https://doi.org/10.17221/201/2021-CJFS

Effect of pretreatments on solar dehydration of different varieties of apple (*Malus domestica*)

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Citation: Karaaslan S., Ekinci K. (2022): Effect of pretreatments on solar dehydration of different varieties of apple (*Malus domestica*). Czech J. Food Sci., 40: 93–101.

Abstract: In this study, four different apple varieties were dried in a solar tunnel dryer using four different methods. Apple slices were immersed in a solution consisting of 0.5% ascorbic acid, 0.5% sodium metabisulphite, and 0.5% citric acid for 3 min. Constant measurements were performed in various parts of the dryer for drying air temperature, solar irradiation, air velocity, and relative humidity during drying. The change in the mass of apples was measured on a daily basis. Furthermore, ten mathematical models were used to study the drying process, which were Newton, Page, Henderson and Pabis, logarithmic, diffusion, two-term, two-term exponential, Midilli, Alibas, and logistic equation. Then, these models were compared in terms of their performance levels based on correlation coefficient (R^2), chi-square value (χ^2), and root mean square error (RMSE) between moisture ratios (MR) that were observed and predicted. Furthermore, we observed that the Alibas model and the two-term model revealed the ratio of drying in a satisfactory way for all drying methods.

Keywords: solar tunnel dryer; citric acid; ascorbic acid; sodium metabisulphite; mathematical modelling

Apple (*Malus domestica*) is a stone fruit that belongs to the family Rosaceae. There are more than 7 500 different kinds of apples known in the world, differing mainly in shape, colour, and herbal nourishing composition. Gala, Golden Delicious and Red Delicious, Granny Smith, and Fuji are some popular apple varieties.

One traditional way to dry apples is to dry them in the sun. However, there is a need for large areas and long drying periods in open sun drying. There is a need for only a small amount of capital in this method yet drying in the open sun depends on the presence of sunlight. Products are highly susceptible to getting contaminated from contaminating substances such as sand and dust, and fungal and insect infestations that develop in humid conditions. It may be inconvenient to use such contaminated products. Therefore, many other methods have been developed instead of drying the products in the open sun. Drying agricultural products in closed systems can be given as an example of these methods. This is also one of the most effective methods of reducing the low quality associated with post-harvest losses and traditional sun drying methods (Rathorea and Panwarb 2010).

After the dehydration process, it is increasingly important to preserve the quality features (colour and texture) and nutritional quality of fruits and vegetables. These properties can be improved by pretreatment before drying the products. Proper pretreatment can enhance the process of drying by shortening the drying period and saving more energy (Hii et al. 2012). Some common commercially available pretreatments are methyl and ethyl ester emulsions, ascorbic acid, potassium carbonate, potassium metabisulphate and potassium and sodium hydroxide.

Mathematical modelling of the drying process is a significant part of drying technology (Naderinezhad et al. 2016). Mathematical modelling and simulation of drying curves under various circumstances is highly signifi-

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cant for obtaining more efficient studies. In this context, several studies have been carried out on mathematical modelling of post-harvest processes to simulate the process. The drying kinetics should be determined by modelling the drying process because the drying property of each agricultural product is unique, and changes based on drying conditions and methods.

Although there is a study where slices of Gala type apples were dried by hot air method with three different pretreatments (ascorbic acid, citric acid, and sodium metabisulphite solutions) (Dipersio et al. 2003), no study was reported where three different solutions were applied to four different apple varieties which were dried in a solar dryer. Based on this, the present study mainly aimed to *i*) dry four different slices of apple in a solar tunnel dryer, *ii*) determine how drying characteristics are affected by the pretreatment with three different solutions, *iii*) fit ten thin-layer models to the experimental drying data.

