Drying and rehydration kinetics of peeled and unpeeled green apple slices (Granny Smith cv)

Mathias Riveros-Gomez\textsuperscript{a}, Yanina Bald\textsuperscript{a}, María Celia Rom\textsuperscript{a}, María Paula Fabani\textsuperscript{b}, Germán Mazza\textsuperscript{c,d}, and Rosa Rodríguez\textsuperscript{a}

\textsuperscript{a}Grupo Vinculado al PROBIEN (CONICET-UNCo), Instituto de Ingeniería Química, Facultad de Ingeniería (UNSJ), San Juan, Argentina; \textsuperscript{b}Facultad de Ingeniería (UNSJ), Instituto de Biotecnología, San Juan, Argentina; \textsuperscript{c}Biotecnología y Energías Alternativas, PROBIEN (CONICET-UNCo), Instituto de Investigación y Desarrollo en Ingeniería de Procesos, Neuquén, Argentina; \textsuperscript{d}Patagonia Confluencia, Centro Científico Tecnológico CONICET, Neuquén, Argentina

\textbf{ABSTRACT}

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 °C, 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. Effective diffusivity (\(D_{\text{eff}}\)) and the convective mass transfer coefficient (\(h_m\)) were also determined, both coefficients increase with drying temperature, being \(1.25 \times 10^{-9}\) m\(^2\) s\(^{-1}\) and \(9.53 \times 10^{-7}\) m\(^2\) s\(^{-1}\) the highest values obtained for the peeled apple slices respectively. Peleg and Weibull models were adjusted to the rehydration experimental data obtaining a good fit \((R^2 > 0.99)\). \(D_{\text{eff}}\) values increase significantly with rehydration temperature but take similar values between peeled and unpeeled samples. Acidity, pH, moisture content, solid soluble content, and equivalent diameter were determined to compare the fresh apple slices with those after dehydration and the 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 results, it is convenient to dry the apple slices unpeeled at 70 °C and rehydrate them at \(T_b\).

\textbf{GRAPHICAL ABSTRACT}

\textbf{ARTICLE HISTORY}

Received 2 June 2022
Accepted 1 September 2022

\textbf{KEYWORDS}

Dehydration; rehydration; kinetics; apple slices

\textbf{Abbreviations:} SD: standard deviation; SSE: sum of squared errors; RMSE: squared root squared errors

\section*{Introduction}

Apples, \textit{Pyrus malus} L. (Rosaceae family) are one of the most cultivated fruits around the world, its production worldwide is about \(4.10 \times 10^7\) tons per year\textsuperscript{[1]}, being China the main producer. Argentina is one of the principal producers in Latin America, with an annual production of \(5.63 \times 10^5\) tons and a productive area of \(5.00 \times 10^4\) ha\textsuperscript{[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\textsuperscript{[3]}. Apples are a
A dried fruit market report predicted the global dried fruits market to grow with a Compound Annual Growth Rate (CAGR) of 6.12% over the forecast period from 2018 to 2024. 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. The increasing consumption of dehydrated fruits is related to the global trend of consuming nutritious and healthy foods as well as avoiding wasting fruit.

To obtain dried products, conventional air drying is the most widely used drying operation due to it is a simple process. This unit operation comprises the water content reduction through simultaneous mass and heat transfers. The water remotion is carried out through evaporation, consuming important energy quantities, for that, drying is denominated as an energy-intensive process. 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. According to Shrestha et al., 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 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. real-time monitored the hot-air drying of apple cylinders using computer vision. Ma et al. 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. 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. 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. 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.

Dincer et al. 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. Few researchers studied the Dincer and Dost model to characterize the mass transfer in food geometric objects during drying. Beigi et al. investigated the influence of drying air parameters (i.e., temperature, rate, and relative humidity of the air) on the effective diffusivity coefficient and the mass transfer coefficient of apple slices. Model validation showed that the prediction of the experimental drying curves of the samples had a good precision. Bezerra et al. 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, in which the food mass increases according to the rehydration kinetics. 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.

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. 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. 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 in addition to Peleg and Weibull model, which have been used by several researchers.

