the drying coefficients and delay factor, based on an analogy between the cooling and drying profiles, which exhibit an exponential function in time [26]. Few researchers studied the Dincer and Dost model to characterize the mass transfer in food geometric objects during drying [21]. Beigi et al. [27] investigated the influence of drying air parameters (i.e., temperature, rate, and relative humidity of the air) on the effective D_{eff} and the h_m of apple slices. Model validation showed that the prediction of the experimental drying curves of the samples had a good precision. Bezerra et al. [25] evaluated the mass transfer characteristics of the passion fruit peel using the analytical model proposed by Dincer and Dost. According to the literature consulted so far, there is no known work on the effect of apple peel on drying behavior.

Considering the end-user habits of some consumers, dehydrated products must be rehydrated in solutions (e.g. water, sweetened water, or saline), before being consumed. Rehydration is the process of recovering water for dry products [28], in which the food mass increases according to the absorption of water during this process. The rehydration rate decreases because the value of moisture content of the product approaches the value of the equilibrium moisture content, while the water absorption rate is initially high [29]. This process depends on structural changes in the vegetal tissues and the cells of the material during drying. It is important to remark that during the drying, contraction, and collapse are carried out, reducing the water absorption capacity and avoiding the complete rehydration of the dried product [30]. The food rehydration process is considered as a measure of the damage degree to the raw material. However, rehydration cannot be treated simply as the opposite of dehydration. Different factors affect the rehydration process such as composition variables, drying method, physical structure, and medium characteristics. The study of the rehydration kinetics of dry vegetal tissues is composed of three simultaneous processes: water adsorption, swelling, and leaching of soluble compounds [31]. To model the rehydration kinetics of fruits and vegetables, the equation of Fick's second law and semiempirical equations based on it are generally used [32], in addition to Peleg and Weibull model, which have been used by several researchers [29, 33].

Until now, no reports have been found related to the drying of Granny Smith apple slices peeled and unpeeled varying the drying temperature and subsequently rehydration at T_a and T_b. Moreover, the effect of drying and rehydration on apple quality parameters has not been described.

1.1. Objectives of this work

In this article, the main objective was to model the drying and rehydration kinetics of green apple slices (Granny Smith variety) peeled and unpeeled to compare in what way these processes affect the quality parameters of fresh apple slices. Different drying temperatures were taken into account: 50, 60, and 70 ºC, and then samples were rehydrated in water at ambient and boiling temperatures (T_a and T_b, respectively). The drying kinetics were adjusted with the Dincer and Dost model, and the D_{eff} and h_m were calculated. Then, for the rehydration modeling, the Peleg and Weibull models were adjusted to the experimental data at both rehydration conditions, and the D_{eff} was calculated. Diameter, pH, acidity, moisture, and solid soluble content were considered to compare between fresh, dehydrated, and rehydrated apple slices. Figure 1 shows a roadmap of this work.

2. Materials And Methods

2.1. Sample preparation

Fresh apples (Granny Smith variety) were provided by the cooperative 'Valles Iglesianos' from Iglesia, San Juan, Argentina. The apples were stored in a refrigerator at 4°C until use within 2-4 days after sampling. Before drying the apples, they were cleaned with fresh water and the core of the fruit was removed, half of the apples were peeled and the other half were not. The peeled and unpeeled samples were cut with a mandolin to obtain the slices (thickness: 2.0 ± 0.1 mm).

2.2. Drying procedure

Drying experiments with apple slices peeled and unpeeled were performed using a macro-TGA, according to the methodology described by Baldán et al. [11] at three different temperatures: 50, 60 y 70°C. These experiences were made in triplicate and the average weight loss at each time was reported. After the drying process, the samples were bagged, sealed, and stored in a dark place until rehydration tests were carried out, within 2-3 days.

2.3. Rehydration procedure

Rehydration experiments were performed in triplicate by immersing a previously weighed dried apple slice into distilled water at two different temperatures: boiling temperature (T_b = 98°C, San Juan is located at 640 meters above sea level), and ambient temperature (T_a = 20°C). The rehydration process lasted 120 minutes and to study rehydration kinetics the apple slices were taken out of the rehydration solution every 2 minutes, covered with tissue paper for 30 seconds to remove surface water, weighted, and immersed again [34–36].

2.4. Apple slices characterization

The fresh, dehydrated, and post-rehydrated apple slices were characterized to compare between them. The characteristics taken into account were: pH (AOAC 10.042 Method, the pH meter used was Adwa AD1030 multiparametric with glass body pH electrode, previously calibrated at pH 4 and 7; the reading was performed at 20-25°C), acidity (AOAC 942.15 Method), moisture content (AOAC 925.10 Method), solid soluble content (AOAC 932.12 Method) [37], and the equivalent diameter (D_{eq}), determined using ImageJ software [38].

Table 1
Used equations to describe the drying and rehydration kinetics.

The moisture ratio (MR) [9]
$MR=\frac{M_t-M_e}{M_0-M_e}$ (1)
Dincer and Dost drying model [27, 42, 43]
$MR = G \exp(-St)$ (2)
Peleg rehydration model [39]
$M_t = M_0 + \frac{t}{k_1 + k_2 t}$ (3)
$M_e = M_0 + \frac{1}{k_2}$ (4)
Weibull rehydration model [40]
$\frac{M_t-M_e}{M_0-M_e} = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]$ (5)

3. Kinetic Analysis And Determination Of Models' Parameters

The Dincer and Dost model was used to determine the mass transfer characteristics during the drying process of the apple slices (Table 1).

Peleg model [39] is a non-exponential empirical model with two parameters and was applied to describe the rehydration procedure. The model equations are described in Table 1. Eq. 3 was linearized before its application to obtain the k_1 and k_2 from the experimental data. Moreover, the Weibull rehydrated model, a probabilistic model with three parameters, was applied to describe the rehydration process [40]. The model equation is described in Table 1. In Eq. 5, α and β are the shape and rate parameters respectively. α describes the water absorption rate, and it is higher when α values decrease. β defines the rate of the moisture uptake process and represents approximately the time required to complete 63% of the rehydration and depends on the process mechanism [41]. M_e is an additional parameter compared with the Peleg model. This model was solved using an iterative process, obtaining the value for α, β, and M_e that improve the statical parameters considered.

