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ORIGINAL RESEARCH ARTICLE

Effect of different pre-treatments on rehydration kinetics of solar and hot-air dried Fuji apple slices

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ABSTRACT

The present study demonstrates the effect of direct solar drying (DSD) and hot air drying (HAD) on the quality attributes of Fuji apple slices. DSD samples took a longer time (150–180 min) to dry and simultaneously reached higher equilibrium moisture content at the end of rehydration than HAD samples. DSD samples have higher rehydration ability, dry matter holding capacity, and water absorption capacity than HAD samples. Among several empirical models, the Weibull model is the best fit with higher R^2 (0.9977), lower root mean square (0.0029), and chi-square error (0.0031) for describing the rehydration kinetics. Rehydrated HAD samples showed better color characteristics than DSD in terms of overall color change, chroma, and hue angle values. Whereas the hardness and chewiness of rehydrated DSD samples were better than HAD samples because of higher dry matter holding capacity in DSD. Apart from color retention, the DSD samples showed better rehydration capacity and a good texture upon rehydration than HAD slices.

Keywords: solar drying; apple slices; rehydration indices; thin layer modeling; color; hardness

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1. Introduction

Apple is a good source of dietary fiber, energy, calcium, iron, potassium, vitamin A, vitamin C, and also some amount of proteins[1,2] which helps to maintain good health. Drying is an important process that involves moisture removal from a food product to decrease microbial attack and increase shelf life. Drying induces various structural changes in the food product based on the drying conditions, which further influences the rehydration ability of the food[3–5]. Generally, drying is carried out in conventional dryers that are costly and use fossil fuels[6]. Therefore, more highlighting is given on solar drying nowadays. However, the solar drying technique takes a little longer time in comparison to other drying techniques to reach the desired moisture content[7]. The different types of solar dryers are, direct (commodity receives direct sunlight), indirect (commodity receives heat from collector being heated from sunlight), and mixed (mix of direct and indirect), and hybrid type (advanced version)[8].

Solar drying and hot air drying are two methods used for food and material preservation, each with its own set of advantages and disadvantages[9]. Solar drying harnesses the sun's energy, making it eco-friendly and cost-effective. It reduces dependency on conventional energy sources, promotes sustainability, and is ideal for small-scale operations[6]. However, its efficiency is weather-dependent, impacting drying rates. On the other hand, hot air drying offers consistent results regardless of weather conditions. It's faster, and applicable to various scales, but may consume more energy and incur higher costs. Balancing these methods depends on factors like scale, location, and resource availability[10].

Rehydration involves three concomitant processes namely, water absorption into the dried cellular matrix, swelling of the dried matrix, and the leaching of soluble solutes[11]. It involves two cross-current mass fluxes; one is water flux which enters the dried matrix from the rehydration solution and the other is the flux of soluble solutes which comes out from the rehydrating product because of leaching. Various factors influence the process of rehydration such as pre-drying treatments, drying conditions and techniques, immersion media's composition, rehydration temperature, etc. All these factors induce irreversible changes in the product and because of these changes, the equilibrium moisture content attained after rehydration is not the same as that of the original product[12].

Apples are a rich source of polyphenols and hence it is highly susceptible to browning, therefore are need to be pre-treated before drying[13]. Pre-treatment can be done either by a physical method such as blanching or chemical methods which includes the application of chemicals[14,15]. Similar results were reported by Doymaz[16] for the blanching of Amasya red apples, and Lewicki et al.[3] by treating apple slices with 0.5% ascorbic acid solution to limit enzymatic browning.

However, any study regarding rehydration of Fuji apple slices has not been thoroughly researched in the literature. Therefore, in the present study rehydration characteristics of Fuji apple slices were studied with different pretreatments and drying conditions viz. solar and hot air drying. Additionally, the rehydration kinetics and the effect of drying techniques on the color and texture of Fuji apple slices were also investigated.

2. Materials and methods

Fuji apples (*Malus domestica*) were procured from the community market of IIT Kharagpur, India. Apple slices of (30 mm × 5 mm) were prepared from raw apples with an average weight of 3.05 ± 0.35 g each. Pre-treatments such as blanching at 70 °C and dipping in ascorbic acid (0.5%) were applied before drying for 2 min each to eliminate the effect of enzymatic activity and browning. Some samples were kept without pretreatment termed as un-treated and used for comparison purposes.

2.1. Experimentation

Drying experiments were carried out in a direct solar dryer (DSD) (in-house built) and laboratory-scale hot air dryer (HAD) (Plausible Instruments Private Limited, Delhi). The natural convection direct solar dryer consists of an inner black absorbing surface that collects the light and converts it to heat. It had opposite inlet and outlet vents for the flow of air and also a top glass cover that traps the light inside the drier further increasing the temperature inside it. The products to be dried were kept on a wire mesh tray inside the dryer. The experiments were performed on a bright sunny day with an average solar intensity level of 600 W/m^2, relative humidity of 40 ± 0.5% inside the dryer and the air velocity inside solar dryer was negligible. The hot air dryer consisted of an air temperature electronic controller, an air blower, an electric heater, and a balance heater for increasing the temperature rapidly initially. The dryer was sustained at a relative humidity of 22.45 ± 0.64%, air velocity of 1.3 ± 0.16 m/s, and 60 °C temperature.

The dried samples were then rehydrated in a constant temperature water (EIE Instruments PVT LTD) bath having three heaters for attaining the desired temperature and an electronic proportional controller for controlling the temperature.

2.2. Instrumentation and measurements

Pyranometer (Delta OHM, Model: LP PYRA-03; Italy) was used for measuring solar radiation intensity, and the weight of samples was measured by an electronic weighing balance (Sartorius BSA 2202S, accuracy ± 0.01 g; Goettingen, Germany) was used for measuring weight. The air-flow rate and humidity inside the dryer were measured using a probe anemometer (AM-4213, Lutron, Taiwan) and a probe humidity meter (HT-

305, Lutron, Taiwan), respectively. A colorimeter (KONICA MINOLTA, Osaka, Japan) was used for measuring color and the texture was measured by a texture analyzer (Brookfield texture analyzer CT3 version 2.1, US).

2.3. Drying kinetics of apple slices

The moisture content of fresh apples was determined as 86.88 ± 1.59% (wb) by the oven drying method (AOAC 925.09, 2002). All the samples were dried until a constant weight of the samples was achieved (which was around a moisture content of less than 3% (wb))[17,18]. The samples were then cooled and kept in sealable low-density polythene pouches and were used for rehydration experiments at 30 and 50 °C temperatures afterward. The moisture content of dried samples has been converted to moisture ratio (MR) as follows[19]:

$$MR = \frac{M_e - M_t}{M_e - M_0} \quad (1)$$

where M_e, M_t, and M_0 are equilibrium moisture content (db), moisture content at any time during drying (db), and initial moisture content (db) of the sample, respectively.

