

RESEARCH ARTICLE

Thin layer drying kinetics and quality dynamics of persimmon (*Diospyros kaki*) treated with preservatives and solar dried under different temperatures

Abdul Khaliq^{1,2}, Wen-Fang Li¹, Shahbaz Ali^{3*}, Syed Tanveer Shah^{4,5*}, Zong-Huan Ma¹, Juan Mao¹, Yasir Niaz³, Bai-Hong Chen^{1*}, Inzamam Ul Haq⁴, Rashid Al-Yahyai^{5,6}, Mohamed A. A. Ahmed⁷, Abdullah Ahmed Al-Ghamdi⁸, Mohamed S. Elshikh⁸, Ali Tan Kee Zuan^{9*}

1 College of Horticulture, Gansu Agricultural University, Lanzhou, China, **2** Department of Horticulture, The University of Agriculture Peshawar, Peshawar, Pakistan, **3** Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Punjab, Pakistan, **4** Department of Plant Protection, College of Crop Protection, Gansu Agricultural University, Lanzhou, China, **5** Department of Plant Sciences, College of Agricultural and Marine Sciences, Sultan Qaboos University, Muscat, Oman, **6** Department of Crop Science, University of Reading, Reading, United Kingdom, **7** Plant Production Department (Horticulture—Medicinal and Aromatic Plants), Faculty of Agriculture (Saba Basha), Alexandria University, Alexandria, Egypt, **8** Department of Botany and Microbiology, College of Science, King Saud University, Riyadh, Saudi Arabia, **9** Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, UPM Serdang, Selangor, Malaysia

* tanweersyed@gmail.com (STS); shahbaz@kfueit.edu.pk (SA); bhch@gsau.edu.cn (BHC); tkz@upm.edu.my (ATKZ)

Abstract

Poor postharvest handling, microbial infestation, and high respiration rate are some the factors are responsible for poor storage life of perishable commodities. Therefore, effective preservation of these commodities is needed to lower the damages and extend shelf life. Preservation is regarded as the action taken to maintain desired properties of a perishable commodity as long as possible. Persimmon (*Diospyros kaki*) is perishable fruit with high nutritive value; however, has very short shelf-life. Therefore, effective preservation and drying is needed to extend its storage life. Drying temperature and preservatives significantly influence the quality of perishable vegetables and fruits during drying. The current study investigated the effect of different temperatures and preservatives on drying kinetics and organoleptic quality attributes of persimmon. Persimmon fruits were treated with preservatives (25% honey, 25% aloe vera, 2% sodium benzoate, 1% potassium metabisulfite, and 2% citric acid solutions) under different drying temperatures (40, 45, and 50°C). All observed parameters were significantly affected by individual effects of temperatures and preservatives, except ash contents. Similarly, interactive effects were significant for all parameters except total soluble sugars, ash contents, and vitamin C. Generally, fruits treated with citric acid and dried under 50°C had 8.2% moisture loss hour⁻¹, 14.9 drying hours, 0.030 g H₂O g⁻¹ hr⁻¹, 1.23° Brix of total soluble solids, 6.71 pH, 1.35% acidity, and 6.3 mg vitamin C. These values were better than the rest of the preservatives and drying temperatures used in the study. Therefore, treating fruits with citric acid and drying at 50°C was found a promising



OPEN ACCESS

Citation: Khaliq A, Li W-F, Ali S, Shah ST, Ma Z-H, Mao J, et al. (2022) Thin layer drying kinetics and quality dynamics of persimmon (*Diospyros kaki*) treated with preservatives and solar dried under different temperatures. PLoS ONE 17(3): e0265111. <https://doi.org/10.1371/journal.pone.0265111>

Editor: Ansar Hussain, Ghazi University, PAKISTAN

Received: December 9, 2021

Accepted: February 23, 2022

Published: March 30, 2022

Copyright: © 2022 Khaliq et al. Except for Fig 1, is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All relevant data are within the paper and [Supporting Information](#) files.