MATERIAL AND METHODS

Material

Four different apple varieties were used in the trials. Golden Delicious, Granny Smith, Red Chief, and Pink Lady varieties constitute the material of our study. Apples of the same ripeness were harvested from the orchard of the Agricultural Research and Application Centre at Isparta University of Applied Sciences, Isparta, Turkey. To ensure the consistency of the physical properties of apple samples, apples with similar diameters (75 ± 3 mm) and weights (114 ± 4 g) were selected and stored at 4 °C (TNIAA 9 FTKA; Indesit Turkey) before the experiment commenced. In order to determine the initial mean moisture content of fresh apple varieties, the samples were dried in an oven at a temperature of 105 °C (UN 55; Memmert, Germany). The values of the moisture content obtained [in g water (g wet weight)$^{-1}$] were 80.62 for Golden Delicious apple, 84.82 for Granny Smith apple, 84.86 for Red Chief apple, and 86.77 for Pink Lady apple (Gf 600; AND, Japan). The seeds of the apple samples were removed with a household appliance. Then, the samples were washed using tap water and cut into cubes of 10 mm thickness using a stainless steel knife. Apple cubes were immersed in 0.5% ascorbic acid, 0.5% sodium metabisulphite, and 0.5% citric acid solution for 3 min. It is useful to apply these solutions before drying the apple samples in order to inactivate bacterial contamination. Table 1 presents the pretreatments selected in this study.

For each experiment, approximately 500 g of apple samples were put in aluminium trays of 20 cm × 20 cm in size, in one layer inside the solar tunnel-type dryer. The drying process commenced once the loading was completed at 09:00 and stopped at 17:00. The weight loss of apple slices placed in the dryer was calculated with a digital precision scale 0.01 g (GP3202; Sartorius, Germany) at one-hour intervals during the drying period. Apple slices were kept in the dryer during the night under environmental conditions after 17:00. The weighing of the samples was continued until no change was observed between two consecutive weighings. The experiments were carried out on October 17–22, 2019. Solar radiation was measured on an hourly basis (09:00–17:00) using a pyranometer (DO 9847; Delta OHM, Italy) on a horizontal surface. The drying air temperature, the inner temperature of apples and the relative humidity were detected using K-type thermocouples (HH 25 KC; OMEGA, US) and DT-3 hygrometer (TBT, China), respectively. A hotwire anemometer (405i; Testo, Germany) was used to measure drying air velocity at the outlet of the tunnel.

Experimental set-up and procedure

A solar tunnel dryer designed and built at Isparta University of Applied Sciences (Isparta, Turkey) was used for the experiments (Figure 1). This dryer is composed of a solar cell module, a flat plate solar collector, a small axial fan, and a drying tunnel. All units of the dryer are attached onto the metal frame. The base of the collector, which is painted in black, consists of hexagonal channels connected to the tunnel. The solar collector is coated using a transparent polycarbonate plaque. The dryer is fitted with a 150 W solar cell module to move air through a fan. The area of the collector is 2 m long and 1.9 m wide. The tunnel has an area that is twice as large as the collector. The dryer is placed in the east-west direction, with the drying area facing south. The drying tunnel is exposed to sunlight between 09:00 and 17:00.

Theoretical principles

Moisture ratio (MR). The moisture ratio (MR) was found based on the moisture content as a function of time (t) [$M(t)$], the initial moisture content of the samples (M_0), and the equilibrium moisture content of the samples (M_e). It was neglected because M_e is much lower than M_0 or M_t (Saçilik and Eliçin 2006).

$$MR = \frac{M(t) - M_e}{M_0 - M_e} \tag{1}$$

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Table 1. The list of the pretreatments and their application conditions

Pretreatments	Application conditions
Without pretreatment	no treatment (control)
Citric acid	immersing in 0.5% citric acid solution for 3 min at room temperature
Ascorbic acid	immersing in 0.5% ascorbic acid solution for 3 min at room temperature
Sodium metabisulphite	immersing in 0.5% sodium metabisulphite solution for 3 min at room temperature

Mathematical modelling. There are various mathematical models that describe the characteristics of drying of agricultural products. Table 2 lists ten empirical models used to simulate drying curves. These models were assessed by root mean square error (RMSE), chi-squared (χ^2), and coefficient of determination (R^2) (Minaei et al. 2012). These can be calculated as follows:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} \left(MR_{pre,\,i} - MR_{exp,\,i} \right)^2}{\sum_{i=1}^{N} \left(MR_{exp,\,i} - MR_{pre,\,i} \right)^2} \right] \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,\,i} - MR_{pre,\,i} \right)^2}{N - Z} \quad (3)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(MR_{pre,i} - MR_{exp,i} \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

where: $MR_{exp,\,i}$, $MR_{pre,\,i}$ – experimental and predicted dimensionless MR values; N – number of observations; Z – number of drying constants.