2.4. Rehydration of dried apple slices

The HAD and DSD dried apple slices were rehydrated using a constant temperature water bath with solid to liquid ratio of 1:50. The dried samples were placed in petri dishes containing distilled water and kept inside the constant temperature water bath at temperatures of 30 °C and 50 °C. The sample weight was measured at every 15-min time interval until it reached the equilibrium moisture content. The blotting of samples was done with tissue paper to remove the surface water before measuring weight. The ability of the samples to imbibe water was quantified in terms of rehydration ratio and was calculated as follows[20]:

$$\text{Rehydration ratio} = \frac{\text{Weight of rehydrated sample (g)}}{\text{Weight of dried sample (g)}} \quad (2)$$

2.5. Modeling of rehydration kinetics

To describe the kinetics of the rehydration of Fuji apple slices, three empirical models were employed as given in **Table 1**. The moisture sorption curves for rehydration have been described by a non-exponential equation of the Peleg model for several types of commodities[21–24]. The constants k_1 (min kg d.m./kg water) and k_2 (kg d.m./kg water) are two parameters of Peleg's model. Weibull model as explained by Dr. Walodi Weibull represents the breaking strength distribution of the materials and it explains the working pattern of systems that have a degree of variability[25]. The constants α (dimensionless) and β (min) are two parameters of the Weibull model. For describing the mass transfer phenomenon of the process of rehydration, a first-order kinetic model (FOKM) was also considered to carry out the modeling[26], in which k_r represents the rate of rehydration (/min).

Table 1. Mathematical models applied to rehydration of Fuji apple slices.

Model name	Model
Peleg model	$M_t = M_0 + \frac{t}{k_1 + k_2 t}$
First order kinetic model (FOKM)	$\frac{M_e - M_t}{M_e - M_0} = e^{-k_r t}$
Weibull model	$\frac{M_t - M_0}{M_e - M_0} = 1 - e^{\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]}$

2.6. Assessment of rehydration indices

During rehydration, leaching of soluble solids from the cellular matrix of the sample leads to significant loss of minerals, amino acids, sugars, and vitamins[3,27]. Three indices were used for the estimation of the rehydration characteristics of dried foods[3], viz., rehydration ability (RA), dry matter holding capacity (DHC), and water absorption capacity (WAC). WAC as given in Equation (3) varies in the range from 0 to 1 and is the measure of the capability of the dried matrix to imbibe water for the water loss during the drying process[28].

$$\mathrm{WAC} = \frac{M_r(1 - S_r) - M_d(1 - S_d)}{M_0(1 - S_0) - M_d(1 - S_d)} \tag{3}$$

where M_r, M_d, and M_0 represent the mass of the rehydrated sample, dried sample, and fresh sample (before drying), respectively, and S_r, S_d, and S_0 represent the percentage dry matter content of the rehydrated sample, dried sample, and fresh sample, respectively.

DHC measures the capacity of the material to hold its soluble solids after rehydration and shows a clear indication of the amount of damage in the tissue of the materials during drying. DHC varies in the range of 0 to 1 and can be computed as follows[9]:

$$\mathrm{DHC} = \frac{M_r S_r}{M_d S_d} \tag{4}$$

Rehydration ability RA as given in Equation (5) is the measure of the capacity of the dried material to rehydrate by accounting for the capacity to absorb water and losses due to leaching of soluble solids and varies in the range of 0 to 1[9].

2.7. Color and texture measurements

$$\mathrm{RA} = \mathrm{WAC} \,.\, \mathrm{DHC} \tag{5}$$

Color is an important attribute essential for determining the quality of a product. Color measurements of rehydrated apple slices were done (Konica Minolta Colorimeter, Europe) in terms of overall color change (ΔE), chroma (C^*), and hue angle (h^*) in view of the basic color combination of lightness (L^*), redness (a^*), and yellowness indexes (b^*) as given in Equations (6)–(8)[29]:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{6}$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{7}$$

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{8}$$

where ΔL^*, Δa^* and Δb^* indicate the lightness, redness, and yellowness index changes of rehydrated slices with respect to fresh slices.

The textural characteristics of the rehydrated samples were measured in terms of chewiness and hardness using the texture analyzer (TA-XTplus, Stable Micro Systems Products). The measurement was performed at a constant speed of 1 mm s^{-1} using a 6 mm diameter cylindrical puncture probe.

2.8. Statistical analysis

The experiments were carried out in triplicates. The accuracy of different rehydration models was analyzed statistically using the root mean square error (RMSE), chi-square (χ^2), and coefficient of determination (R^2), as given in Equations (9)–(12)[30]. The experimental drying and rehydration data were analyzed using ANOVA. The significance of difference was determined by a one-factor analysis of variance ($p \leq 0.05$).

$$\mathrm{RMSE} = \frac{1}{n}\left[\sum_{i=1}^{n}(M_{\exp} - M_{\mathrm{pre}})^2\right]^{0.5} \tag{9}$$

$$\chi^2 = \sum_{i=1}^{n} \frac{(M_{exp} - M_{pre})^2}{M_{pre}} \tag{10}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left[M_{exp} - M_{pre}\right]^2}{\sum_{i=1}^{n} \left[M_{exp} - M_{mean}\right]^2} \tag{11}$$

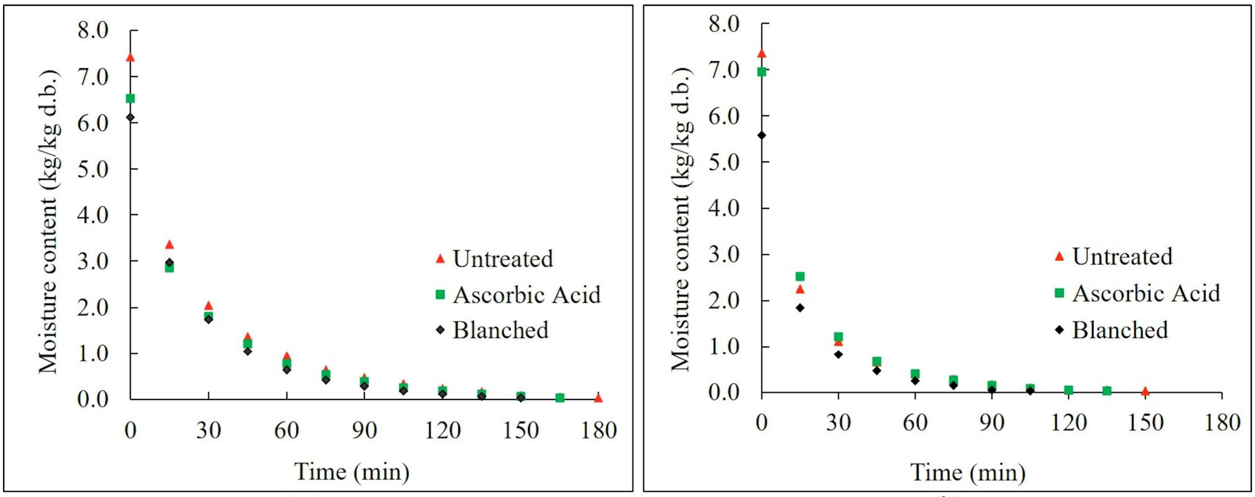
$$M_{mean} = \frac{\sum_{i=1}^{n} M_{exp}}{n} \tag{12}$$

where n is the number of experimental data points, and M_{pre} and M_{exp} are predicted and experimental values, respectively. The best-fit model was considered based on the least χ^2 and RMSE, and highest R^2 values.