Funding: The current study was partially supported by University of Agriculture, Peshawar, Pakistan. The authors extend their appreciation to the Researchers Supporting Project number (RSP2022R483), King Saud University, Riyadh, Saudi Arabia. There was no additional external funding received for this study. The funders provided support in the form of salaries for authors AK, STS, AAA and MSE but did not have any

additional role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The specific roles of these authors are articulated in the 'author contributions' section.

Competing interests: The authors have declared that no competing interests exist.

technique to extend storage life of persimmon fruits. It is recommended that persimmon fruits dried at 50°C and preserved in citric acid can be used for longer storage period.

Introduction

Persimmon (*Diospyros kaki*) belonging to Ebenaceae family is dicot and astringent fruit with higher flavonoid and lycopene contents, and antioxidant properties [1, 2]. This fruit neutralizes the adverse impacts of free radicals responsible for numerous degenerative diseases (i.e., cancer, Parkinson's disease, vision loss, and pre-mature ageing), enhances the immune system, and reduces cholesterol [3, 4]. It is highly nutritive with 81.32 g water, 0.19 g fat, 0.6 g protein of 15.2 g carbohydrate, and 70 Kcal energy in 100 g serving [5–7]. Since persimmon fruits have a very short shelf-life, they are dried and preserved for future consumption [4, 8]. The dried persimmon are tasty, full of nutrients and have increased demand due to odour, taste, texture, and medicinal importance [9, 10]. However, dried persimmon is affected by the presence of aflatoxins that are generally produced by a fungus [11]. In addition, vitamin-C content in persimmon is significantly decreased if the fruits are dried under higher temperature for longer time interval [12]. Water contents evaporate from fruits and vegetables during drying process, which enhances quality and extends storage life [10, 13]. Moreover, storage space is saved due to reduced food size, and dried fruits are sweeter because of concentrated sugars, and bear better flavour and aroma due to good texture [9, 14]. Persimmon fruits are preserved for future use due to shorter shelf-life and dried persimmon have good quality [15, 16].

Dehydration under sun is one of the most ancient and valuable technique for drying persimmon fruits [2]; however, it is unhygienic with drying time extended to few weeks under uncontrolled humidity [17]. The successful dehydration process depends on a slow and steady heat supply to guarantee uniform drying [10]. Modern and sophisticated drying techniques are either oven drying [18, 19] or solar drying by solar air heaters [20–22]. Commercially, solar drying is carried out for drying of persimmon, which results in extended shelf-life [23], reduced microbial attack [17], better quality, and constant nutritional attributes [9, 24]. Air temperature used during drying process is one of the major issues affecting drying rate. Excessively high temperature during drying can damage the product, or create an undesirable situation of 'case hardening'. Furthermore, beneficial properties of chemical components are either completely destroyed or substantially reduced under higher temperature. Therefore, limits should be imposed on drying temperatures for most food products. Hanif et al. [11] and Senadeera et al. [23] reported that increased slice thickness and decrease in drying temperature affect vitamin C in persimmon fruit. They concluded that persimmon must be dried at a temperature below 50°C with 1.0 cm slice thickness for higher vitamin C contents.

Another study reported that increased drying temperature resulted in decreased fungus contamination up to 22.1%, and honey performed better than aloe vera gel to reduce aflatoxins in dried fruits [12]. Similarly, exogenous application of 10.0% persimmon peel extract helped in maintaining nutritional cum mineral composition of persimmon fruits. Moreover, peel extract could effectively maintain nutritional value compared to commercially available synthetic preservatives [9, 25]. Bolek and Obuz [3] treated fruit samples with sodium metabisulfite before drying, then dried at different temperatures and found the highest re-hydration amount and ascorbic acid at 50°C. Moreover, control treatments had the utmost activity of mesophilic aerobic bacteria during storage, while treated samples had the lowest activity of these bacteria, suggesting antimicrobial effects of sodium metabisulfite. Another study reported that

blanching time and drying temperature significantly impacted moisture loss per hour, drying time. The shortest drying time and highest re-hydration values were obtained with 5 min blanching time [9]. Similarly, another research based on pre-treating persimmon with nitrogen and carbon dioxide showed that both treatments maintained texture and nutritional qualities after three weeks of storage. It was further noted that nitrogen-treated fruits had better appearance, while carbon dioxide-treated fruits had better flavour [26].