The most acceptable model for defining the drying properties of apple samples is a model with the highest R^2 and the lowest χ^2 as well as RMSE values (Naderinezhad et al. 2016).

Figure 1. The experimental solar tunnel dryer

Table 2. Model constant and statistical parameters for the various mathematical models given by authors tested for moisture ratio (MR) determination

No.	Mathematical models	Model equations
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Henderson and Pabis	$MR = a\exp(-kt)$
4	logarithmic	$MR = a\exp(-kt) + c$
5	diffusion	$MR = a\exp(-kt) + (1 - a)\exp(-kbt)$
6	two-term	$MR = a\exp(k_0t) + b\exp(-k_1t)$
7	two-term exponential	$MR = a\exp(-kt) + (1 - a)\exp(-kat)$
8	Midilli*	$MR = a\exp(-kt^n) + bt$
9	Alibas**	$MR = a\exp[(-kt^n) + (bt)] + g$
10	logistic	$MR = a_0/[1 + a\exp(kt)]$

*Midilli et al. (2002); **Alibas (2012); a, c, b, g – experimental constants; k – drying rate constant; t – drying time; n – exponent

Statistical analysis

The SigmaPlot (Scientific Graph System 12.00) was made use of to complete the statistical analyses. Non-linear regression analysis was carried out by means of the SigmaPlot software 12.00 in order to calculate equation parameters. The results of the regression analysis of apple samples dried by the tunnel-type solar drying method include coefficient of determination (R^2), chi-square value (χ^2), and RMSE.

RESULTS AND DISCUSSION

Apple cubes were dried in a solar dryer in October 2019. This 6-day experiment was performed only once. Figure 2 shows the temperature pattern and relative humidity of the drying air. The drying air temperature varied between 18.88 °C and 46.63 °C while the ambient air temperature ranged from 9.0 °C to 35.6 °C. The apple inner temperature changed between 9.6 °C and 38.7 °C. Relative humidity of drying air was recorded between 31% and 86% during the experiment. Figure 3

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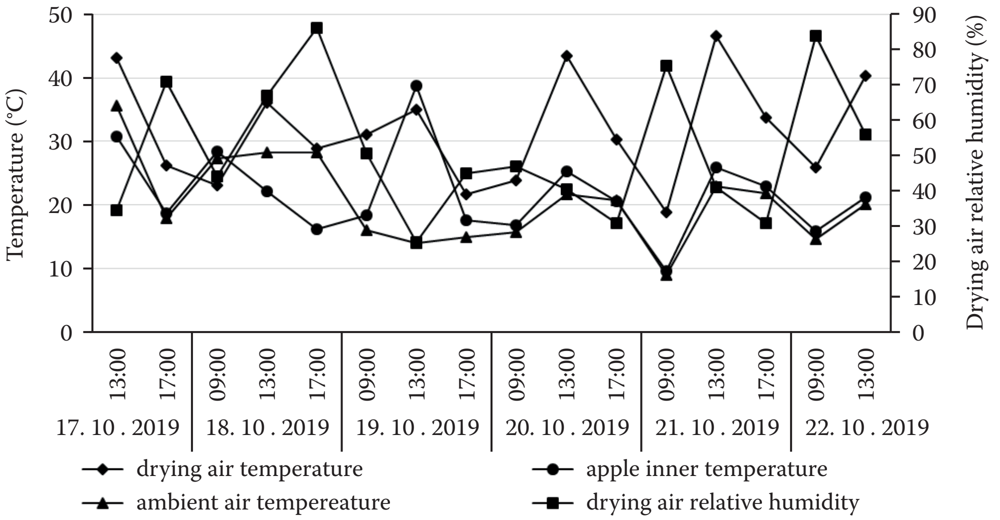