3. Results and discussion

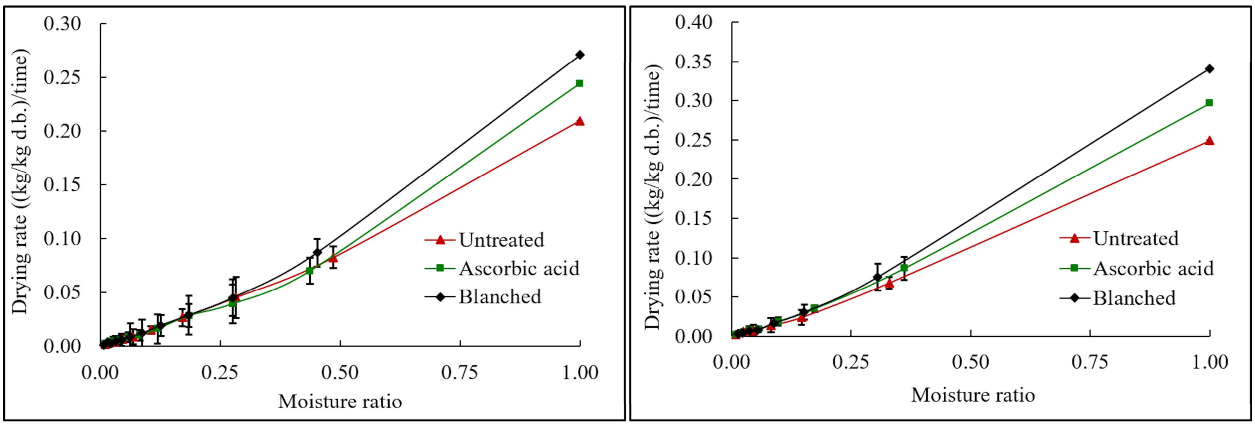
3.1. Drying kinetics of apple slices

Figure 1 shows the drying kinetics of un-treated and pre-treated apple slices dried in DSD and HAD, respectively. **Figure 2** represents the variation in the rate of drying as a function of the moisture ratio of DSD and HAD samples. It could be noticed that the moisture content of the samples decreased with time and the constant rate drying period was not detected. The falling period range involves the entire drying process. A similar type of result was concluded by Doymaz[16] in apple slices during the hot-air drying. It can also be



(a) (b)

Figure 1. Drying kinetics of un-treated and pre-treated Fuji apple slices dried in (a) direct solar dryer and (b) hot air dryer.



(a) (b)

Figure 2. Variation in drying rate as a function of moisture ratio (a) direct solar dryer and (b) hot air dryer.

noticed that the various pre-treatments had a notable effect on the drying time of apple slices as the blanched samples dried faster (105 min for HAD and 150 min for DSD) than the ones which are un-treated (150 min for HAD and 180 min for DSD) and pre-treated with ascorbic acid (135 min for HAD and 165 min for DSD) in both HAD and DSD samples. The blanched, ascorbic acid pre-treated, and un-treated samples took 105, 135, and 150 min, respectively in HAD and a slightly longer time of 150, 165, and 180 min, respectively in DSD to obtain the anticipated moisture content. The reason behind this is that solar drying works on the principle of natural convection and so it takes a little longer time to dry a particular product as compared to hot air drying which is based upon the principle of forced convection (and hence takes less time).

3.2. Rehydration kinetics

3.2.1. Rehydration kinetics of DSD and HAD apple slices

The rehydration kinetics of blanched, ascorbic acid pre-treated, and un-treated solar dried and hot air-dried apple slices at 30 and 50 °C, respectively are shown in **Figure 3**. In terms of final EMC attained at the end of the rehydration process, blanched samples attained the highest moisture content (3.61 and 3.79 kg/kg d.b. at 30 and 50 °C, respectively for HAD samples and 3.73 and 4.09 kg/kg d.b. at 30 and 50 °C for DSD samples), followed by ascorbic acid pre-treated (3.10 and 3.41 kg/kg d.b. at 30 and 50 °C, respectively for HAD samples and 3.33 and 3.62 kg/kg d.b. at 30 and 50 °C for DSD samples) and un-treated samples (2.79 and 2.98 kg/kg d.b. at 30 and 50 °C, respectively for HAD samples and 3.01 and 3.21 kg/kg d.b. at 30 and 50 °C for DSD samples). This trend was obtained for samples rehydrated at both 30 and 50 °C rehydration temperatures. In terms of time taken for the samples to attain EMC, blanched samples took a long time (180 min and 165 min at 30 and 50 °C for HAD samples and 195 min and 180 min at 30 and 50 °C for DSD samples, respectively) as compared to ascorbic acid pre-treated (165 min and 135 min at 30 and 50 °C for HAD samples

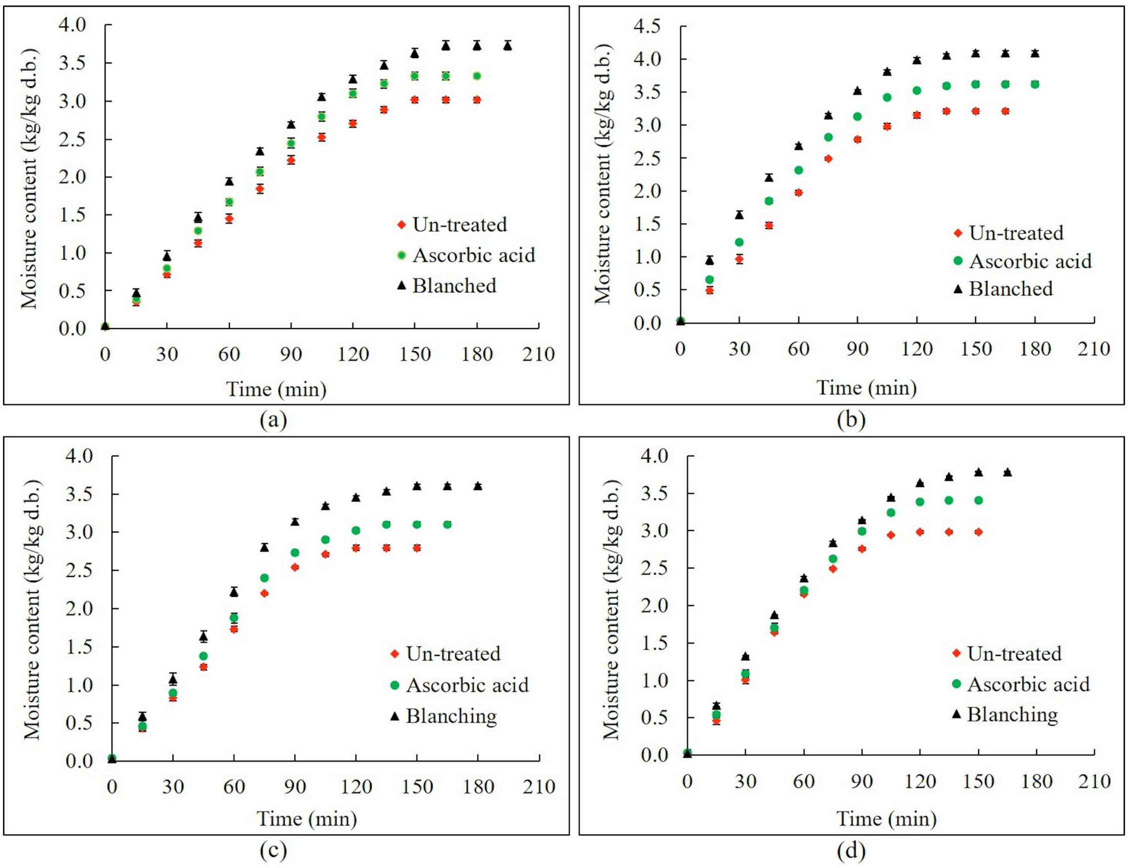


Figure 3. Rehydration kinetics of solar dried (a) and (b) and hot air-dried (c) and (d) apple slices rehydrated at 30 °C and 50 °C, respectively.