Sun-dried persimmon, dehydrated for 12 hours at 60°C temperature had lower polyphenols than fresh fruit, and variances in trace elements, minerals, and the contents of dietary fibres were non-significant in fresh well as dried persimmon [14]. According to Karakasova et al. [1] citric acid pre-treated persimmon showed the highest dry matter, glucose, fructose, and vitamin C. Furthermore sulphur treatment significantly affected physicochemical characteristics and aromatic compounds of dried apricot and around 45 aroma compounds were detected. In short, drying temperature, and preservatives significantly affect the quality of dried fruits. Although individual effects of preservatives and drying temperatures have been explored, almost no information is available on the combined effects of drying temperature and preservatives (both natural and synthetic) on drying kinetics and organoleptic quality attributes of persimmon. The current study assessed the individual and interactive effects of different drying temperatures, and natural and artificial preservatives on drying kinetics and organoleptic characteristics of persimmon. It was hypothesized that combined effect of drying temperatures and different preservatives will improve the quality and organoleptic characteristics of persimmon. The results of the study would help to preserve persimmon fruits for longer period without quality loss.

Materials and methods

Experimental site

This study was conducted at the rooftop of Department of Agriculture Mechanization, The University of Agriculture Peshawar, Khyber Pakhtun Khawa, Pakistan (34.02°N, 71.48°E with an altitude of 359.0 m) during 2021.

Experimental details

Fresh persimmon fruits (cultivar 'Fuyu') were collected from the Horticulture Research Farm, The University of Agriculture Peshawar, Khyber Pakhtun Khawa, Pakistan (34.02°N, 71.48°E with an altitude of 359.0 m). The sun-shine hours were approximately 13.0 h per day at the experimental site. The collected fruits were washed, blanched at 70°C in warm water and positioned on the trays of solar dryer for the drying process. Two factors, i.e., drying temperature and food preservatives (two natural and three artificial) were included in the study. There drying temperatures (40, 45, and 50°C) and five preservatives (25% honey solution, 25% aloe vera solution, 2% sodium benzoate (C₇H₅NaO₂) solution, 1% potassium metabisulfite (K₂S₂O₅) solution, and 2% citric acid (C₆H₈O₇) solution) were used in the study. The experiment was laid out according to factorial design and each treatment had three replications.

Flat plate solar drier

The drier setup consisted of an exclusively forced convective dryer based on solar radiation, a flat plate solar radiation collector, a cabinet dryer, and a fan for circulation (Fig 1). The solar radiation collector was made from deodar (*Cedrus deodara*) and poplar (*Populus tremula*) wood with dimensions of 1.83 m × 0.91 m × 0.18 m and 0.30 m³ inner volume. The side walls and bottom were insulated using 40 mm thick polyurethane material, and collector box was painted in black to render it fully airtight, reducing heat losses from the radiation absorber



Fig 1. General overview of the solar drier. Fig 1 is excluded from this article's CC-BY license. See the accompanying retraction notice for more information.

<https://doi.org/10.1371/journal.pone.0265111.g001>

plate. A v -corrugated sheet of steel (0.32 mm thick) was allocated behind the transparent cover that acted as heat absorber plate to exploit heat captivation of solar radiations. Cover glass (8 mm thick), having dimensions of $1.83\text{ m} \times 0.91\text{ m}$, was positioned at the collection box's top with a 20 mm gap between the glass shield and the radiation absorber. The purpose of this glass cover was to protect the absorber from winds that blow across the collector's surface by reducing temperature loss from the absorber and permitting a significant amount of heat radiation at the absorber unit. The inlet and outlet channels made up of PVC (polyvinyl-chloride) with 10 cm diameter were built to the collector's top and bottom (Fig 1). The collector's inlet was attached to the fan with an inlet channel to push the surrounding air to the collecting unit.

Moreover, a controller was used to establish 1.5 kg min^{-1} of air mass flow. On the other hand, the collector was maintained and slanted through a four-legged frame. The collector was positioned to the southern side to exploit solar radiation.