Figure 2. Change of drying air temperature, apple inner temperature, ambient air temperature and relative humidity as a function of time for solar drying of apple

presents air velocity change as a function of time and days. According to Figure 3, the velocity values obtained from the fans reached a peak approximately in the middle of the day. Air velocity values were synchronised with temperatures, and so modulated the drying temperature. The larger the amount of energy the collector received at high solar irradiance (Figure 3), the higher the temperature of drying air, which was equated by increased air velocity. The solar cell provided the fan with power; therefore, the velocity of airflow varied as a function of solar irradiance. The values of solar irradiance that were measured between October 17 and October 22, 2019, are shown in Figure 3. Solar irradiance levels were low in the morning and in the afternoon as solar angles varied throughout the day. The change in the values of solar irradiance was greater than the normal levels expected for the geographical location of Isparta. Generally speaking, the direct measurement of the airflow rate in the dryer was problematic due to air velocity values varying with time and position vertical to the flow. During the time the power was supplied by the solar cell module, the fan was not controlled and continued to work.

Figure 4 presents the MR *versus* drying time for pretreated samples of Golden Delicious apples. The necessary drying periods to reduce the initial moisture from 78.9–86.8% [wet basis (w.b.)] to 12.42% (w.b.) in the Golden Delicious apple variety were 7 440 min for non-pretreated samples, 5 760 min for apple samples pre-

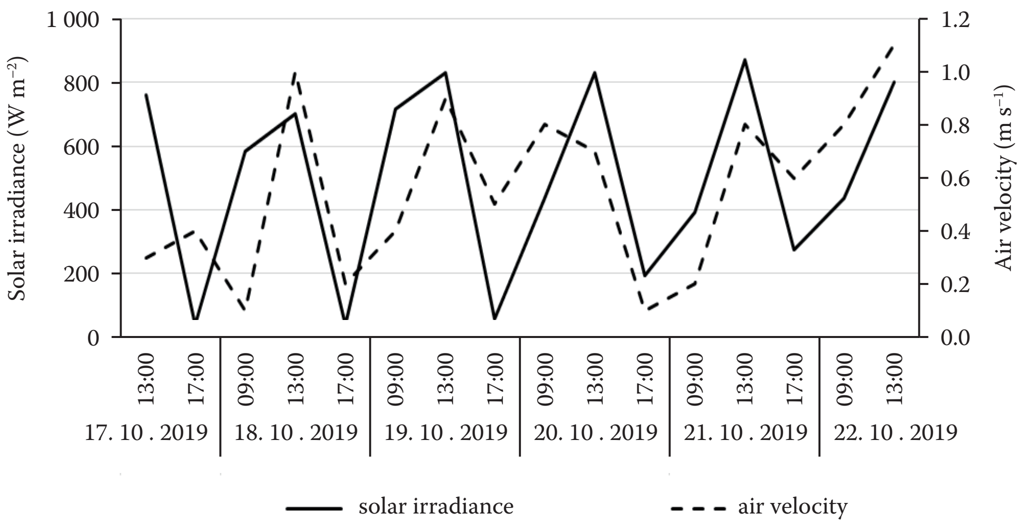

Figure 3. Change of solar irradiance and air velocity of drying air at the outlet of drying tunnel as a function of time