4. Determination Of Effective Diffusivity (Deff) And Convective Mass Transfer Coefficient (Hm)

D_{eff} is an important parameter that takes into account the moisture transference at drying and rehydration processes. It is very important to evaluate the D_{eff} to design different types of dehydrators. D_{eff} depends on the moisture content of samples and the drying or rehydration temperature. To obtain this coefficient a simple diffusion model based on Fick's second law was used. The Eqs. (6) to (9) were used to obtain D_{eff} (Table 2).

h_m ($m.s^{-1}$), is another important parameter in the drying process. It is correlated with D_{eff} using the Biot number for mass transfer (B_i) described by Eq. (10) (Table 2). Factor G is linked with Bi number by the Eq. (11), described in Table 2.

Table 2
Used equations to calculate Deff and hm.

Determination of effective diffusivity (D_{eff}) [32]	
$$MR = \frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}t}{4L^2}\right)$$	(6)
$$F_0 = \frac{D_{eff}t}{L^2}$$	(7)
$$F_0 = \frac{4}{\pi^2}\left[\ln\left(\frac{\pi^2}{8}\right) - \ln MR\right]$$	(8)
$$D_{eff,avg} = \frac{\int_{M_{initial}}^{M_{final}} D_{eff}(M)\,dM}{\int_{M_{initial}}^{M_{final}} dM}$$	(9)
Determination of convective mass transfer parameter (h_m) [27, 32]	
$$B_i = \frac{h_m L}{D_{eff}}$$	(10)
The Bi value describes different resistances according to the range, i.e. [44]:	
Bi ≤ 0.1	Indicate negligible internal resistance to the moisture diffusivity within the solid material.
0.1< Bi < 100	Suggest a finite internal and surface resistance to the moisture transfer, exist in practical applications.
Bi > 100	Imply negligible surface resistance to the moisture transfer at the solid material.
$$G = \exp\left[\frac{0.2533\,B_i}{1.3+B_i}\right]$$	(11)

5. Statical Analysis

All analysis was carried out by triplicate and the data were reported as mean ± standard deviation (SD). The results were analyzed by one-way ANOVA and significant differences between mean values were determined by Tuckey's test ($p < 0.05$) using the software InfoStat [32, 38]. Pearson's correlation analysis was used to determine statistical significance.

To compare the drying models, the statistical coefficients used to evaluate the fit of the different mathematical models with the experimental data were those applied by Baldán et al. [45], i.e., R^2 (coefficient of correlation), χ^2 (Chi-square), SSE (Sum Squared Error) and RSME (Root Mean Square Error) were calculated.

6. Results And Discussion

6.1. Drying of apple slices

The experimental data of the apple slice drying process, peeled and unpeeled and at different temperatures, were used to analyze the D_{eff} of moisture and the h_m. The data of experimental moisture content of the sample vs. time (50, 60, and 70°C) are shown in Figure 2.

Several authors concluded that food products kinetics drying is highly affected by temperature [45–47], due to the moisture changes with time at different drying temperatures showing a similar trend, decreasing rapidly and then slowly with drying time [32, 38]. The time required to achieve a specific moisture content decreased markedly with increasing drying temperature. The fast decrease of the moisture ratio is due to the increased rate of heat supply from the air to the peels, resulting in accelerated moisture migration [48]. In addition, it can be seen in Figure 2 that there is a small increase in drying time when drying unpeeled apple slices, suggesting that the peel hinders the drying of the apple slices [49].

Table 3 shows the drying coefficient (S) and the lag factor (G) obtained by Dincer and Dost model (Eq. 2). The drying coefficient (S) is directly related to the drying process and shows the sample drying capacity per unit of time. The lag factor (G) is an indicator of the magnitude of the internal and external resistance of a solid to the transfer of heat and/or humidity during the drying process as a B_i function. Furthermore, S, G, and the B_i values calculated using Eq. 7 are presented in Table 3.

Table 3
Drying kinetics parameters.

Apple	Drying temperature [°C]	Model parameters		
		Dincer and Dost		
		G	S [s^{-1}]	Bi
Unpeeled slices	50	1.09	1.96×10^{-4}	0.67
	60	1.11	3.34×10^{-4}	0.88
	70	1.11	4.26×10^{-4}	0.94
Peeled slices	50	1.10	2.14×10^{-4}	0.81
	60	1.11	3.41×10^{-4}	0.91
	70	1.10	5.07×10^{-4}	0.76

The G values remain in a range of 1.09-1.11 for apple slices peeled and unpeeled for the temperatures studied. Shewale et al. [43] obtained similar values when studying the influence of the drying air parameters on the D_{eff} and the h_m of apple slices (*Malus pumila var Chaubatia Anupam*) purchased in Mysore, India [43]. The highest resistance to heat and/or moisture transfer during the drying process occurs for apples unpeeled at 70°C. Moreover, during drying at 50 and 60°C, a small increase of resistance to moisture diffusion was observed between peeled and unpeeled apples, demonstrating that peel is a barrier to air and water vapor exchange with the environment. This may be because a cementation phenomenon occurs in the peeled apple, forming a hard surface on the outer layer of the endocarp (solidified sugars) and decreasing the rate of moisture transport to the surface [49]. However, at 70°C, the transport of water was favored, which may be due to the deterioration of the cells and the formation of channels in the food matrix [20].

The coefficient S varies from 1.96×10^{-4} to 5.07×10^{-4} s^{-1}. It showed an increase with the drying air temperature (from 50 to 70°C), by related by literature [47]. Also, Ilicali and Icier [42] reported that the S coefficient increases with the drying temperature for tomato slices. The same trend was observed for apple slices [27] and carrot and pumpkin in slab form [50].