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 in water at ambient temperature and boiling temperature. Moreover, the effect of drying and rehydration on apple quality parameters has not been described.

**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 how these
processes affect the quality parameters of fresh apple slices. Different drying temperatures were taken into account: 50, 60, and 70 °C, and then samples were rehydrated in water at $T_a$ and $T_b$. 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 fresh, dehydrated, and rehydrated apple slices. Figure 1 shows a roadmap of this work. 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 fresh apple slices characteristics are taken into account.

**Materials and methods**

**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 their cores were 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).

**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 and 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.

**Rehydration procedure**

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

**Apple slices characterization**

The fresh, dehydrated, and post-rehydrated apple slices were characterized. 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]

**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 hydrated 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), $\alpha$ and $\beta$ are the shape and rate parameters respectively. $\alpha$ describes the water absorption rate, and it is higher when $\alpha$ values decrease. $\beta$ defines the rate of the moisture
Table 1. Used equations to describe the drying and rehydration kinetics.

| Equation | Description |
|----------|-------------|
| MR = \frac{M_t - M_e}{M_0 - M_e} | Moisture Ratio (MR) |
| MR = G \exp \left( -\frac{t}{k_1 + k_2} \right) | Dincer and Dost drying model |
| M_t = M_0 + \frac{t}{k_1 + k_2} t | Peleg rehydration model |
| M_t - M_e = \exp \left( -\frac{t}{k_2} \right) | Weibull rehydration model |

MR is the Moisture Ratio (dimensionless), \( M_t \) is the moisture content at time \( t \) (\%), \( M_0 \) is the equilibrium moisture content (\%), \( M_e \) is the initial moisture content (\%), \( G \) is a preexponential factor known as lag factor (dimensionless), \( S \) represents drying coefficient (s\(^{-1}\)), \( k_1 \) is a Peleg model parameter (s\(^{-1}\) kg\(_{dry\ matter}\) kg\(_{water}\)^{-1}), \( k_2 \) is a Peleg model parameter (kg\(_{dry\ matter}\) kg\(_{water}\)^{-1}), \( z \) is the Weibull shape parameter (dimensionless), and \( \beta \) is the Weibull rate parameter (h).

Determinations of \( d_{eff} \) and \( h_m \)

\( d_{eff} \) is an important parameter that takes into account the moisture transfer in 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 the sample and the drying or rehydration temperature. To obtain this coefficient a simple diffusion model based on Fick’s second law was used. Eqs. (6)–(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 the \( B_i \) number by Eq. (11), described in Table 2.

Statistical 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.,\(^{[42]} \) coefficient of correlation (\( R^2 \)), Chi-square (\( \chi^2 \)), Sum Squared Error (SSE) and Root Mean Square Error (RMSE) were calculated.

Results and discussion

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 moisture \( d_{eff} \) 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 drying kinetics of food products 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 relative humidity in the drying process was 35%. 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 slices, 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 Dincer and Dost model parameters (Eq. (2)). The \( S \) coefficient is directly related to the drying process and shows the sample drying capacity per unit of time. The \( G \) parameter 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. 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 Chabatia 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 hardening 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), the same trend was reported by other authors.\(^{[47]} \) 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 Bi 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 Bi was higher than 0.1, this indicates that the drying process, and thus the diffusion of water, is controlled by internal resistance.\[53\]

Analyzing the statical coefficients value of the mathematical model adjustment, it is possible to affirm that the drying of apple slices peeled and unpeeled to all temperatures under study is well described by Dincer and Dost model. The best fit is found when SSE, RMSE, and $\chi^2$ are lowest, and $R^2$ is highest. The obtained values of these parameters

\[
\begin{align*}
\text{Table 2. Equations used to calculate } D_{\text{eff}} \text{ and } h_m. \\
\text{Determination of } D_{\text{eff}}^{[32]} \\
MR &= \frac{8}{\pi^2} \exp \left(-\frac{\pi^2 D_{\text{eff}} t}{4 L^2}\right) \\
F_0 &= \frac{D_{\text{eff}} t}{L^2} \\
F_0 &= \frac{4}{\pi^2} \left[ \ln \left(\frac{\pi^2}{8}\right) - \ln MR \right] \\
D_{\text{eff,avg}} &= \frac{M_{t=final} D_{\text{eff}}(M) dM}{M_{t=final} dM} \\
\text{Determination of } h_m^{[27,32]} \\
MR &= G \exp \left(-St\right)
\end{align*}
\]