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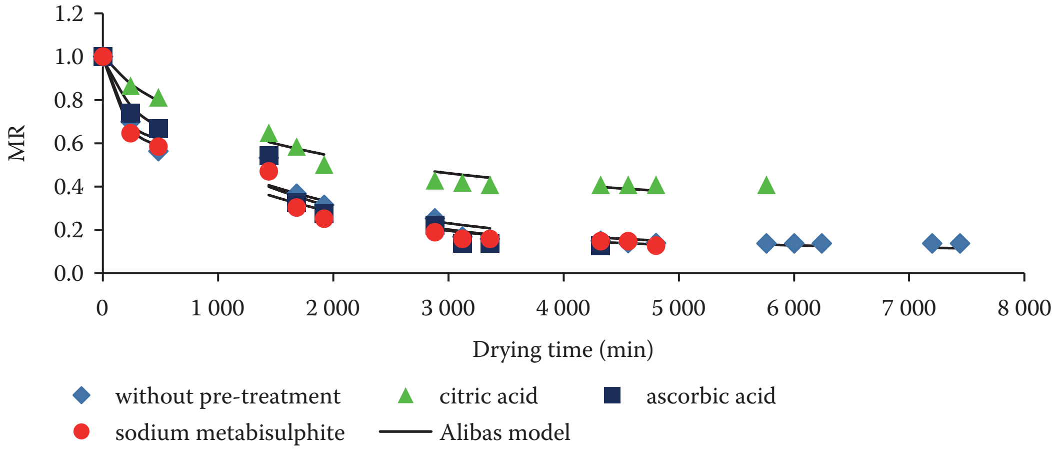

Figure 4. Variation of experimental and predicted moisture ratios (MR) by the Alibas drying model with drying time for the Golden Delicious apple variety

treated with citric acid, 4 320 min for samples pretreated with ascorbic acid, and 4 800 min for samples pretreated with sodium metabisulphite. The observations showed that the moisture content constantly dropped depending on the drying time. Drying times of the Granny Smith apple varieties were 7 440, 3 360, 4 800, and 4 800 min, respectively, with the application of no pretreatment, citric acid, ascorbic acid and sodium metabisulphite pretreatments (Figure 5). The Red Chief apples, which were pretreated with citric acid, ascorbic acid and sodium metabisulphite applications, were dried in 4 560, 4 800, and 4 800 min, respectively (Figure 6). Like with other apple varieties, the drying time of the Red Chief apple varieties without any pretreatment was 7 200 min. The shortest drying time of Pink Lady apple slices, like in Granny Smith varieties, was achieved with the application of citric acid pretreatment. Drying times of Pink Lady apple varieties were 7 200, 4 320, 4 800, and 4 560 min, respectively, with the application of no pretreatment, citric acid, ascorbic acid and sodium metabisulphite pretreatments (Figure 7). It was determined that the drying times were almost the same in applications with/without pretreatment, ascorbic acid, and sodium metabisulphite with all apple varieties. Among the varieties, the most significant change in drying times was observed in citric acid-treated apples. In addition, the shortest drying times for all apple varieties were obtained through pretreatment with citric acid.

Earlier researchers also reported similar results for food products. Doymaz (2009) reported that the drying times of apple samples that were pretreated with citric acid were shorter, and they had higher rates of drying and rehydration and better colour characteristics than

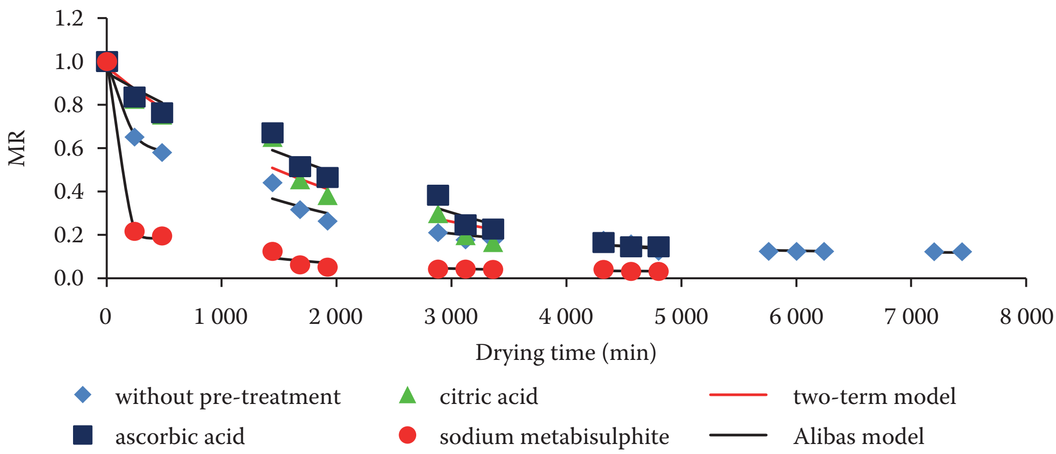

Figure 5. Variation of experimental and predicted moisture ratios (MR) by the two-term and Alibas drying models with drying time for the Granny Smith apple variety