The drying compartment was built from the wood as a parallel piped inclusion with dimensions of $0.7\text{ m} \times 0.5\text{ m} \times 1.15\text{ m}$. The entrance to the inner side of the drying chamber was through an insulated gate ($1.12\text{ m} \times 0.65\text{ m}$). The whole structure was insulated using polyurethane material having 40 mm thickness. The distance between the drying chamber's bottom and tray's bottom was $\sim 7.5\text{ mm}$, and the distance among each tray was 0.50 cm. Moreover, a pyranometer was installed to quantify the incident radiations falling on the surface of the collector, and thermo-hygro-meters were used to note the relative humidity and air temperature at different sites in the dryer and the surrounding air. The observations were recorded at one-hour intervals from the thermo-hygrometers and the pyranometer. An ASHARE Psychometric table was utilized to estimate the air's dry and wet bulb temperatures [11, 12].

Organoleptic quality attributes

Weight loss after every hour was noted using a digital electric balance (model: LC SK1 Round Pan) having accuracy of 0.001 g, and moisture loss and drying rate hour^{-1} were calculated

using the following formulas [27] [28]:

$$M_c = \frac{W_i - W_f}{W_i} \times 100$$

$$D_r = \frac{W_i - W_f}{D_m \times A_p \times D_t}$$

Where W_i and W_f represent fresh and dry weight (g) of fruit, respectively. Similarly, D_m , A_p , and D_t are dry matter (g), cross-sectional area (cm^2), and drying time of fruit (min), respectively.

Drying time and total soluble sugars (TSS) in terms of degrees Brix were recorded following the method of Ouabou et al. [29] and Bozkir et al. [30], respectively. Titrable acidity, pH, and ash contents were measured according to methods devised by International [31], while vitamin C was determined according to Hernández et al. [32].

Mathematical models

Five common and published equations were used to determine the moisture ratio of persimmon (Table 1). Rootmean square error (RMSE) and coefficient of regression (R^2) were measured for each model using the standard equations. The higher R^2 value and the lower RMSE values designated that model has a higher goodness of fit.

The R^2 and RMSE values for modeling of moisture ratio were calculated statistically using the following formula [37] [38],

$$R^2 = 1 - \frac{\sum (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (MR_{pre} - MR_{exp,i})^2}$$

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

Statistical analysis

The data were collected and subjected to two-way analysis of variance (ANOVA) using SPSS statistical software (SPSS v22.0, SPSS Inc., USA). Afterwards, Duncan's multiple range test was used to detect differences between the treatment groups where ANOVA indicated significant differences. Origin v 9.1 was used to draw figures. Pearson's correlation analysis was performed among different organoleptic quality attributes of persimmon fruit treated with preservatives and dried under different temperatures. The minimal dataset of the study are given in S1 Dataset.

Table 1. Mathematical models for testing of thin-layer drying kinetics of persimmon.

Equation	Name	Reference
$MR = \exp(-kt)$	Newton	[33]
$MR = \exp(-kt^n)$	Page	[9]
$MR = \exp(-(kt)^n)$	Modified page	[34]
$MR = a^1 \exp(-kt)^1 + a^2 \exp(-kt)^2$	Two term exponential	[35]
$MR = 1 + at + (at)^2$	Wang and Singh	[36]

<https://doi.org/10.1371/journal.pone.0265111.t001>

Table 2. Probabilty and significance for moisture loss, drying time, drying rate, total soluble sugars, pH, acidity, ash contents and vitamin C of persimmon fruit subjected to different drying temperatures and preservatives.

Treatments	Moisture loss(% hr ⁻¹)	Drying time(hrs)	Drying rate(g H ₂ O g DM hr ⁻¹)	TSS(°Brix)	pH	Acidity(%)	Ash(g)	Vitamin C(mg)
Temperature (T)	0.0031**	0.0051**	0.0000**	0.0212*	0.0000**	0.0312*	0.0472*	0.0112*
Preservative (P)	0.0216*	0.0011**	0.0000**	0.0000**	0.0000**	0.0011**	0.0305*	0.0099**
T × P	0.0360*	0.0096**	0.0016**	0.0763 ^{ns}	0.04205*	0.0451*	0.3861 ^{ns}	0.0993 ^{ns}

* and ** show that values are significant at 0.05% and 0.01% confidence interval respectively, while ns indicates non-significant values at 0.05% confidence interval.