The values obtained for the B_i varied between 0.67 and 0.94. This dimensionless number shows the ratio between internal and external resistance of the mass transfer [44]. Similar results were observed by Onwude et al. [51] for sweet potato and Bualung et al. [52] for papaya seeds. In all cases, the B_i was higher than 0.1, indicating that the internal resistance was significant and the water diffusivity on time and space [53].

As can be seen in Table 4, the Dincer and Dost model presented low statistical parameters (SSE, RMSE, and χ^2) to describe the drying process of apple slices peeled and unpeeled to all temperatures under study (R^2> 0.976).

Table 4
Statistical parameters for Dincer and Dost model adjustment to the experimental data.

Apple	Drying temperature [°C]	Statistical parameters		
		Dincer and Dost		
		R^2	χ^2	RMSE
Unpeeled slices	50	0.98	1.00×10^{-3}	4.70×10^{-2}
	60	0.99	2.00×10^{-3}	4.40×10^{-2}
	70	0.98	2.00×10^{-3}	4.30×10^{-2}
Peeled slices	50	0.98	2.00×10^{-3}	4.30×10^{-2}
	60	0.98	2.00×10^{-3}	4.30×10^{-2}
	70	0.98	2.00×10^{-3}	4.00×10^{-2}

6.2. Apple slices rehydration kinetics analysis

The rehydration curves were obtained by plotting MR vs. time at the two different rehydration conditions: T_a and T_b, for the dehydrated samples at 50, 60, and 70°C.

As can be seen in Figure 3, the rehydration process had two steps. At the first 20 minutes, the rehydration process was fast, it was observed in the exponential growth of the sample mass. Additionally, the rate of water absorption was reduced considerably after the first 20 minutes and the curves began to get close to the equilibrium moisture content of the sample (M_E). Comparing the rehydration process at T_a and T_b, it could be observed that when the rehydration temperature was higher, the rehydration rate and the M_E obtained after the process were higher, too [34, 41, 54]. Mahiuddin et al. [54] informed two main causes of material shrinkage during the drying process: a) the tissues incapacity to hold its structural arrangement when the water leaves different spaces free, and they are occupied by air, and b) the structure collapse. Comparing the peeled and the unpeeled samples, it is possible to see that unpeeled ones absorb slightly more water than the peeled ones at all drying temperatures. This may be due to the apple peel helping to maintain the sample shape and structural arrangement avoiding shrinkage [54].

6.1.1. Peleg model

The results for Peleg coefficients to approximate the mass gained during apple slices rehydration at all different conditions are shown in Table 5.

The values estimated in this work through Peleg parameters models had the same order of magnitude as those obtained by other authors for different dried products such as spinach [31], pumpkin slices [41], red pepper [55], blueberries [56], apples [57], chestnuts [58], and tomato [59]. Comparing the values of the Peleg constant k_1, that is related to the inverse of the water absorption rate, it is possible to observe that it is decreased with the rehydration temperature. Moreover, at the same rehydration condition, the values of the parameters were similar for all drying temperatures. Considering the Peleg constantk_2, related to maximum water absorption capacity, its values were lower at the boiling rehydration condition than at room temperature as was expected. M_e values are higher at T_b, as it was expected, because temperature improves the water diffusion to the slices, and comparing the unpeeled with the peeled samples, the first ones reached higher M_e values and this is probably because the peel helps to maintain the shape of the slices and absorb more water.

Table 7 shows the statistical parameters for Peleg model adjustment. This model describes correctly the rehydration process for apple slices at T_a and T_b and it had an excellent adjustment to the experimental data (R^2 > 0.99).

Table 5
Peleg model coefficients and equilibrium moisture for each drying and rehydration condition and determination coefficient for the adjustment.

Apple	Rehydration Condition	Drying temperature [ºC]	M_e $\left[kgH_2O\ kgsolid^{-1}\right]$	k_1 $\left[kg\ solid\ kg\ H_2O^{-1}\right]$	k_2 $\left[kg\ solid\ kg\ H_2O^{-1}\right]$
Unpeeled slices	T_a	50	3.44	229.01	0.30
		60	3.99	148.58	0.26
		70	3.53	243.35	0.29
	T_b	50	4.08	54.34	0.25
		60	4.23	65.75	0.24
		70	4.26	102.47	0.24
Peeled slices	T_a	50	3.24	197.57	0.32
		60	2.98	123.47	0.35
		70	3.21	102.69	0.32
	T_b	50	3.39	116.61	0.30
		60	4.22	151.41	0.24
		70	3.92	117.044	0.26

6.1.2. Weibull model

The results for Weibull model coefficients are shown in Table 6. The values estimated in this work through Weibull parameters models were of the same order of magnitude as those obtained by other authors for different dried products such as tomatoes [34], kiwifruit [60], red pepper [55], Chilean sea cucumber [61] and Chinese ginger [36]. The Weibull shape factor (α) is related to the inverse of water absorption rate, it is possible to see that when the rehydration temperature is increased, the value of the parameters decreased. Also, at the same rehydration condition, it is possible to observe that, for all drying temperatures, this parameter values were similar. The Weibull rate factor (β), was lower at T_b than T_a as was expected. The β value corresponds approximately to the time required to complete 63% of the rehydration process. Between samples peeled and unpeeled at the same rehydration condition, no significant differences were observed for this parameter.

Table 6
Weibull model coefficients for each drying and rehydration condition and determination coefficient for the adjustment.