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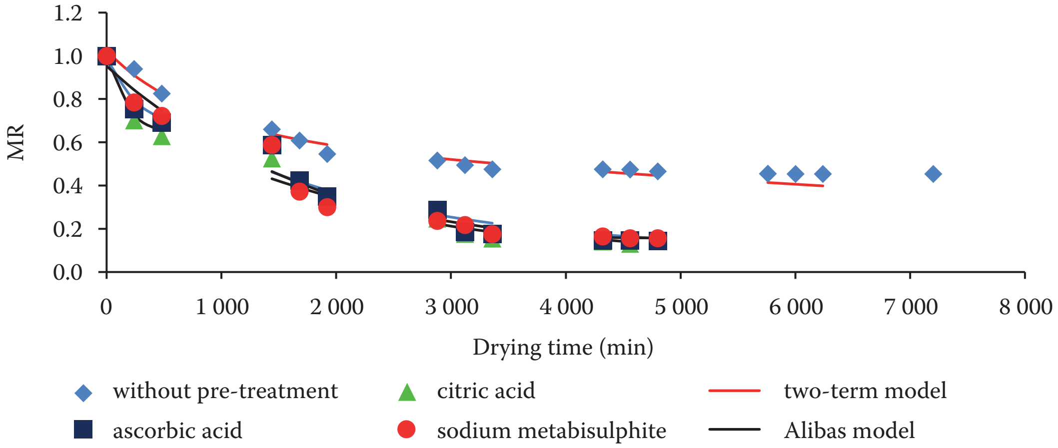

Figure 6. Variation of experimental and predicted moisture ratios (MR) by the two-term and Alibas drying models with drying time for the Red Chief apple variety

the control samples. Pretreatments e.g. with citric acid belong to the most important parameters affecting the drying time. However, one study determined that citric acid applied as a pretreatment prevented fresh Chinese water chestnuts from browning and extended their shelf life (Jiang et al. 2003). Numerous studies performed thorough investigations on the best concentrations of citric acid and the optimum holding times for a variety of vegetables and fruits. In a study by Doymaz (2010), red apple was dried at 55, 65, and 75 °C and with 2.0 m s^{-1} airflow. In the study, two pretreatment applications were used: dipping in 0.5% citric acid solution and scalding. Furthermore, five different mathematical models were used for calculations. According to the calculations made with these models, the best method to dry the samples was dipping the apples in 0.5% citric acid solution. In another study with apples, the apple samples were dried in a laboratory tray dryer with pretreatment methods of dipping in 0.5% ascorbic acid solution; 0.3% l-cysteine solution; 0.1% 4-hexyl resorcinol solution; 0.5% sodium metabisulfite solution; mixed solution of 0.05% 4-hexyl resorcinol and 0.5% sodium metabisulfite. In the study, the best results were obtained when samples were pretreated with 4-hexyl resorcinol (Jokić et al. 2009).

The drying rate is determined by the moisture content and temperature of the dried products, the temperature of the air in contact with the products, the relative humidity and the velocity of the air. The rate of drying is the final moisture content divided by the drying time (dM/dt). In general, the drying rate increased in apple varieties that were dried by applying different pretreatments compared to the varieties that were dried without pretreatment. Kaymak-Ertekin and Sultanoğlu