and 180 min and 150 min at 30 and 50 °C for DSD samples, respectively) and un-treated samples (150 min and 120 min at 30 and 50 °C for HAD samples and 165 min and 135 min at 30 and 50 °C for DSD samples, respectively) for both the rehydration temperatures. It can also be observed that each of the samples rehydrated at 50 °C attained higher moisture content (3.79, 3.41 and 2.98 kg/kg d.b. for blanched, ascorbic acid treated, un-treated HAD samples and 4.09, 3.62 and 3.21 kg/kg d.b. for blanched, ascorbic acid treated, un-treated DSD samples, respectively) than those at 30 °C (3.61, 3.10 and 2.79 kg/kg d.b. for blanched, ascorbic acid treated, un-treated HAD samples and 3.73, 3.33 and 3.01 kg/kg d.b. for blanched, ascorbic acid treated, un-treated DSD samples, respectively). The reason behind this could be the more swelling of the cellular matrix in a shorter time interval with an increase in rehydration temperature. Thus, it could be concluded that the water absorption rate of dried slices increased with rehydration at higher temperatures because of the rate of increment in diffusion of water[9]. The blanched slices showed 10.72% and 19.30% higher water absorption capacity than ascorbic acid pre-treated and un-treated samples, respectively at 30 °C and 11.49% and 21.51%, respectively at 50 °C.

A similar tendency was obtained as in the case of DSD apple slices and the blanched samples were reported to attain higher final EMC than the ascorbic acid-treated and un-treated samples for both the rehydration temperatures. Each of the rehydrated samples at 50 °C gained higher final equilibrium moisture content in a shorter time as compared to the samples rehydrated at 30 °C. The blanched sample was observed to be superior in terms of higher water absorption capacity, i.e., 14.12% and 22.71% more at 30 °C, and, 10.02% and 21.37% more at 50 °C than the ascorbic acid pre-treated and un-treated samples, respectively.

3.2.2. Rehydration ratio of DSD and HAD apple slices

Figure 4 represents the variation of the rehydration ratio of solar-dried and hot-air dried slices with time at 30 and 50 °C, respectively. It can be depicted that blanched samples (4.12 at 30 °C and 4.33 at 50 °C for

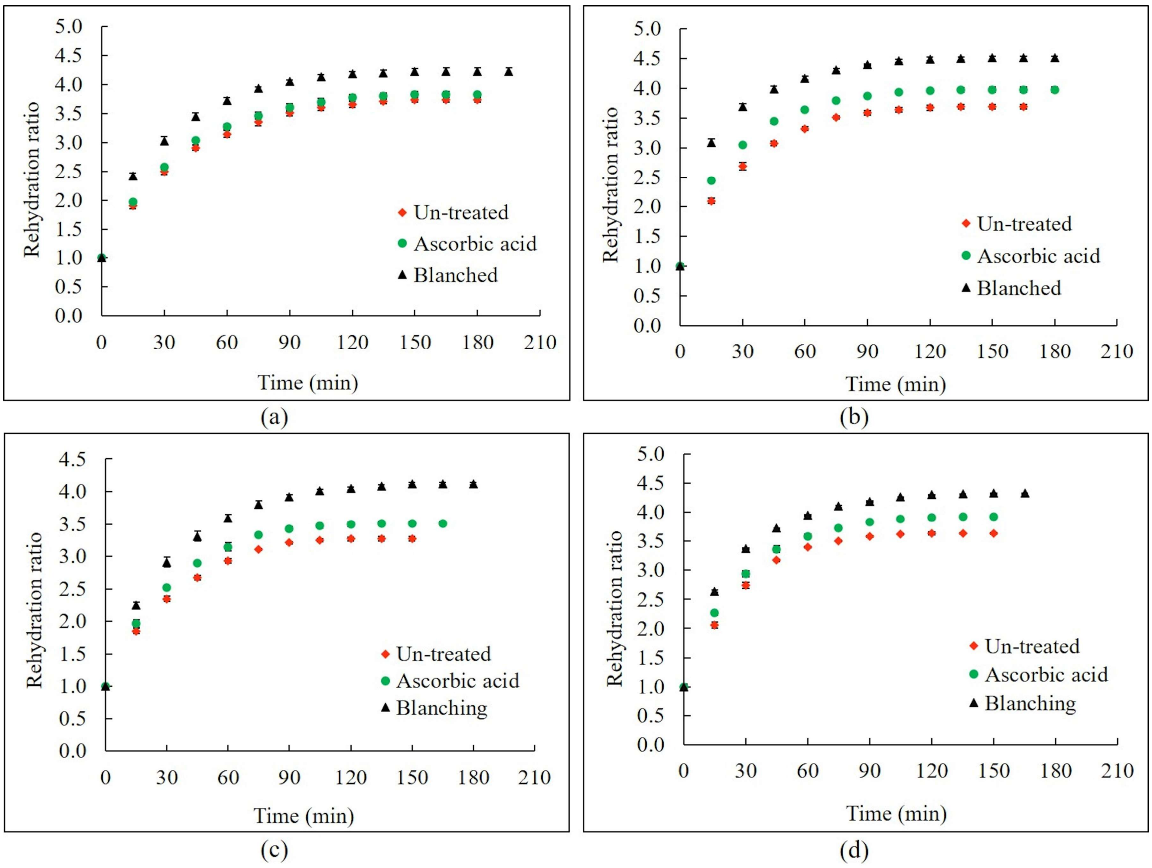


Figure 4. Variation of rehydration ratio of solar dried (a) and (b) and hot air-dried (c) and (d) apple slices rehydrated at 30 °C and 50 °C, respectively.

HAD samples and 4.23 at 30 °C and 4.51 at 50 °C for DSD samples) attained a higher rehydration ratio than ascorbic acid pre-treated (3.51 at 30 °C and 3.92 at 50 °C for HAD samples and 3.83 at 30 °C and 3.98 at 50 °C for DSD samples) and un-treated samples (3.27 at 30 °C and 3.64 at 50 °C for HAD samples and 3.69 at 30 °C and 3.74 at 50 °C for DSD samples). This may be because of the loosening of the cellular matrix due to blanching hydro-thermal treatment thereby increasing the overall size of pores which aided in reducing drying time and increased water uptake while rehydration. Ascorbic acid treatment on the other hand can be considered as a surface phenomenon (in comparison to blanching which is a bulk phenomenon), which when applied to the samples creates partial osmosis because of which water comes out from the matrix thus widening the pores due to osmotic pressure difference. Since the ascorbic acid treatment only resulted in a widening of the surface pores, it follows that the ascorbic acid-treated samples had a lower equilibrium moisture content than the blanched ones. Instead, the low number of enlarged pores in un-treated samples meant that they could not absorb more water throughout the rehydration procedure.