<https://doi.org/10.1371/journal.pone.0265111.t002>

Results

Drying temperature, and preservatives significantly affect the quality and drying kinetics of dried fruits. Most of the studied parameters were significantly affected by individual effects of drying temperatures and preservatives, except ash contents. Moreover, the interactive effect of drying temperature, and preservatives was significant for all the parameters except TSS, ash, and Vitamin C.

Moisture loss (%)

Individual and interactive effects of drying temperatures, preservatives, significantly affected moisture loss (Table 2). The mean comparison of drying temperatures showed that 8.2% moisture was lost per hour at 50°C, followed by 6.8% at 45°C, and minimum (6.1%) was recorded at 40°C. The data for preservatives showed that the highest 7.8% moisture was lost per hour in persimmon treated with 2% citric acid solution, while the lowest moisture loss (6.4%) was recorded with 1% potassium metabisulfite solution (Table 3). Overall, the highest moisture loss (9.3%) was recorded at 50°C drying temperature treated with 2% citric acid solution, and the lowest (6.1%) moisture was lost at 40°C treated with 25% honey solution (Fig 2A).

Table 3. Moisture lost (%), drying time (hrs) and drying rate (g_{H2O}·g_{DM}·hr⁻¹) of dried persimmon as affected by drying temperatures and preservatives.

Treatments	Moisture lost (%.hr ⁻¹)	Drying time (hrs)	Drying rate (g _{H2O} ·g _{DM} ·hr ⁻¹)
Storage temperature (°C)			
40	6.1 c	17.3 a	0.023 b
45	6.8 b	16.2 b	0.025 b
50	8.2 a	13.8 c	0.031 a
LSD (P<0.05)	0.44	1.04	0.004
Preservatives			
25% Honey	6.9 c	16.5 a	0.026 b
25% Aleovera	6.5 d	16.2 a	0.026 b
2% Sodium Benzoate	7.3 b	15.3 b	0.024 c
1% Potassium meta bisulphate	6.4 d	15.2 b	0.027 b
2% citric acid solution	7.8 a	14.1 c	0.030 a
LSD (P<0.05)	0.35	0.84	0.002
Interaction (SxP)			
Significance	* (Fig 2A)	** (Fig 2B)	** (Fig 3A)

means sharing the same letters are non-significant at p<0.05.