The Bi value describes different resistances according to the range, i.e.\[44,\]:

- $0.1 < Bi < 100$ 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.

\[
G = \exp \left[\frac{0.2533 M_i}{1.3 + Bi}\right]
\]

$L$ is the sample half-thickness (m), $F_0$ is the Fourier number (dimensionless), $D_{\text{eff, avg}}$ is the average effective diffusivity (m$^2$ s$^{-1}$), $Bi$ is the Biot number (dimensionless).

Figure 2. Experimental drying curves for apple slices at 50, 60, and 70 °C.

| Table 3. Drying kinetics parameters.       | Model parameters |
|------------------------------------------|------------------|
|                                        | G    | $S$ (s$^{-1}$) | Bi   |
| **Unpeeled slices**                     |      |               |      |
| 50                                      | 1.09 | $1.96 \times 10^{-4}$ | 0.67 |
| 60                                      | 1.04 | $3.34 \times 10^{-4}$ | 0.88 |
| 70                                      | 1.11 | $4.26 \times 10^{-4}$ | 0.94 |
| **Peeled slices**                       |      |               |      |
| 50                                      | 1.10 | $2.14 \times 10^{-4}$ | 0.81 |
| 60                                      | 1.11 | $3.41 \times 10^{-4}$ | 0.91 |
| 70                                      | 1.10 | $5.07 \times 10^{-4}$ | 0.76 |
were: $\text{SSE} \leq 1.01$, $\text{RMSE} \leq 4.70 \times 10^{-2}$, $\chi^2 \leq 2.00 \times 10^{-3}$, and $R^2 \geq 0.98$ (Table 4).

**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. In the first 20 min, 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 min and the curves began to get close to $M_e$. 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.$^{[34,41,54]}$ Mahiuddin et al.$^{[54]}$ informed two main causes of material shrinkage during the drying process: (a) the incapacity of tissues to hold their structural arrangement when the water leaves different spaces free, and they are occupied by air, and (b) the structure collapse. It is possible to see that the unpeeled slices absorb slightly more water than the peeled slices at all drying temperatures. This may be due to the apple peel helping to maintain the sample shape and structural arrangement avoiding shrinkage.$^{[34]}

**Peleg model**

The results for Peleg coefficients to approximate the mass gained during apple slices rehydration under 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 constant $k_2$, related to maximum water absorption capacity, its values were lower at $T_b$ than at $T_a$ as was expected. $M_e$ values are higher at $T_b$ due to temperature improving water diffusion to the slices. The unpeeled samples reached higher $M_e$ values and this is probably because 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 $T_b$ ($R^2 > 0.99$).

**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 $x$ value is related

---

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

| Apple  | Drying temperature (°C) | Statistical parameters |
|--------|-------------------------|------------------------|
|        |                         | $R^2$       | SSE           | RMSE           | $\chi^2$          |
| Unpeeled slices | 50 | 0.98 | 1.01 | $4.70 \times 10^{-2}$ | $1.00 \times 10^{-3}$ |
|         | 60 | 0.99 | 0.60 | $4.40 \times 10^{-2}$ | $2.00 \times 10^{-3}$ |
|         | 70 | 0.98 | 0.42 | $4.30 \times 10^{-2}$ | $2.00 \times 10^{-3}$ |
| Peeled slices | 50 | 0.98 | 0.79 | $3.00 \times 10^{-2}$ | $1.00 \times 10^{-3}$ |
|         | 60 | 0.98 | 0.51 | $4.30 \times 10^{-2}$ | $2.00 \times 10^{-3}$ |
|         | 70 | 0.98 | 0.32 | $4.00 \times 10^{-2}$ | $2.00 \times 10^{-3}$ |

---

Figure 3. Fit curves of the rehydration models to the experimental data. The solid line curves correspond to the rehydration at $T_a$ and the stroke line curves at $T_b$. 