Apple	Rehydration Condition	Drying temperature [ºC]	M_E $\left[kgH_2O\ kgsolid^{-1}\right]$	α	β[h]
Unpeeled slices	T_a	50	2.79	0.86	0.22
		60	3.45	0.84	0.19
		70	3.00	0.83	0.27
	T_b	50	3.64	0.76	0.08
		60	3.55	0.87	0.08
		70	3.78	0.77	0.15
Peeled slices	T_a	50	2.64	0.96	0.18
		60	2.57	1.21	0.17
		70	2.75	1.34	0.16
	T_b	50	3.37	0.68	0.19
		60	3.37	0.87	0.17
		70	3.48	0.77	0.16

Table 7 shows the statistical parameters for Weibull model adjustment. This model describes correctly the rehydration process for apple slices for all the variables considered. The high R^2 values obtained (R^2 > 0.99) show that the Weibull model adjusts correctly the experimental data. The approximation of the Weibull and Peleg models are comparable, however, the Peleg model has fewer parameters than the Weibull model, for that, it would be recommended to use the Peleg model to describe the apple slices peeled and unpeeled rehydration.

Table 7
Statistical parameters for Peleg and Weibull models adjustment.

Apple	Rehydration condition	Drying temperature [°C]	Statical parameters					
			Peleg			Weibull		
			R^2	χ^2	RMSE	R^2	χ^2	RMSE
Unpeeled slices	T_a	50	0.99	1.00×10^{-3}	2.10×10^{-2}	0.99	1.00×10^{-3}	2.90×10^{-2}
		60	0.99	2.00×10^{-3}	4.50×10^{-2}	0.99	1.00×10^{-3}	2.50×10^{-2}
		70	0.99	02.00×10^{-3}	3.70×10^{-2}	0.99	1.00×10^{-3}	2.60×10^{-2}
	T_b	50	0.99	2.00×10^{-3}	3.60×10^{-2}	0.99	1.20×10^{-2}	9.40×10^{-2}
		60	0.99	7.00×10^{-3}	7.20×10^{-2}	0.99	6.00×10^{-3}	6.60×10^{-2}
		70	0.99	3.00×10^{-3}	4.40×10^{-2}	0.99	2.00×10^{-3}	3.70×10^{-2}
Peeled slices	T_a	50	0.99	4.00×10^{-3}	5.60×10^{-2}	0.99	2.00×10^{-3}	3.60×10^{-2}
		60	0.99	3.00×10^{-3}	4.90×10^{-2}	0.99	2.00×10^{-3}	3.60×10^{-2}
		70	0.99	6.00×10^{-3}	7.40×10^{-2}	0.99	4.00×10^{-3}	5.80×10^{-2}
	T_b	50	0.99	2.00×10^{-3}	4.10×10^{-2}	0.99	1.00×10^{-3}	2.50×10^{-2}
		60	0.99	1.00×10^{-3}	2.50×10^{-2}	0.99	1.00×10^{-3}	2.10×10^{-2}
		70	0.99	2.00×10^{-3}	4.20×10^{-2}	0.99	2.00×10^{-3}	3.30×10^{-2}

6.2. Determination of effective diffusivity (D_{eff}) and convective mass transfer coefficient (h_m)

6.2.1. Drying process

Experimental measurements of apple moisture were used for the infinite slab and to estimate the moisture transfer parameters, such as the D_{eff} and the h_m of the drying process. The results are shown in Table 8.

Table 8
D_{eff} and h_m obtained at different drying temperatures.

Apple	**Drying temperature [°C]**	**D_{eff} [m^2s^{-1}]**	**h_m [$m\ s^{-1}$]**
Unpeeled slices	50	5.12×10^{-11}	3.43×10^{-08}
	60	8.80×10^{-11}	7.78×10^{-08}
	70	1.10×10^{-10}	1.03×10^{-07}
Peeled slices	50	5.58×10^{-11}	4.51×10^{-08}
	60	8.96×10^{-11}	8.16×10^{-08}
	70	1.25×10^{-10}	9.53×10^{-08}

D_{eff} was estimated by substituting the positive values of F_0, the time and the mean thickness of the thin layer (L) in Eq. 7 [62]. D_{eff} values increase when the moisture content decrease in all drying conditions, as shown in Figure 4 [63, 64]. The variation in moisture diffusivity with moisture content is a complex and system-specific function. This may indicate that as the moisture content decreased, the D_{eff} increased, not only due to the increase in temperature but also due to the increase of water transport rate from the interior of the product to the surface, increasing the permeability steamed, as long as the pore structure remained open. In the final stages of drying, a reduction in D_{eff} was observed, due to the deterioration of the cellular structure, as a consequence of the food cells' collapse [20, 62].

D_{eff} values varied in the range from 5.12×10^{-11} to 1.10×10^{-10} m^2 s^{-1} for infinite slab (Table 8). Similar D_{eff} values were reported by Mujundar [65] for dry agricultural products.

D_{eff} increase with the drying temperature due to the drying process being controlled by mass transfer mechanisms [46]. Similar diffusivity values were found for peeled apple slices [43]. Differences in the moisture diffusion of materials during drying arise from several factors, such as the physical-chemical properties, the initial and final moisture content of the product, and the drying method and conditions [66].

Another parameter important during the mass transfer is h_m [67]. h_m values were between 3.43×10^{-8} and 1.03×10^{-7} ms^{-1} for unpeeled apple slices and between 4.51×10^{-8} and 9.53×10^{-7} ms^{-1} for the peeled samples. As can be seen, with the temperature increase, the coefficient h_m increases. Similar values were obtained by Beigi et al. [27] during the study of drying air parameters influences on the D_{eff} and the h_m for apple slices. Values in the range were also reported for purple onion [32].

6.2.2. Rehydration process

The values for D_{eff} were calculated using the equilibrium moisture obtained by the Peleg model because it had a satisfactory adjustment. These are shown in Table 10.

Table 9
Average moisture diffusivities for the three drying temperatures and the two rehydration conditions at peeled and unpeeled apples.