** and * indicate correlation is significant at the 0.01 and 0.05 level, respectively.

<https://doi.org/10.1371/journal.pone.0265111.t003>

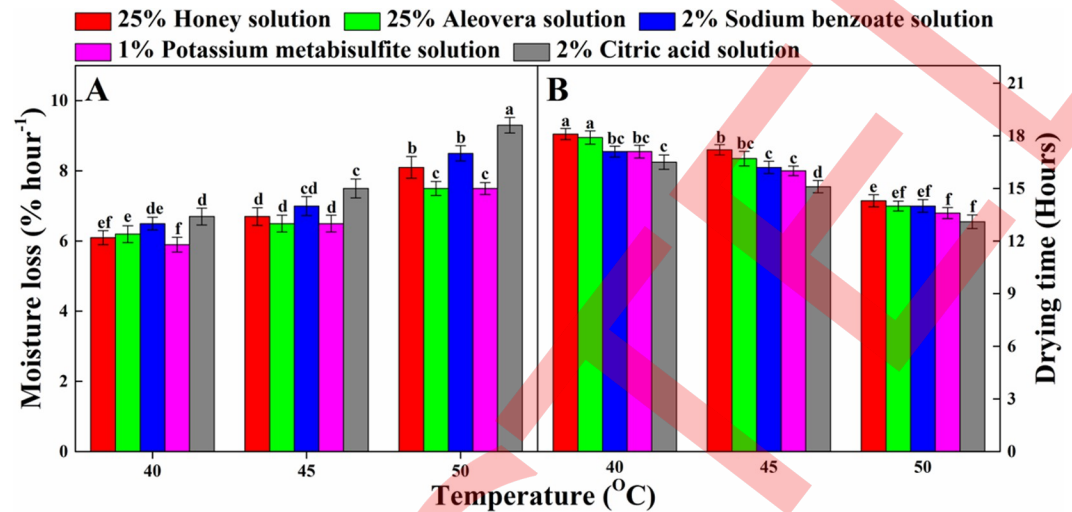


Fig 2. The interaction effect of drying temperature and preservatives on moisture loss (A) and drying time (B) of persimmon fruit. Bars in the figure represent means \pm S.E. (n = 3), and means sharing the same letters are non-significant at $p < 0.05$.

<https://doi.org/10.1371/journal.pone.0265111.g002>

Drying time

Drying temperature, preservatives, and their interaction significantly affected drying time of persimmon fruits (Table 2). The drying temperature showed that 17.3 and 13.8 hours were taken during drying under 40°C and 50°C, respectively. On the other hand, preservative showed that the highest (16.5 hours) and the lowest (14.1 hours) drying time was taken by persimmon treated with 25% honey solution and 2% citric acid, respectively (Table 3). Generally, the longest time, i.e., 18.1 hours for drying time was recorded at 40°C and 25% honey solution, while the shortest drying time (13.1 hours) was taken by 50°C and 2% citric acid solution (Fig 2B).

Drying rate

Drying temperature, preservatives, and their interaction had significant influence on the drying rate of persimmon fruits (Table 2). The data showed that the highest drying rate (0.031 g of H₂O g⁻¹ of dry matter hour⁻¹) was noted at 50°C, whereas the lowest drying rate (0.023 g of H₂O g⁻¹ of dry matter hour⁻¹) was noted at 40°C. Similarly, the highest (0.030 g of H₂O g⁻¹ of dry matter hour⁻¹) and the lowest (0.024 g H₂O g⁻¹ dry matter hour⁻¹) drying rate was recorded for 2% citric acid and 2% sodium benzoate solutions, respectively (Table 3). Regarding interactive effect, the highest (0.036 g of H₂O g⁻¹ of dry matter hour⁻¹) and the lowest (0.021 g of H₂O g⁻¹ of dry matter hour⁻¹) drying rate was observed for 50°C and 2% citric acid solution, and 40°C and 25% honey solution, respectively (Fig 3A).

Total soluble sugars

The TSS was significantly influenced by drying temperature and preservatives, while their interaction was non-significant ($p < 0.001$) (Table 2). The mean comparison of drying temperature showed the highest (1.25° Brix) and the lowest (1.04° Brix) TSS was recorded for 50°C and 40°C drying temperatures, respectively. Similarly, the highest lowest (1.23° Brix) and the lowest (1.07° Brix) were recorded for 2% citric acid and 25% aloe vera solutions, respectively (Table 4).