3.2.3. Comparison between rehydration characteristics of DSD and HAD apple slices

The rehydration kinetics of DSD and HAD blanched samples for the two different rehydration temperatures and the variation of rehydration ratio with time for the same have been shown in **Figure 5**. The figure depicted that both HAD and DSD blanched samples, showed maximum water absorption capability for the two rehydration temperatures (3.73 kg/kg d.b. at 30°C, 4.09 kg/kg d.b. at 50 °C for DSD blanched samples and 3.61 kg/kg d.b. at 30 °C, 3.79 kg/kg d.b. at 50 °C for HAD blanched samples). The rehydration ratio is the usual expression of the rehydration ability of dried apple slices[11], therefore the optimization of the rehydration process was done based on the rehydration ratio of HAD and DSD samples. Samples that achieved higher rehydration capacity among all other samples, i.e., blanched HAD and DSD samples for both the rehydration temperatures have been selected for further analysis. From these figures, it could be anticipated that with an increment in the rehydration temperature, there is a significant increase in the water absorption capability for both DSD (3.73 to 4.09 kg/kg d.b.) and HAD (3.61 to 3.79 kg/kg d.b.) blanched samples. **Figure 6** represents the variation in rehydration kinetics of DSD and HAD blanched samples at 30 and 50 °C, respectively. It could be deduced that for both the rehydration temperatures, DSD blanched slices gained higher EMC (3.73 and 4.09 at 30 and 50 °C, respectively) as compared to HAD blanched samples (3.61 and 3.79 at 30 and 50 °C respectively). The reason behind this could be the more structural disruption in HAD samples making them less efficient in attaining higher EMC as compared to DSD samples as the latter is based on the concept of natural convection where the samples are subjected to the natural flow of hot air, whereas in a HAD, the air is circulated by blower and forced convection prevails. Since DSD samples suffered less cellular damage, they were able to soak up more water for a longer period of time, which may have contributed to the longer time required to reach the EMC.

3.3. Rehydration indices

The values of water absorption capacity, dry matter holding capacity, and rehydration ability of DSD and HAD blanched samples rehydrated at 30 and 50 °C have been given in **Table 2**. It is observed from the table that the DSD apple slices have higher water absorption capacity (0.592 and 0.658, at 30 and 50 °C, respectively) than HAD samples (0.577 and 0.632 at 30 and 50 °C, respectively) for both the rehydration temperatures. Also, DSD samples have been found to possess more dry matter holding capacity (0.300 and 0.286 at 30 and 50 °C, respectively) because of minimum cellular damage while drying due to which samples tend to absorb more water and also retain more soluble solids as compared to HAD samples (0.259 and 0.246 at 30 and 50 °C, respectively). It can be seen from the table that with an increase in rehydration temperature, dry matter holding capacity value decreases. This is because, with an increase in soaking temperature, the cellular matrix of apple slices widens up much faster, which ultimately leads to more flux of soluble solids coming out from the samples to the rehydrating solution causing a decrease in dry matter holding capacity. The higher dry matter holding capacity values of DSD samples mean that the samples will be high in nutrient content as compared

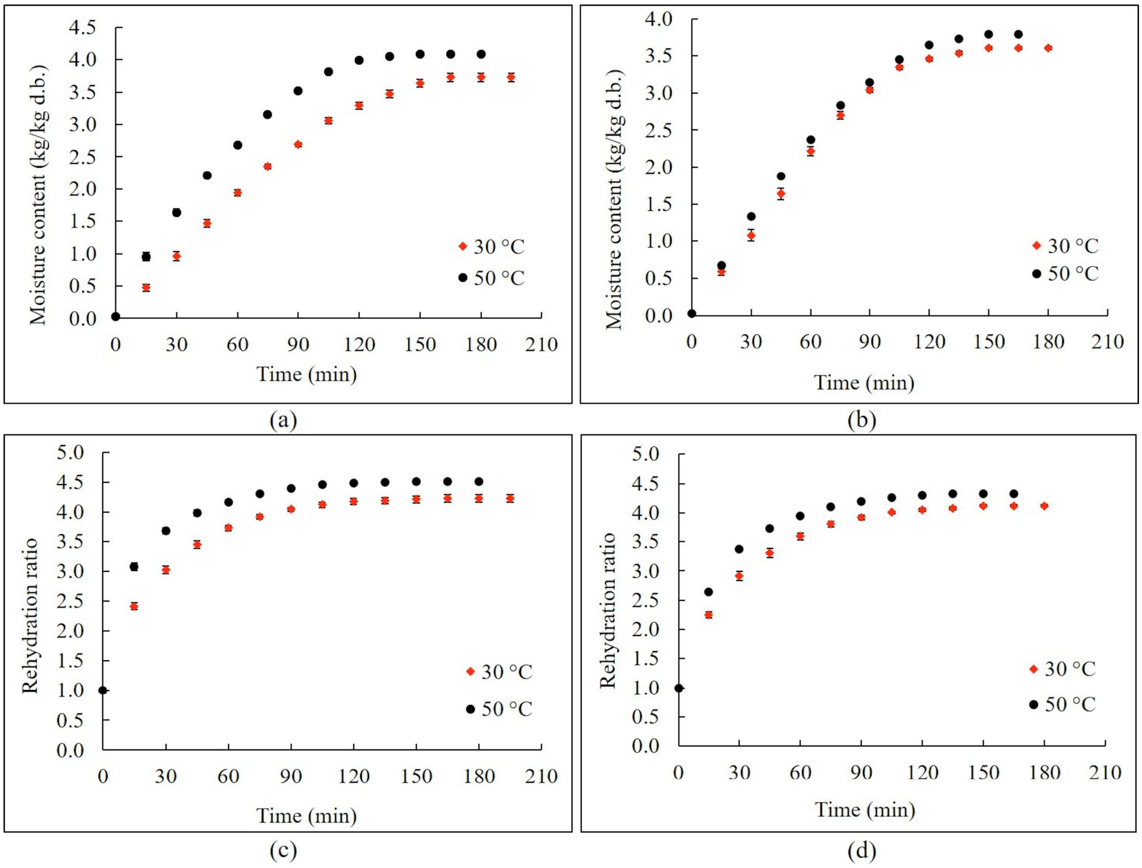


Figure 5. Rehydration kinetics (a) and (b) and rehydration ratio (c) and (d) of blanched samples dried in direct solar dryer (a) and (c) and hot air dryer (b) and (d) at 30 °C and 50 °C.