---

840  M. RIVEROS-GOMEZ ET AL.
was expected. The same parameter, no significant differences were observed for the rehydration condition, it is possible to observe that, for all drying temperatures, \( x \) values were similar. On the other hand, the \( \beta \) parameter was lower at \( T_b \) than \( T_a \) as was expected. The \( \beta \) value corresponds approximately to the time required to complete 63% of the rehydration process. Comparing peeled and unpeeled slices at the same rehydration condition, no significant differences were observed for this parameter.

### 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 (°C) | \( M_e \) (kg\( \text{water} \) kg\( \text{solid} \)^{-1}) | \( k_1 \) (s kg\( \text{water} \) kg\( \text{water} \)^{-1}) | \( k_2 \) (kg\( \text{water} \) kg\( \text{water} \)^{-1}) |
|-------------|-----------------------|-------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Unpeeled    | \( T_a \)             | 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      | \( T_a \)             | 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                                             |

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

| Apple       | Rehydration condition | Drying temperature (°C) | \( M_e \) (kg\( \text{water} \) kg\( \text{solid} \)^{-1}) | \( \alpha \) | \( B \) (h) |
|-------------|-----------------------|-------------------------|-------------------------------------------------|---------------|-------------|
| Unpeeled    | \( T_a \)             | 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      | \( T_a \)             | 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. Statistical parameters for Peleg and Weibull models adjustment.

| Apple       | Rehydration condition | Drying temperature (°C) | Statistical parameters |
|-------------|-----------------------|-------------------------|------------------------|
| Unpeeled    | \( T_a \)             | 50                      | Peleg                  |
|             |                       | 60                      | \( R^2 \)              | 0.99          |
|             |                       | 70                      | \( \chi^2 \)           | 2.10 \times 10^{-2} |
|             | \( T_b \)             | 50                      | \( \chi^2 \)           | 1.00 \times 10^{-3} |
|             |                       | 60                      | \( \chi^2 \)           | 3.00 \times 10^{-3} |
|             |                       | 70                      | \( \chi^2 \)           | 4.00 \times 10^{-2} |
| Peeled      | \( T_a \)             | 50                      | \( \chi^2 \)           | 2.10 \times 10^{-2} |
|             |                       | 60                      | \( \chi^2 \)           | 4.00 \times 10^{-3} |
|             |                       | 70                      | \( \chi^2 \)           | 4.00 \times 10^{-2} |

### Table 8. \( D_{\text{eff}} \) and \( h_m \) obtained at different drying temperatures.

| Apple       | Drying temperature (°C) | \( D_{\text{eff}} \) (m² s⁻¹) | \( h_m \) (m s⁻¹) |
|-------------|-------------------------|--------------------------------|------------------|
| Unpeeled    | 50                      | 5.12 \times 10^{-11}          | 3.43 \times 10^{-18} |
|             | 60                      | 8.80 \times 10^{-11}          | 7.78 \times 10^{-18} |
|             | 70                      | 8.10 \times 10^{-10}          | 2.03 \times 10^{-18} |
| Peeled      | 50                      | 5.58 \times 10^{-11}          | 4.51 \times 10^{-18} |
|             | 60                      | 8.96 \times 10^{-11}          | 8.16 \times 10^{-18} |
|             | 70                      | 1.25 \times 10^{-09}          | 9.53 \times 10^{-17} |

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.