		Unpeeled apples	**Peeled apples**
Rehydration Condition	Drying Temperature [°C]	D_{eff} [m^2s^{-1}]	D_{eff} [m^2s^{-1}]
T_a	50	5.91×10^{-12}	6.35×10^{-12}
	60	6.83×10^{-12}	9.77×10^{-12}
	70	5.24×10^{-12}	1.05×10^{-11}
T_b	50	1.26×10^{-11}	6.19×10^{-12}
	60	1.23×10^{-11}	6.37×10^{-12}
	70	7.31×10^{-12}	6.70×10^{-12}

Finally, the D_{eff} average values are between 5.24×10^{-12} and 1.05×10^{-11} m^2s^{-1} for the rehydration at ambient temperature and 6.19×10^{-12} and 1.26×10^{-11} m^2s^{-1} for the rehydration at boiling temperature. As was expected, the range for the moisture diffusivity takes higher values at higher rehydration temperatures. Moreover, when the rehydration was carried out at T_a, it is possible to see that D_{eff} values are higher for the peeled slices than for the unpeeled ones, and for T_b the opposite situation is observed. The rehydration process is longer at T_a compared to when it is carried out at T_b. When the process is carried out at T_a, the apple peel, with time, starts to have a significant influence on the water absorption process [20].

6.3. Characterization of fresh and rehydrated apple slices

For obtaining the apple slices, the fresh apples were cored and half of them were peeled. The fruit yields to obtaining apple slices peeled and unpeeled were 71.60 ± 1.60% and 90.40 ± 0.60% respectively. According to the averages of the yields obtained, there was 9.60% of waste generated at coring apples and this quantity increased 18.80% when the samples were also peeled. Figure 5 shows the fresh, dehydrated, and rehydrated apple slices unpeeled and peeled.

The fresh and rehydrated apple slices samples (unpeeled and peeled) were characterized considering equivalent diameter (D_{eq}), pH, acidity, solid soluble, and moisture content (Figure 6).

As can be seen in Figure 6, there are no visible differences between the samples dehydrated at different temperatures and rehydrated at T_a and T_b.

A reduction of equivalent diameters was observed for all the samples when comparing fresh with rehydrated slices at T_a and T_b, being the most representative an average reduction of 22.53% at the samples that were unpeeled and dehydrated at 50°C and 26.39% for the peeled samples dehydrated at 60°C, both of them rehydrated at boiling temperature. The unpeeled apple slices showed the lowest diameter reduction due to the apple peel helping to maintain the shape during the dehydration and rehydration processes [20]. When rehydration was carried out at T_a, the samples reached higher diameters compared to the samples rehydrated at T_b for all samples. The ANOVA showed that there were significant differences between the peeled and unpeeled samples, being the equivalent diameters higher at the unpeeled ones.

Acidity, pH, and soluble solid content are important characteristics with influence on the taste and thus also for the acceptability of the product. All these characteristics were different in the rehydrated samples compared with the fresh ones. Considering the pH, there were no significant differences between the dehydration temperatures, the peeled and unpeeled samples, but the pH at the samples rehydrated at T_a was higher than the rehydrated at T_b, it is probably because the samples rehydrated at T_a takes twice as long to reach equilibrium humidity (Figure 3). As expected, acidity has the opposite compartment: the acidity takes significative lower values at the rehydration condition.

For the solid soluble content, there are no significant differences between the drying conditions and the peeled and unpeeled samples, but the solid soluble content obtained at rehydration at T_b is higher than those at T_a, it is explained for the same reason as the differences in pH and acidity.

Finally, analyzing the moisture content, it is possible to affirm that the rehydrated samples at T_a and T_b reached higher humidity compared with the fresh apple slices peeled and unpeeled, it is probably because during the drying process the apple slices tissue is damaged, which produces an increase in porosity and thus the increase in the water absorption capacity [68]. The fresh apple slices peeled and unpeeled moisture content was 83.22 and 83.88%, respectively. No significant differences are comparing the moisture content of the rehydrated samples peeled and unpeeled considering the drying temperature, but the water absorbed rehydrating at T_b (95.02 – 96.22%) was slightly higher than at T_a (93.63 – 94.52%).

As it can be seen, all the characteristics considered take important differences between the fresh and the apple slices after rehydration. Comparing the rehydrated samples, there are no significant differences between the peeled and unpeeled apple slices and the dehydration temperature, but there are differences between the samples rehydrated at T_a and T_b. It is important to remark that the values obtained for the fresh apple are similar to the obtained for several authors [69, 70].

7. Conclusions

The drying and rehydration process for apple slices with and without peel was studied. For the drying process, the variable considered was the temperature: 50, 60, and 70°C. The experimental data were fitted to Dincer and Dost model giving a good adjustment (R^2 > 0.98). The values obtained for the B_i varied between 0.67 and 0.94, which shows the internal and external existence of the mass transfer. D_{eff} and h_m increased their values with temperature, being the highest values: $1.25x10^{-9}$ $m^2.s^{-1}$ and $9.53x10^{-7}$ $m.s^{-1}$, respectively for the peeled apple slices.

The rehydration process was carried out for the samples dried at 50, 60, and 70°C, at two different temperatures: T_a and T_b. The experimental data were fitted to Peleg and Weibull models giving excellent adjustment (R^2 > 0.99) for all studied conditions. The D_{eff} values increased significantly with the rehydration temperature but take similar values between peeled and unpeeled apple slices.

Comparing the pH, acidity, % Bx, D_{eq}, and moisture content of fresh and rehydrated samples at the two conditions, the ones rehydrated at T_b preserve better the characteristics of fresh samples due to the short times immersed at whatever, no significant differences were observed at peeled and unpeeled samples, except for the equivalent diameter that was longer for the unpeeled apple slices, preserving better the fresh apple slices shape.

Considering the obtained results, it is convenient to dry the apple slices at 70°C and rehydrate them at T_b. To preserve the shape of the fresh samples would be recommendable not to peel the apple slices.