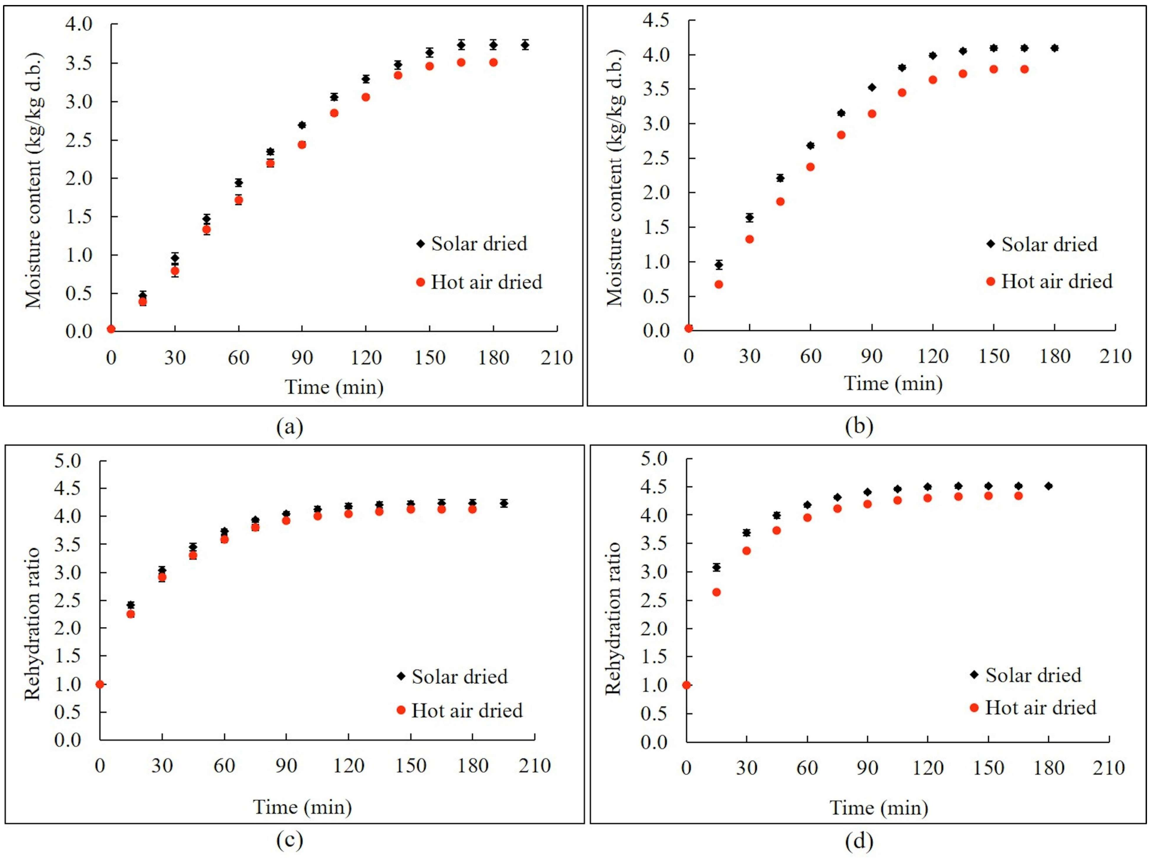


Figure 6. Variation in rehydration kinetics (a) and (b) and rehydration ratio (c) and (d) of direct solar dryer and hot air dryer blanched samples rehydrated at 30 °C and 50 °C, respectively.

Table 2. Rehydration indices of hot air dried and solar dried blanched Fuji apple slices rehydrated at 30 °C and 50 °C.

Rehydration temperature (°C)	Drying technique	WAC	DHC	RA
30	SD	0.592 ± 0.027[bc]	0.300 ± 0.011[a]	0.178 ± 0.009[ab]
	HAD	0.577 ± 0.006[cd]	0.259 ± 0.009[b]	0.150 ± 0.007[cd]
50	SD	0.658 ± 0.027[a]	0.286 ± 0.010[a]	0.189 ± 0.014[a]
	HAD	0.632 ± 0.018[ab]	0.246 ± 0.019[bc]	0.155 ± 0.011[c]

[a,b,c,d]: Values in the same column with different letters represents significant difference ($p \leq 0.05$).

to HAD samples. The overall rehydration ability values were found to be higher for DSD blanched samples (0.178 and 0.189 at 30 and 50 °C, respectively) as compared to HAD blanched samples (0.150 and 0.155 at 30 and 50 °C, respectively) for both the rehydration temperatures.

3.4. Modeling of rehydration kinetics

Table 3 shows the values of various constants of Peleg's model, first-order kinetic model (FOKM), and Weibull model along with some other statistical parameters. For Peleg's model, the values of both k_1 (20.638 to 10.728 for DSD samples and 15.696 to 13.369 for HAD samples) and k_2 (1.218 to 1.193 for DSD samples and 1.221 to 1.215 for HAD samples) were found to decrease with an increase in rehydration temperature. This trend was found to be the same for both DSD and HAD samples. As the values of k_1 decreased with the temperature increment (from 20.638 at 30 °C to 10.728 at 50 °C for DSD samples and from 15.696 at 30 °C to 13.369 at 50 °C for HAD samples) at initial moisture content, therefore, the water transfer increased with an increase in temperature. Analogous results were explained for different products by researchers with regard to the rehydration[23,31–33]. Values of k_2 were also found to decrease with temperature (from 1.218 at 30 °C to 1.193 at 50 °C for DSD samples and from 1.221 at 30 °C to 1.215 at 50 °C for HAD samples), indicating that water absorption capacity increase with temperature. In the case of the first-order kinetic model, the parameter k_r is found to be decreasing with an increment in rehydration temperature for both DSD (0.043 to 0.032) and HAD (0.040 to 0.039) apple slices. This decrease in the model parameter indicates an increment in the capacity to absorb water with an increase in rehydration temperature. This result is in accordance with other researches during the rehydration modeling of cassava chips[34]. Weibull model parameters also showed a similar trend and both the parameters, i.e., α (0.983 to 0.928 for DSD samples and 1.013 to 0.904 for HAD samples) and β (32.379 to 21.758 for DSD samples and 27.015 to 23.939 for HAD samples) were found to decrease with an increase in rehydration temperature. The drop in the parameters clearly explains the increment in the capacity of apple slices to absorb water with an increase in rehydration temperatures.

Table 3. Statistical parameters of modeling of rehydration kinetics of apple slices.

Model	Rehydration Temperature (°C)	Product	k_1	k_2	k_r	α	β	R^2	RMSE	χ^2
Peleg	30	SD	20.638	1.193	-	-	-	0.9833	0.0088	0.0319
		HAD	15.696	1.221	-	-	-	0.9762	0.0104	0.0341
	50	SD	10.728	1.218	-	-	-	0.9793	0.0095	0.0269
		HAD	13.369	1.215	-	-	-	0.9823	0.0096	0.0249
FOKM	30	SD	-	-	0.032	-	-	0.9989	0.0023	0.0015
		HAD	-	-	0.039	-	-	0.9962	0.0042	0.0048
	50	SD	-	-	0.043	-	-	0.9959	0.0042	0.0062
		HAD	-	-	0.039	-	-	0.9970	0.0039	0.0049
Weibull	30	SD	-	-	-	0.983	32.379	0.9994	0.0015	0.0008
		HAD	-	-	-	1.013	27.015	0.9977	0.0029	0.0031
	50	SD	-	-	-	0.928	21.758	0.9985	0.0023	0.0015
		HAD	-	-	-	0.904	23.939	0.9993	0.0017	0.0007

The variation in experimental v/s predicted moisture content of Peleg's model, FOKM model, and Weibull model as attained from the solar dried and hot air-dried slices rehydrated at 30 °C and 50 °C have been depicted in **Figure 7** and **Figure 8**, respectively. For the Peleg model, the value of R^2 was above 0.9762, and RMSE and χ^2 values were below 0.0104 and 0.0249, respectively for the rehydration of DSD and HAD samples. For the FOKM model, the value of R^2 was above 0.9959, and RMSE and χ^2 values were below 0.0042 and 0.0062, respectively. The results displayed that the Weibull model has the maximum R^2 values above 0.9977 and minimum RMSE and χ^2 values below 0.0029 and 0.0031, of the three mathematical models which have been applied to the rehydration kinetics of Fuji apple slices. The rehydration kinetics of Fuji apple slices dried in both sun and hot air dryers are best described by the Weibull model, which was found to be the best fit.