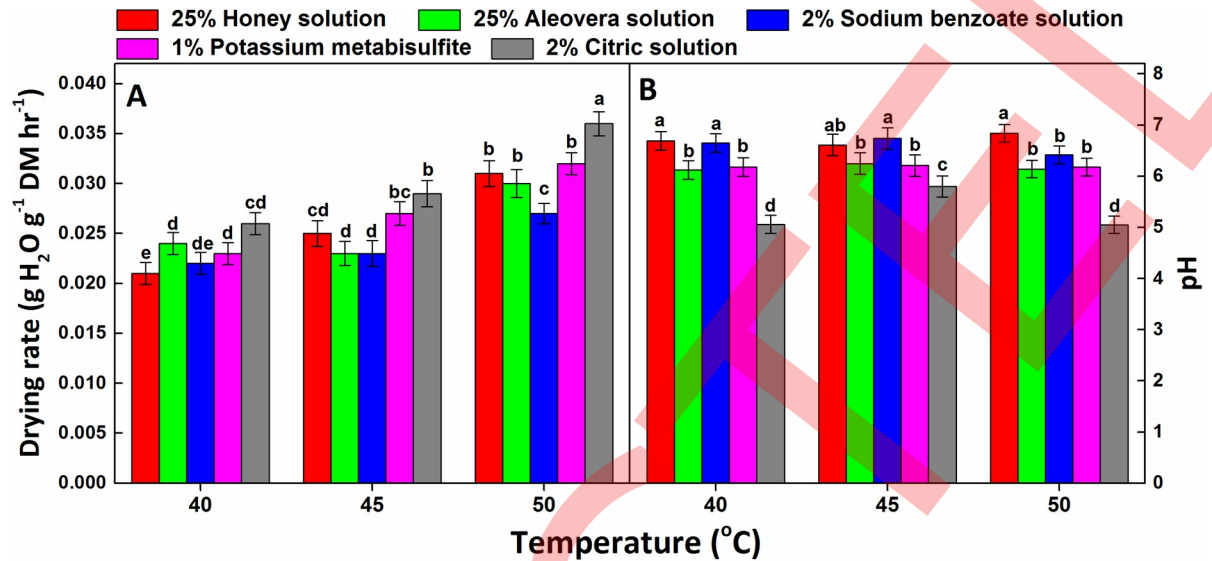


Fig 3. The effect of drying temperature and preservatives on drying rate (A) and pH (B) of persimmon fruit. Bars in the figure represent means \pm S.E. (n = 3), and means sharing the same letters are non-significant at $p < 0.05$.

<https://doi.org/10.1371/journal.pone.0265111.g003>

pH

The individual and interactive effects of drying temperatures and preservatives had significant effects on pH (Table 2). The highest (6.32) and the lowest (6.13) pH was noted at 45°C and 50°C drying temperatures, respectively. Similarly, 25% honey and 2% citric acid solutions resulted in the highest (6.60) and the lowest pH (5.30), respectively (Table 4). The interaction among 50°C and 25% honey solution results in the highest pH, whereas interaction among 50°C and 2% citric acid solution resulted in the lowest pH (Fig 3A).

Acidity

Acidity was significantly affected by individual and interactive effects of drying temperatures and preservatives (Table 2). The highest (1.11%) and the lowest (0.93%) acidity was recorded for 40°C and 50°C drying temperatures, respectively. Similarly, the highest (1.35%) and the lowest (0.70%) acidity was noted for 2% citric acid and 1% potassium metabisulfite solutions, respectively (Table 4). Regarding interactive effect, 40°C with 25% honey solution recorded maximum acidity (1.40%), whereas 40°C with 2% sodium benzoate solution observed minimum acidity of (0.35%) (Fig 4).

Ash contents

The drying temperatures and preservatives had significant effects, while their interaction had non-significant ($P < 0.001$) effects on ash contents (Table 2). The highest ash contents (5.81 g) were recorded for 50°C and the lowest ash contents (4.28 g) were recorded at 40°C. Regarding the means for preservatives, the highest (5.69 g) and lowest (4.20 g) ash content was observed in fruits preserved in 25% honey solution and 2% citric acid solution respectively (Table 4).

Vitamin C

The individual effects of drying temperature and preservatives had significant impact on vitamin C, while their interactive effect was non-significant (Table 2). The highest vitamin C (5.60 mg) was noted for 40 and 45°C, whereas the lowest (5.24 mg) was recorded for 50°C. Similarly,

Table 4. TSS ($^{\circ}$ Brix), pH, Acidity (%), Ash (g) and Vitamin C (mg) of dried persimmon as affected by drying temperatures and preservatives.