Abbreviations

SD	Standard Deviation
SSE	Sum of Squared Errors
RMSE	Squared Root Squared Errors

	Nomenclature
T_a	ambient temperature, 20 *°C*
T_b	boiling temperature, 98 *°C*
MR	moisture ratio, *dimensionless*
M_t	moisture content at time t, *kg water kg dry matter^{-1}*
T	time, *s*
M_e	moisture content at equilibrium, *kg water kg dry matter^{-1}*
M_0	initial moisture content, *kg water kg dry matter^{-1}*
G	lag factor, *dimensionless*
S	drying coefficient, *s^{-1}*
k_1	Peleg model parameter, *s kg dry matter kg water^{-1}*
k_2	Peleg model parameter, *kg dry matter kg water^{-1}*
A	Weibull shape parameter, *dimensionless*
B	Weibull rate parameter, *h*
D_{eff}	effective diffusivity, *m^2 s^{-1}*
L	sample half-thickness, *m*
F_o	Fourier number, *dimensionless*
$D_{eff,avg}$	averages effective diffusivity, *m^2 s^{-1}*
M	moisture content, *kg water kg dry matter^{-1}*
h_m	convective mass transfer, *m s^{-1}*
Bi	Biot number, *dimensionless*
χ^2	reduced chi-square, *dimensionless*
R^2	correlation coefficient, *dimensionless*

Declarations

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Declarations Conflict of interest

The authors declare no confict of interest.

Data Availability

The datasheets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

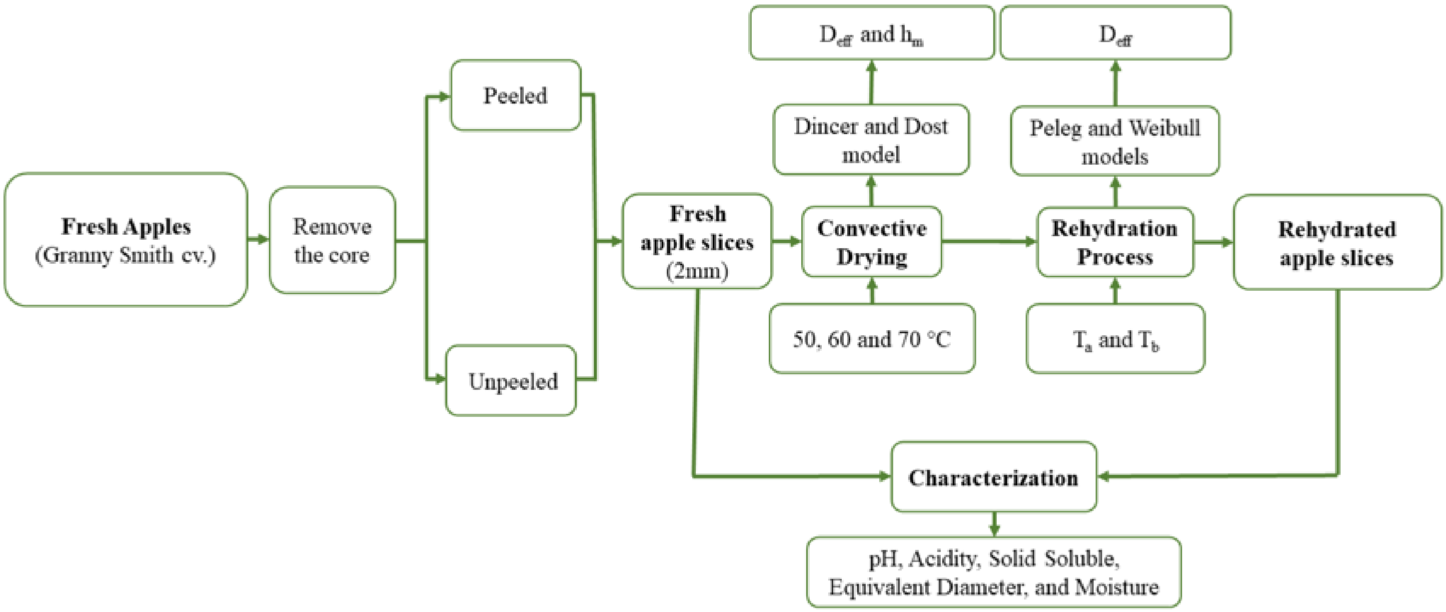

Figure 1

Logic Diagram.