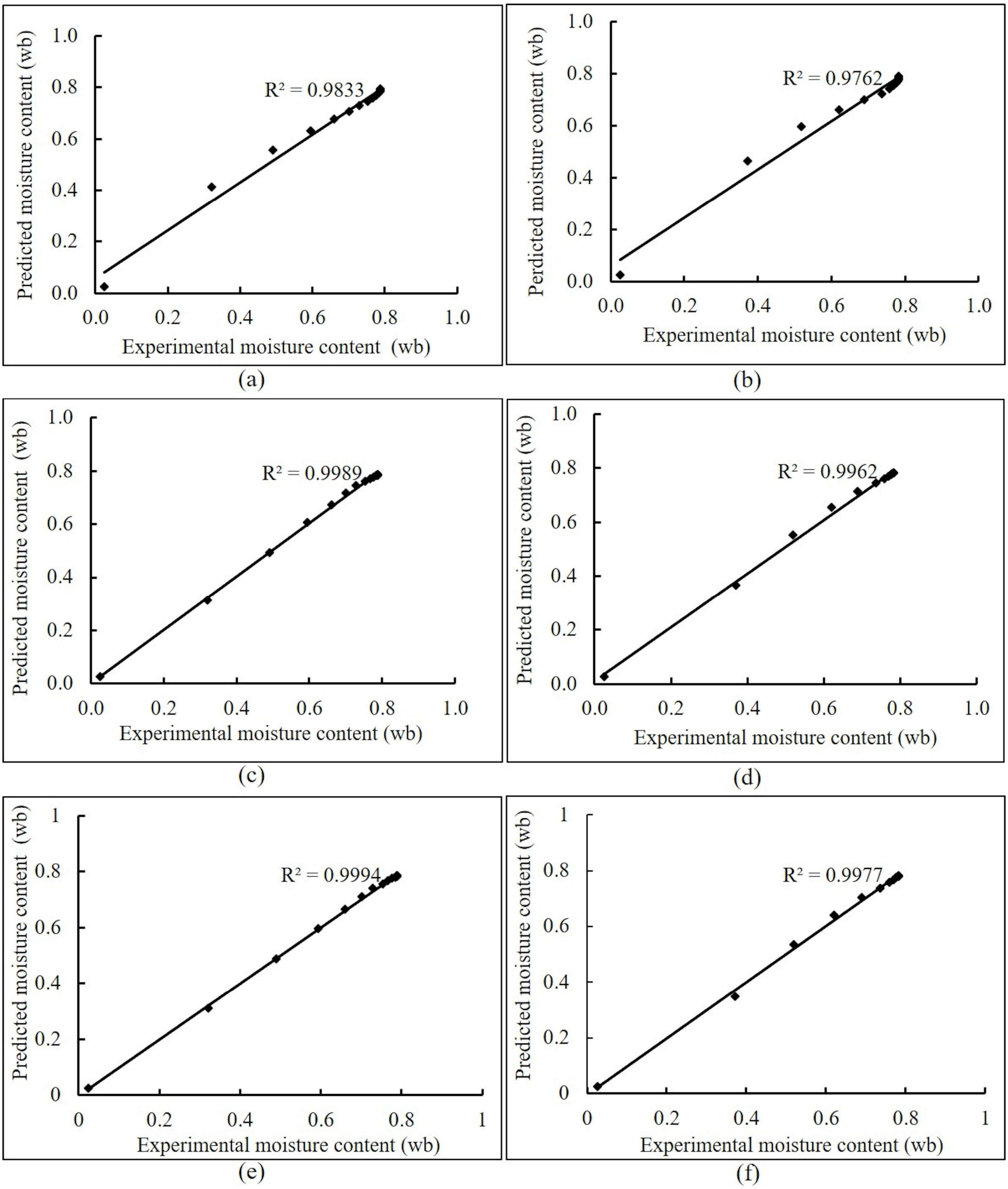


Figure 7. Variation in experimental v/s predicted moisture content of Peleg's model (a) and (b), First order kinetic model (c) and (d) and Weibull model (e) and (f), respectively as obtained from solar dried and hot air dried sample rehydrated at 30 °C.