### Determination of \( D_{\text{eff}} \) and \( h_m \)

#### Drying process

Experimental measurements of apple moisture were used for the infinite slab and to estimate the moisture transfer parameters, such as the \( D_{\text{eff}} \) and \( h_m \) of the drying process. The results are shown in Table 8. \( D_{\text{eff}} \) was estimated by...
substituting the positive values of $F_0$, $t$, and $L$ in Eq. (7). \[62\]

$D_{eff}$ values increase when the moisture content decreases in all drying conditions, as shown in Figure 4. \[63,64\] This phenomenon is not only due to the increase in temperature but also to a greater water transport rate from the interior of the slices 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 cellular structure deterioration, as a consequence of the food cells’ collapse. \[20,62\]

$D_{eff}$ values varied in the range from $5.12 \times 10^{-11}$ to $1.10 \times 10^{-10}$ 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. \[66\]

---

**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.

---

| Rehydration condition | Drying temperature (°C) | $D_{eff,\text{avg}}$ (m$^2$ s$^{-1}$) | $D_{eff,\text{avg}}$ (m$^2$ s$^{-1}$) |
|-----------------------|--------------------------|-------------------------------|-------------------------------|
| $T_a$                 | 50                       | $5.91 \times 10^{-12}$       | $6.35 \times 10^{-12}$       |
|                       | 60                       | $6.83 \times 10^{-12}$       | $9.77 \times 10^{-12}$       |
|                       | 70                       | $5.24 \times 10^{-12}$       | $1.05 \times 10^{-11}$       |
| $T_b$                 | 50                       | $1.26 \times 10^{-11}$       | $6.19 \times 10^{-12}$       |
|                       | 60                       | $1.23 \times 10^{-11}$       | $6.37 \times 10^{-12}$       |
|                       | 70                       | $7.31 \times 10^{-12}$       | $6.70 \times 10^{-12}$       |

---

Another important parameter during the drying process is $h_m$. \[67\] The $h_m$ values are in the range of $3.43 \times 10^{-8}$ and $1.03 \times 10^{-7}$ m s$^{-1}$ for unpeeled apple slices and between $4.51 \times 10^{-8}$ and $9.53 \times 10^{-7}$ m s$^{-1}$ for the peeled samples. When temperature increase, the coefficient $h_m$ take higher values. Similar results 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. \[52\]
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 9. Finally, the $D_{eff}$ average values are between $5.24 \times 10^{-12}$ and $1.05 \times 10^{-11}$ m² s⁻¹ for the rehydration at ambient temperature and $6.19 \times 10^{-12}$ and $1.26 \times 10^{-11}$ m² s⁻¹ for the rehydration at boiling temperature. As was expected, the range for the moisture diffusivity takes higher values at $T_a$. Moreover, when the rehydration was carried out at $T_b$, 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 $T_a$ (Fig. 3), at this condition, the apple peel, has a significant influence on the water absorption as the rehydration proceeds.[20]

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 for 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 by 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 $D_{eq}$, pH, acidity, solid soluble content, and moisture content. 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 $T_b$. The unpeeled apple slices showed the lowest diameter reduction due to the apple peel that helps 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 significant differences between the peeled and unpeeled samples, being the $D_{eq}$ higher at the unpeeled ones.

Acidity, pH, and soluble solid content are important characteristics with influence on the taste and thus also 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 slices, but the pH of the samples rehydrated at $T_a$ was higher than the rehydrated at $T_b$, it is probably because the samples rehydrated at $T_a$ take twice as long to reach equilibrium humidity (Fig. 3). As expected, acidity has the opposite compartment: the acidity takes significative lower values at $T_a$. 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 due to during the drying process the tissue of apple slices is damaged, which produces an increase in porosity and thus the increase in the water absorption capacity.[68] The fresh apple peeled and unpeeled slices’ moisture content was 83.22 and 83.88%, respectively. No significant differences are comparing the moisture content considering the drying temperature, but the water absorbed at $T_b$ was slightly higher than at $T_a$, reaching a moisture content of 95.02–96.22% and 93.63–94.52% respectively.

As it can be seen, all the characteristics considered take important differences between the fresh and the apple slices post-rehydration process. 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
It is important to remark that the values obtained for the fresh apple are similar to those obtained by several authors.\textsuperscript{[69,70]}

**Conclusions**

The drying and rehydration process for apple slices peeled and unpeeled were 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. $D_{\text{eff}}$ and $h_m$ increased their values with temperature, being the highest values: $1.25 \times 10^{-9}$ m$^2$ s$^{-1}$ and $9.53 \times 10^{-7}$ 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, under two different conditions: $T_a$ 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 $D_{\text{eff}}$ values increased significantly with the rehydration temperature but take similar values between peeled and unpeeled apple slices.