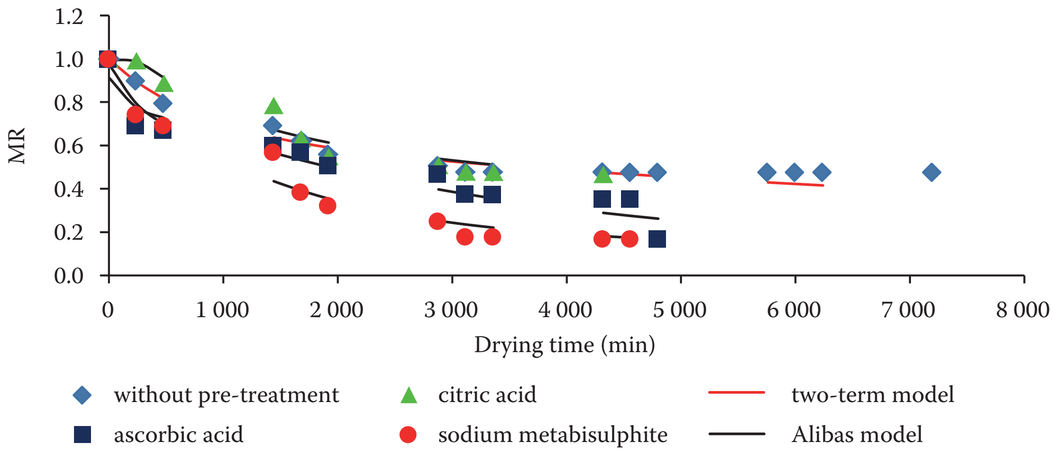

Figure 7. Variation of experimental and predicted moisture ratios (MR) by the two-term and Alibas drying models with drying time for the Pink Lady apple variety

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Table 3. Statistical results of the Alibas and two-term models and their constants and coefficients of apple varieties under different drying conditions

Apple variety	Solutions	Models	*MR* (Alibas and two-term)									
			a	k	n	b	g	a_1	R^2	RMSE	RSS	χ^2
Golden Delicious	without pretreatment	Alibas	0.8916	0.2781	3.5170E–009	–0.0336	0.1043	–	0.9737	0.02647	0.0270	0.005057
	citric acid	Alibas	0.7768	0.3833	0.9771	0.3265	0.2260	–	0.9008	0.06924	0.0738	0.012655
	ascorbic acid	Alibas	0.8950	0.1110	2.5721E–010	–0.0400	0.0925	–	0.9746	0.03354	0.0306	0.005780
	sodium metabisulphite	Alibas	0.8864	0.2859	9.7896E–011	–0.0399	0.1050	–	0.9837	0.01570	0.0165	0.002999
Granny Smith	without pretreatment	Alibas	0.9341	0.9083	1.0128E–009	–0.0380	0.0654	–	0.9964	0.01716	0.0030	0.001751
	citric acid	two-term	0.0275	0.9701	–	0.0038	–	–0.0279	0.9744	0.03200	0.0336	0.005259
	ascorbic acid	Alibas	0.8209	7.3945E–008	3.9615	–0.0228	0.1266	–	0.9851	0.03129	0.0204	0.002416
	sodium metabisulphite	Alibas	0.9699	1.3724	8.7486E–011	–0.0560	0.0299	–	0.9979	0.02668	0.0266	0.001278
Red Chief	without pretreatment	two-term	0.0760	0.3734	–	0.6465	–	0.0047	0.9050	0.06044	0.0633	0.009754
	citric acid	Alibas	0.9337	0.2132	5.0955E–010	–0.0292	0.0572	–	0.9839	0.03268	0.0186	0.004270
	ascorbic acid	Alibas	0.8914	0.1141	6.9812E–010	–0.0321	0.0945	–	0.9764	0.04103	0.0277	0.005025
	sodium metabisulphite	Alibas	0.7954	4.2105E–007	3.6991	–0.0373	0.1571	–	0.9765	0.03456	0.0274	0.003361
Pink Lady	without pretreatment	two-term	0.0040	0.6324	–	0.3654	–	0.0735	0.8880	0.05894	0.0666	0.009643
	citric acid	Alibas	–0.5100	20.2332	–1.1517	0.0025	0.9952	–	0.9019	0.05916	0.0777	0.011163
	ascorbic acid	Alibas	0.8182	0.1091	2.5128E–010	–0.0185	0.0946	–	0.9444	0.03419	0.0530	0.008822
	sodium metabisulphite	Alibas	0.8398	0.0874	4.9841E–010	–0.0394	0.1359	–	0.9743	0.01754	0.0281	0.004477