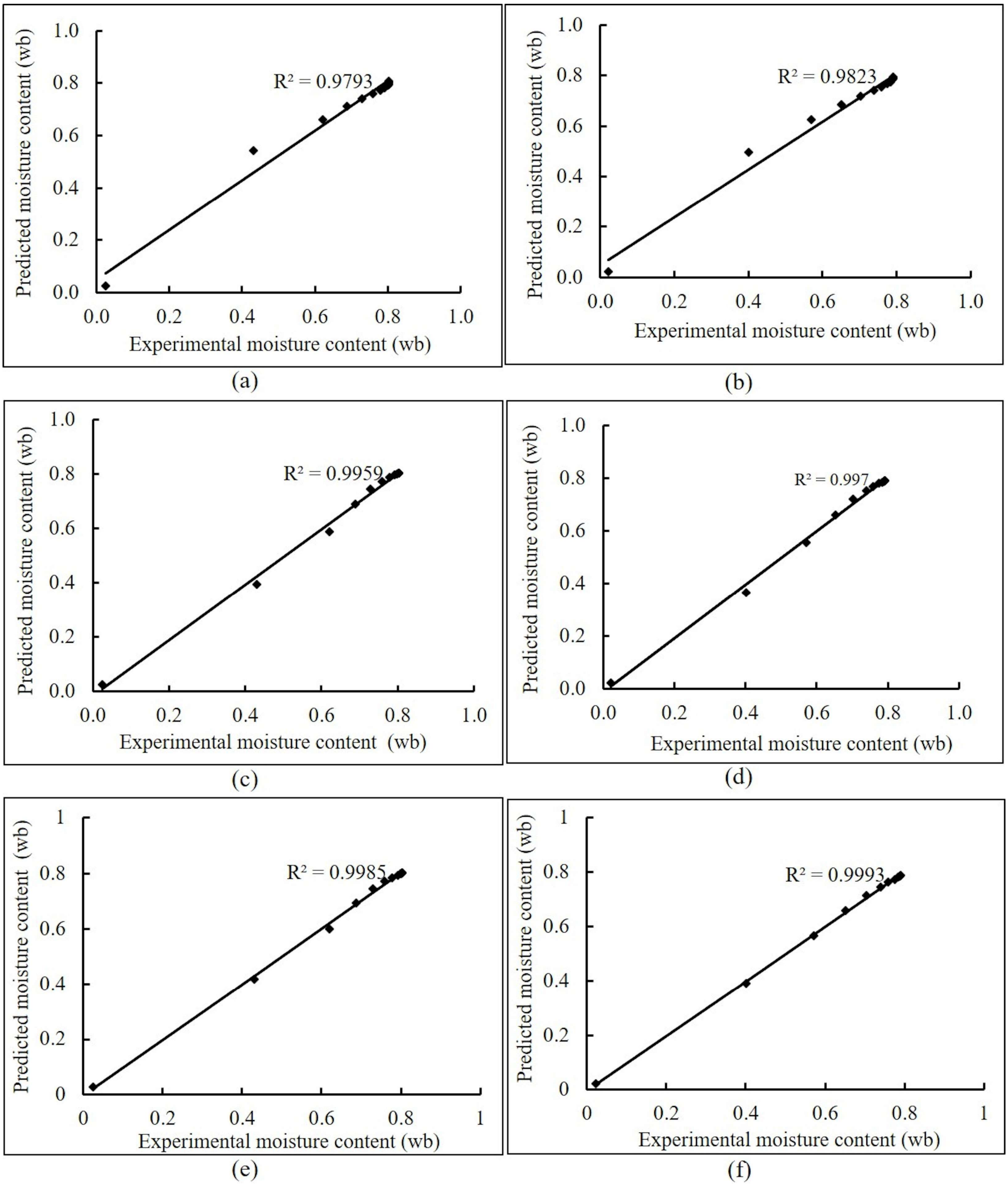


Figure 8. Variation in experimental v/s predicted moisture content of Peleg's model (a) and (b), First order kinetic model (c) and (d) and Weibull model (e) and (f), respectively as obtained from solar dried and hot air dried sample rehydrated at 50 °C.

3.5. Color and texture measurements

The various color indices of rehydrated apple slices that have been measured are listed in **Table 4**. The rehydrated HAD samples were found to retain more colors than those of DSD samples in terms of lower ΔE and higher C* and h*. The reason behind this can be the direct exposure of the sample during drying in DSD while HAD samples were dried using hot air only at indoor conditions. For samples that were rehydrated at 30°C, the ΔE, C* and h* values were 13.288, 15.870, and 89.517 for DSD samples and 11.884, 32.990 and 95.577 for HAD samples, respectively. Similarly, the values of ΔE, C* and h* for samples rehydrated at 50 °C were 19.636, 13.707, and 66.720 for DSD and 16.141, 18.750 and 88.057 for HAD apple slices, respectively.

All these results indicate that HAD samples upon rehydration retained more color than DSD samples which is in line with the results found by previous researchers[7].

Table 4. Color indices of rehydrated Fuji apple slices.

Color indices	**Rehydration temperature (°C)**			
	30		**50**	
	SD	**HAD**	**SD**	**HAD**
L*	67.800 ± 1.19^{b}	72.123 ± 1.98^{a}	62.100 ± 2.07^{cd}	62.263 ± 1.28^{c}
a*	0.020 ± 0.96^{b}	–3.173 ± 1.01^{a}	5.343 ± 1.04^{d}	0.573 ± 1.72^{bc}
b*	15.853 ± 3.05^{bc}	32.820 ± 2.15^{a}	12.563 ± 1.33^{cd}	18.687 ± 1.16^{b}
ΔE	13.288 ± 2.68^{ab}	11.884 ± 0.94^{a}	19.636 ± 2.64^{cd}	16.141 ± 1.72^{bc}
c*	15.870 ± 3.06^{bc}	32.990 ± 2.09^{a}	13.707 ± 0.83^{c}	18.750 ± 1.15^{b}
h*	89.517 ± 3.23^{b}	95.577 ± 1.93^{a}	66.720 ± 6.14^{c}	88.057 ± 5.18^{b}

^{a,b,c,d}: Values in the same row with different letters represents significant difference ($p \leq 0.05$).

The hardness and chewiness of rehydrated apple slices dried in DSD and HAD have been represented in **Table 5**. It was seen that the required force to break the samples rehydrated at 30 °C was 15.087 N and 13.467 N for DSD and HAD samples, respectively. Similarly, the force required to break the samples rehydrated at 50 °C was 14.547 N and 13.323 N for DSD and HAD samples, respectively. Therefore, it can be deduced that for both the rehydration temperatures, the hardness of DSD apple slices was seen to be more than HAD apple slices. This trend might be because upon rehydration DSD apple slices had more dry matter holding capacity values than HAD apple slices. The presence of more dry matter led to more hardness in DSD apple slices. The chewiness value for the DSD apple slices was also seen to be higher than that of HAD slices which indicates a better mouth feel. The DSD and HAD rehydrated samples have chewiness values of 7.033 mJ and 4.333 mJ at 30 °C and 5.433 mJ and 4.133 mJ at 50 °C, respectively. This indicates that the DSD apple slices were better in terms of texture as compared to the HAD apple slices. The decrease in the values of both hardness and chewiness with increasing rehydration temperature is due to more leaching with an increase in rehydration temperature, as a result, more soluble solids tend to move out from the sample matrix.

Table 5. Textural properties of rehydrated Fuji apple slices.

Rehydration temperature (°C)	**Samples**	**Hardness (N)**	**Chewiness (mJ)**
30	SD	15.087 ± 2.29^{a}	7.033 ± 1.01^{a}
	HAD	13.467 ± 1.09^{ab}	4.333 ± 3.69^{ab}
50	SD	14.547 ± 3.79^{abc}	5.433 ± 2.25^{abcd}
	HAD	13.323 ± 0.84^{a}	4.133 ± 2.71^{abc}

^{a,b,c,d}: Values in the same column with different letters represents significant difference ($p \leq 0.05$).

4. Conclusions

The current research showed a significant effect on the drying time, rehydration ability, color retention, and texture of Fuji apple slices due to the selection of pre-treatments before drying along with different drying methods. The HAD samples have dried faster than DSD samples because of faster moisture removal due to forced convection. The DSD samples on the other hand suffered less structural damage while drying and hence they attained more equilibrium moisture content at the end of the process of rehydration as compared to HAD samples. Additionally, DSD samples had better dry matter holding capacity values (0.300 and 0.286 at 30 and 50 °C, respectively) indicating more retention of soluble solids (nutrients). Rehydrated DSD samples having been dried under direct sunlight were found to lose color properties significantly as compared to rehydrated HAD samples in terms of overall color change ΔE. Because of having higher dry matter holding capacity values, DSD samples were found to have higher hardness (15.087 N, 14.547 N at 30 and 50 °C, respectively) and chewiness (7.033 mJ, 5.433 mJ at 30 and 50 °C, respectively) values which are an indication of better mouth feel. Considering all the above results, it can be concluded that DSD samples were found to have better rehydration characteristics and quality parameters (except color) as compared to HAD samples.

Author contributions

Conceptualization, DD and KD; methodology, DD and KD; validation, DD and KD; formal analysis, DD and KD; investigation, DD and KD; resources, DD; data curation, DD and KD; writing—original draft preparation, DD and KD; writing—review and editing, KD; supervision, PPT; project administration, PPT; funding acquisition, PPT. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no competing interests.

Abbreviations

ANOVA: Analysis of variance

d.m.: Dry matter

db: Dry basis

DHC: Dry matter holding capacity

EMC: Equilibrium moisture content

FOKM: First order kinetic model

HAD: Hot air dried

k_1: Coefficient in Peleg model (min kg d.m./kg water)

k_2: Coefficient in Peleg model (kg d.m./kg water)

k_r: Rehydration rate of first order kinetic model (FOKM) (/min)

MR: Moisture ratio

RA: Rehydration ability

RR: Rehydration ratio

DSD: Solar dried

WAC: Water absorption capacity

wb: Wet basis

α: Shape parameter of Weibull model

β: Scale parameter of Weibull model (min)

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