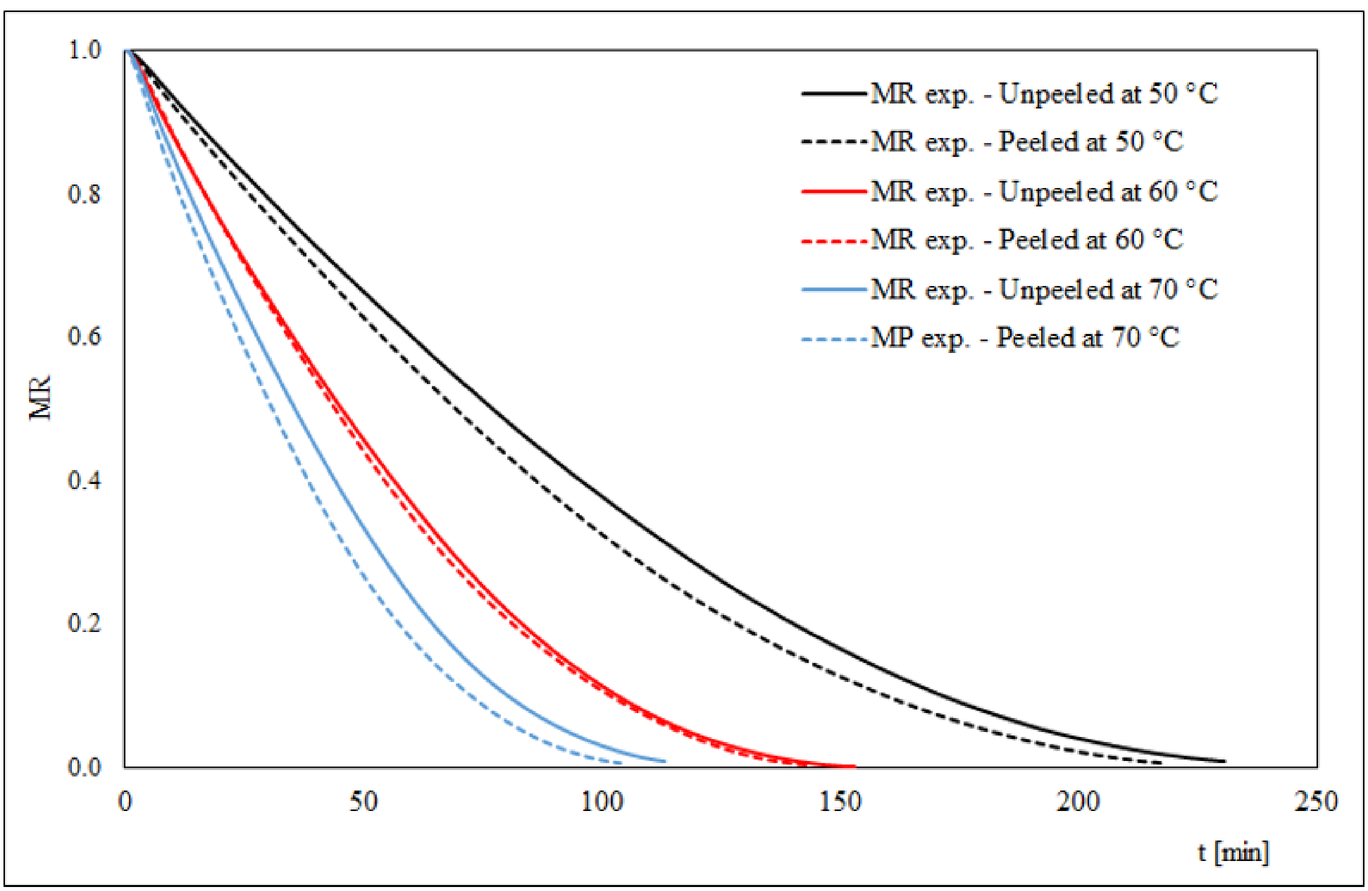

Figure 2

Experimental drying curves for apple slices at 50, 60, and 70 ° C.

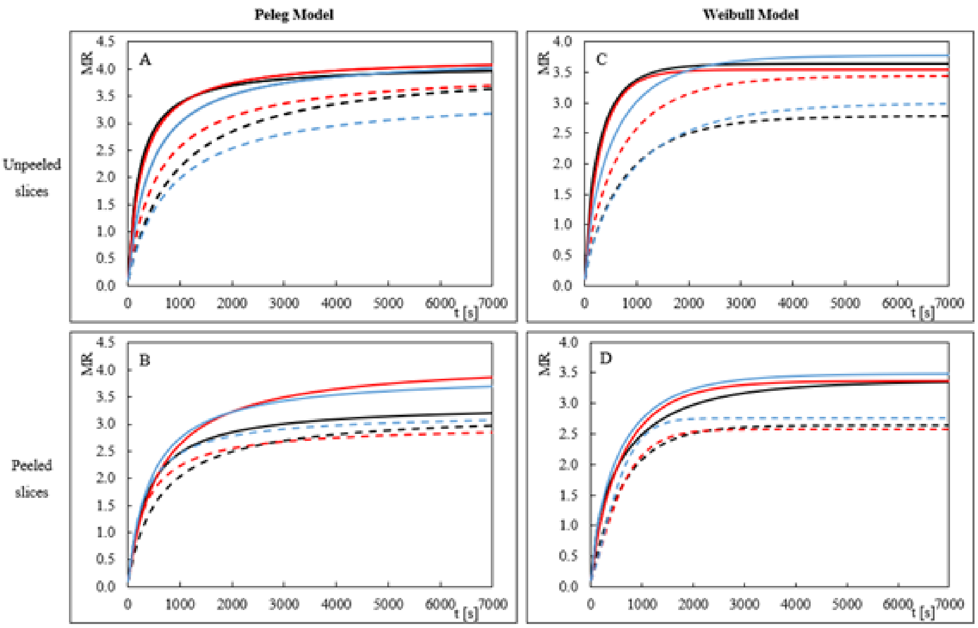

Figure 3

Fit curves of the rehydration models to the experimental data. The solid line curves correspond to the rehydration at T_b and the stroke line curves at T_a.