Comparing the pH, acidity, solid soluble content, $D_{\text{eq}}$, and moisture content of fresh and rehydrated samples under the two conditions, the ones rehydrated at $T_b$ preserve better the characteristics of fresh samples due to the short times immersed in water, 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.

**Acknowledgments**

Mathias Riveros-Gomez, Yanina Baldan, and María Celia Román have doctoral fellowships from CONICET. María Paula Fabani, Germán Mazza, and Rosa Rodríguez are Research Members of CONICET, Argentina.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

**Funding**

The authors wish to thank the support of the following argentine institutions: the University of San Juan [PDTS Res. 1054/18]; the University of Comahue [PIN 04/1223]; National Scientific and Technical Research Council, CONICET [Project PUE PROBIEN-CONICET 22920150100067]; San Juan Province [IDEA Project, Res. 0279/2019]; ANPCYT [FONCYT-PICT 2017-2047 and FONCYT-PICT 2019-01810].

**ORCID**

Rosa Rodríguez [http://orcid.org/0000-0003-1252-4752]

**Data availability statement**

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

- $T_a$: ambient temperature, $20^\circ C$
- $T_p$: boiling temperature, $98^\circ C$
- $MR$: moisture ratio, dimensionless
- $M_t$: moisture content at time $t$, kg water/kg dry matter
- $t$: time, s
- $M_e$: moisture content at equilibrium, kg water/kg dry matter
- $M_0$: initial moisture content, kg water/kg dry matter
- $G$: lag factor, dimensionless
- $S$: drying coefficient, s$^{-1}$
- $k_D$: Peleg model parameter, s kg dry matter kg water$^{-1}$
- $k_D$: 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
- $F_r$: Fourier number, dimensionless
- $D_{avg}$: averages effective diffusivity, m$^2$ s$^{-1}$
- $M$: moisture content, kg water/kg dry matter
- $h_m$: convective mass transfer, m s$^{-1}$
- $B_l$: Biot number, dimensionless
- $\beta'$: reduced chi-square, dimensionless
- $R^2$: correlation coefficient, dimensionless

References

[1] Carpes, S. T.; Bertotto, C.; Bilck, A. P.; Yamashita, F.; Anjos, M.; Baldan, Y.; Fernandez, A.; Reyes Urrutia, A.; Fabani, M. P.; Rodriguez, R.; Mazza, G. Non-Isothermal Drying of Bio-Wastes: Kinetic Analysis and Determination of Effective Moisture Diffusivity. *J. Environ. Manage.* 2020, 262, 110348. DOI: 10.1016/j.jenvman.2020.110348.

[2] Nemzer, B.; Vargas, L.; Xia, X.; Sintara, M.; Feng, H. Phytochemical and Physical Properties of Blueberries, Tart Cherries, Strawberries, and Cranberries as Affected by Different Drying Methods. *Food Chem.* 2018, 262, 242–250. DOI: 10.1016/j.foodchem.2018.04.047.

[3] Salim Hizaji, A.; Maghsoudlou, Y.; Jafari, S. M. Application of Peleg Model to Study Effect of Water Temperature and Storage Time on Rehydration Kinetics of Air-Dried Potato Cubes. *Latin Am. Appl. Res.* 2010, 40, 131–136.

[4] Shrestha, L.; Crichton, S. O. J.; Kulig, B.; Kiesel, B.; Hensel, O.; Sturm, B. Comparative Analysis of Methods and Model Prediction Performance Evaluation for Continuous Online Non-Invasive Quality Assessment during Drying of Apples from Two Cultivars. *Therm. Sci. Eng. Prog.* 2020, 18, 100461. DOI: 10.1016/j.tsep.2019.100461.

[5] Kidoni, M.; Grabowska, J. Bioactive Compounds, Antioxidant Activity, and Sensory Qualities of Red-Fleshe Dried Apples by Different Methods. *LWT Food Sci. Technol.* 2021, 136, 110302. DOI: 10.1016/j.lwt.2020.110302.