$MR = a\exp[(-kt^n) + (bt)] + g$ (Alibas); $MR = a\exp(k_0t) + b\exp(-k_1t)$ (two-term); R^2 – coefficient of determination; RMSE – root mean square error; RSS – residual sum of square; χ^2 – chi-square; a, a_1, b, g – experimental constants; k – drying rate constant (min^{-1}); n – exponent

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(2000) reported that sucrose and glucose solution provided a high drying rate in apple slices. In addition, the drying curves did not display any constant rate periods. Therefore, the complete drying process for all apple varieties occurred within the range of the falling rate period. Similar results were obtained in drying studies carried out on various agricultural products such as peas (Doymaz and Kucuk 2017), strawberries (El-Beltagy et al. 2007), peaches (Kingsly et al. 2009), and yam (Okeleye et al. 2021).

The drying process of the Granny Smith variety without pretreatment was faster than the drying process of other apple varieties without pretreatment. The drying process of Golden Delicious apple had the fastest drying rate, which was obtained in the drying system where sodium metabisulphite was applied. The Granny Smith type had the highest drying rate in the drying process carried out without pretreatment. Again, the lowest drying rate of the same variety was observed in the citric acid application. The drying process of the Red Chief variety with citric acid was faster than drying of other apple varieties with citric acid. The lowest drying rate was observed when drying the Red Chief apple variety without pretreatment. The last variety, Pink Lady, had the highest drying rate in the ascorbic acid application, while the lowest drying rate was found in the citric acid application. In general terms, the drying rates recorded when all four apple varieties were dried in the dryer were at their lowest in the other three apple varieties, except for the Red Chief apple variety.

These findings displayed a good agreement with observations from previous studies regarding the drying of various agricultural products. For all apple varieties, the rates of drying were reduced in the entire process, which occurs in other agricultural products as well (Aghbashlo et al. 2009).

The performance of the given models used in the study was commented with respect to R^2, χ^2, and RMSE, which correspond to the coefficient of determination, reduced chi-square and the RMSE of non-linear regression analysis, respectively. Higher R^2 values and lower χ^2 and RMSE values used in determining the performance of the model equations suggest better goodness of fit.

Statistical results for each model. R^2, χ^2, and RMSE values were within ranges of 0.7358 and 0.9979, 0.001751 and 0.278710, and 0.006108 and 0.198620, respectively, for all the methods and models. Table 3 shows that the Alibas model and two-term model equations yielded the highest R^2 and the lowest χ^2 and RMSE. Similar findings were determined for different foods in the literature. Seiiedlou et al. (2010) stated that the model equation of Aghbashlo et al. (2009) was the best fitting model for apples dried using a hot-air tray dryer. According to Zarein et al. (2013), the model established by Midilli et al. (2002) was the most successful one in describing the drying behaviour of apple slices. It was found out that logarithmic and two-term model equations represented the drying characteristics of tomato slices dried by convective drying (Mariem and Mabrouk 2014). Nukulwara and Tungikara (2020) concluded that the Page model was appropriate for drying turmeric in both indirect natural convection solar dryer (INCSD) and open sun drying.

CONCLUSIONS

The present study investigated how certain pretreatments affected the drying properties of different apple varieties. The drying periods were significantly reduced by applying different solutions as pretreatment to apple varieties. Among all the apple varieties used in the study, the greatest change in drying times was detected in dried apples treated with citric acid. However, the shortest drying times were also obtained from citric acid pretreatment applications. Drying rates of all apple varieties occurred in the falling drying rate period. In addition, the drying curves did not display any constant rate periods. As a result, the recorded drying rates were lowest for the other three apple varieties except for the Red Chief apple variety. Ten thin layer drying models were compared in terms of the values of R^2, χ^2, and RMSE to explain the drying characteristics of apple slices. The Alibas model and two-term model equations were the best fitting models. In addition, it was determined that it was necessary to know the biochemical properties of the products for a more accurate description of the product quality and a more sensitive drying process.

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Received: September 8, 2021
Accepted: January 27, 2022
Published online: April 4, 2022