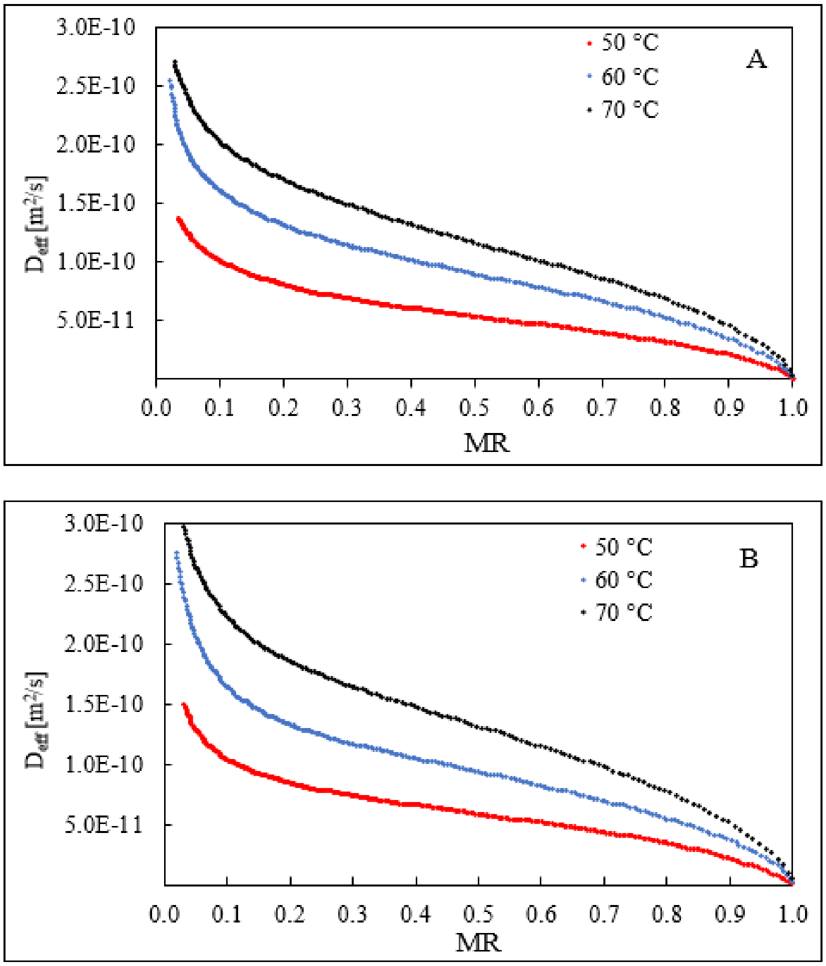

Figure 4

Variation of D_{eff} with MR of dry apple at 50, 60, and 70 °C. (A) Unpeeled apple slices. (B) Peeled apple slices.

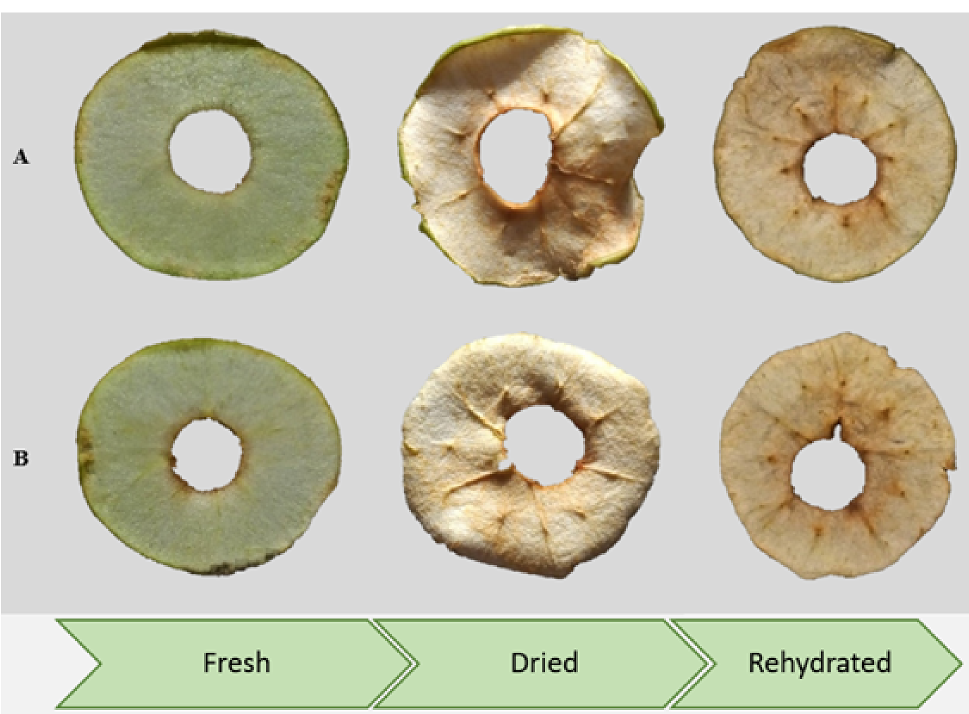

Figure 5

Fresh, dehydrated, and rehydrated apple slices: A) unpeeled and B) peeled.

The images are just illustrative of the changes in fresh, dried, and rehydrated apple slices.

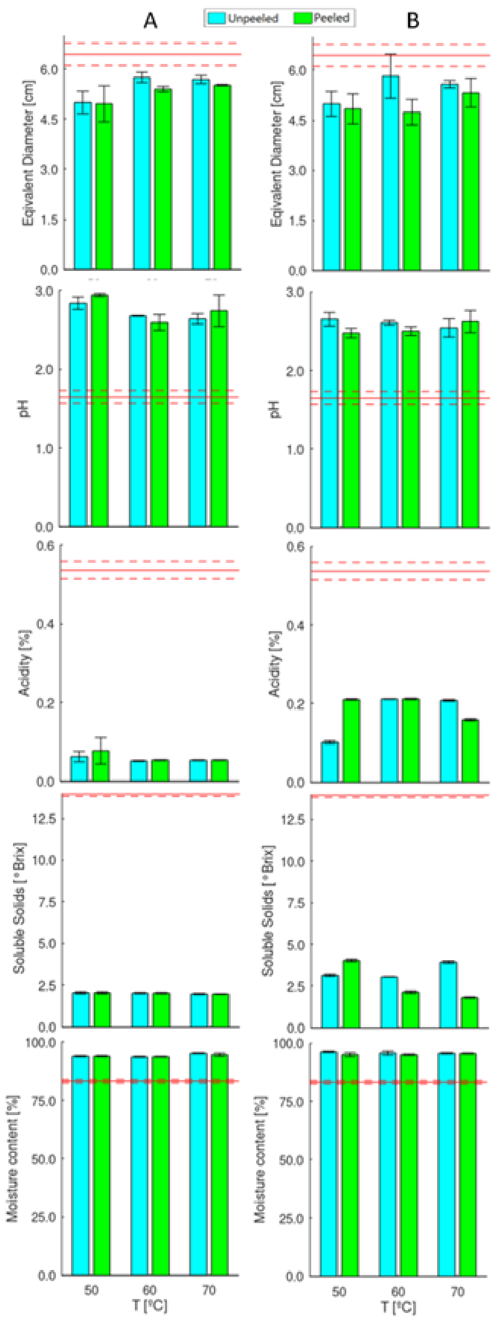

Figure 6

Fresh (red lines) and rehydrated apple slices characterization. A) Rehydrated samples at T_a. B) Rehydrated samples at T_b.

Supplementary Files

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- GraphicalAbstract.tif