[6] Raponi, F.; Moscetti, R.; Nallan Chakravartula, S. S.; Fidaleo, M.; Massantini, R. Monitoring the Hot-Air Drying Process of Organically Grown Apples (cv. Gala) Using Computer Vision. *Biosyst. Eng.* 2021. DOI: 10.1016/j.biosystemseng.2021.07.005.

[7] Ma, Q.; Ji, B.; Ji, Y.; Wu, X.; Li, X.; Zhao, Y. Stability of Phenolic Compounds and Drying Characteristics of Apple Peel as Affected by Three Drying Treatments. *Food Sci. Hum. Wellness* 2021, 10, 174–182. DOI: 10.1016/j.fshw.2021.02.006.

[8] Chen, A.; Achkar, G. E.; Liu, B.; Bennacer, R. Experimental Study on Moisture Kinetics and Microstructure Evolution in Apples during High Power Microwave Drying Process. *J. Eng. Food* 2021, 292, 110362. DOI: 10.1016/j.jfoodeng.2020.110362.

[9] Emingil, M. B.; Yegül, Ü.; Sacilik, K. Drying Characteristics of Blackberry Fruits in a Convective Hot-Air Dryer. *horts* 2019, 54, 1546–1560. DOI: 10.2173/HORTSCI14201-19.

[10] Lentzov, D. I.; Boudouvis, A. G.; Karathanos, V. T.; Xanthopoulou, G. A. Moving Boundary Model for Fruit Isothermal Drying and Shrinking: An Optimization Method for Water Diffusivity and Peel Resistance Estimation. *J. Food Eng.* 2019, 263, 299–310. DOI: 10.1016/j.jfoodeng.2019.07.010.

[11] Roman, C.; Mazza, G.; Rodriguez, R. Determination of Effective Moisture Diffusivity and Thermodynamic Properties Variation of Regional Wastes under Different Atmospheres. *Case Stud. Therm. Eng.* 2018, 12, 248–257.

[12] Niaz, T.; Imran, M. Diffusion Kinetics of Nisin from Composite Coatings Reinforced with Nano-Rhonnosmes. *J. Food Eng.* 2021, 288, 110143. DOI: 10.1016/j.jfoodeng.2020.110143.

[13] Golpour, I.; Kaveh, M.; Chayjan, R. A.; Guin, M. B.; Yegul, U.; Sacilik, K. Drying Characteristics of Blackberry Fruits in a Convective Hot-Air Dryer. *horts* 2019, 54, 1546–1560. DOI: 10.2173/HORTSCI14201-19.

[14] Lentzov, D. I.; Boudouvis, A. G.; Karathanos, V. T.; Xanthopoulou, G. A. Moving Boundary Model for Fruit Isothermal Drying and Shrinking: An Optimization Method for Water Diffusivity and Peel Resistance Estimation. *J. Food Eng.* 2019, 263, 299–310. DOI: 10.1016/j.jfoodeng.2019.07.010.

[15] Roman, C.; Mazza, G.; Rodriguez, R. Determination of Effective Moisture Diffusivity and Thermodynamic Properties Variation of Regional Wastes under Different Atmospheres. *Case Stud. Therm. Eng.* 2018, 12, 248–257.

[16] Niaz, T.; Imran, M. Diffusion Kinetics of Nisin from Composite Coatings Reinforced with Nano-Rhonnosmes. *J. Food Eng.* 2021, 288, 110143. DOI: 10.1016/j.jfoodeng.2020.110143.

[17] Golpour, I.; Kaveh, M.; Chayjan, R. A.; Guin, M. B.; Yegul, U.; Sacilik, K. Drying Characteristics of Blackberry Fruits in a Convective Hot-Air Dryer. *horts* 2019, 54, 1546–1560. DOI: 10.2173/HORTSCI14201-19.

[18] Lentzov, D. I.; Boudouvis, A. G.; Karathanos, V. T.; Xanthopoulou, G. A. Moving Boundary Model for Fruit Isothermal Drying and Shrinking: An Optimization Method for Water Diffusivity and Peel Resistance Estimation. *J. Food Eng.* 2019, 263, 299–310. DOI: 10.1016/j.jfoodeng.2019.07.010.

[19] Roman, C.; Mazza, G.; Rodriguez, R. Determination of Effective Moisture Diffusivity and Thermodynamic Properties Variation of Regional Wastes under Different Atmospheres. *Case Stud. Therm. Eng.* 2018, 12, 248–257.

[20] Niaz, T.; Imran, M. Diffusion Kinetics of Nisin from Composite Coatings Reinforced with Nano-Rhonnosmes. *J. Food Eng.* 2021, 288, 110143. DOI: 10.1016/j.jfoodeng.2020.110143.

[21] Golpour, I.; Kaveh, M.; Chayjan, R. A.; Guin, M. B.; Yegul, U.; Sacilik, K. Drying Characteristics of Blackberry Fruits in a Convective Hot-Air Dryer. *horts* 2019, 54, 1546–1560. DOI: 10.2173/HORTSCI14201-19.

[22] Lentzov, D. I.; Boudouvis, A. G.; Karathanos, V. T.; Xanthopoulou, G. A. Moving Boundary Model for Fruit Isothermal Drying and Shrinking: An Optimization Method for Water Diffusivity and Peel Resistance Estimation. *J. Food Eng.* 2019, 263, 299–310. DOI: 10.1016/j.jfoodeng.2019.07.010.

[23] Roman, C.; Mazza, G.; Rodriguez, R. Determination of Effective Moisture Diffusivity and Thermodynamic Properties Variation of Regional Wastes under Different Atmospheres. *Case Stud. Therm. Eng.* 2018, 12, 248–257.
(Athyonidium chilensis). Food Bioprod. Process. 2020, 123, 284–295. DOI: 10.1016/j.fbp.2020.07.012.

[62] Dak, M.; Pareek, N. K. Effective Moisture Diffusivity of Pomegranate Arils under Going Microwave-Vacuum Drying. J. Food Eng. 2014, 122, 117–121. DOI: 10.1016/j.jfoodeng.2013.08.040.

[63] Sharma, G. P.; Prasad, S. Effective Moisture Diffusivity of Garlic Cloves Undergoing Microwave-Convective Drying. J. Food Eng. 2004, 65, 609–617. DOI: 10.1016/j.jfoodeng.2004.02.027.

[64] Sutar, P. P.; Prasad, S. Modeling Microwave Vacuum Drying Kinetics and Moisture Diffusivity of Carrot Slices. Drying Technol. 2007, 25, 1695–1702. DOI: 10.1080/07373930701590947.

[65] Mujumdar, A. S. Transport Properties of Foods. Drying Technol. 2001, 19, 2383–2384. DOI: 10.1081/DRT-100107506.

[66] Corrêa, P. C.; Horta, F. M.; Oliveira, G. H. H.; Goneli, A. L. D.; Resende, O.; Campos, S. d. C. Mathematical Modeling of the Drying Process of Corn Ears. Acta Scientarium. Agron. 2011, 33, 575–581.

[67] Mota, C. L.; Luciano, C.; Dias, A.; Barroca, M. J.; Guiné, R. P. F. Convective Drying of Onion: Kinetics and Nutritional Evaluation. Food Bioprod. Process. 2010, 88, 115–123. DOI: 10.1016/j.fbp.2009.09.004.

[68] Rahman, M. S.; Al-Zakwani, I.; Guizani, N. Pore Formation in Apple during Air-Drying as a Function of Temperature: porosity and Poresize Distribution. J. Sci. Food Agric. 2005, 85, 979–989. DOI: 10.1002/jsfa.2056.

[69] Ján, B. M.; Davide, S. Selected Quantitative Parameters Comparison of Apples from Bio- and Conventional Production. AJS 2018, 5, 343–354. DOI: 10.30958/ajs.5-4-3.

[70] Ozturk, I.; Bastaban, S.; Ercisli, S.; Kalkan, F. Physical and Chemical Properties of Three Late Ripening Apple Cultivars. Int. Agrophys. 2010, 24, 357–361.