Treatments	TSS ($^{\circ}$ Brix)	pH	Acidity (%)	Ash (g)	Vitamin C (mg)
Storage temperature ($^{\circ}$C)					
40	1.04 b	6.14 b	1.11 a	4.28 b	5.60 a
45	1.06 b	6.32 a	0.94 b	4.67 b	5.60 a
50	1.25 a	6.13 b	0.93 b	5.81 a	5.24 b
LSD ($P \leq 0.05$)	0.09	0.16	0.24	0.68	0.29
Preservatives					
25% Honey	1.08 c	6.71 a	1.12 b	5.69 a	5.20 c
25% Aloe vera	1.07 c	6.17 b	0.89 c	4.23 d	5.72 b
2% Sodium Benzoate	1.15 b	6.60 a	0.70 d	5.17 b	5.42 c
1% Potassium meta bisulphate	1.09 c	6.19 b	0.96 c	4.70 c	5.22 c
2% citric acid solution	1.23 a	5.30 c	1.35 a	4.20 d	6.31 a
LSD ($P \leq 0.05$)	0.06	0.14	0.15	0.45	0.25
Interaction (S\timesP)					
Significance	NS	* (Fig 3B)	* (Fig 4)	NS	NS

NS = non-significant

* = significant.

<https://doi.org/10.1371/journal.pone.0265111.t004>

the highest (6.31 mg) and the lowest (5.20 mg) vitamin C was recorded for 2% citric acid and 25% honey solutions, respectively (Table 4).

Mathematical models for drying kinetics

According to previously published literature, moisture ratio data are analyzed by using mathematical models for thin-layer drying kinetics of persimmon (Table 1). The highest R^2 and the

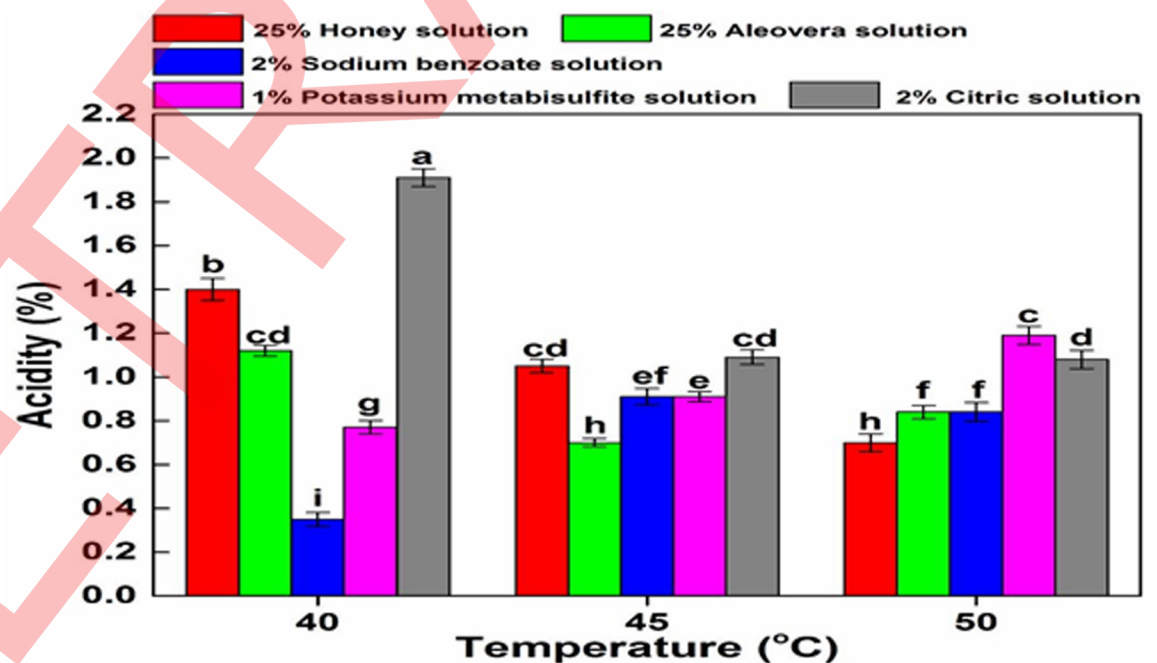


Fig 4. The effect of drying temperature and preservatives on acidity of persimmon fruit. Bars in the figure represent means \pm S.E. ($n = 3$), and means sharing the same letters are non-significant at $p < 0.05$.

<https://doi.org/10.1371/journal.pone.0265111.g004>

Table 5. Coefficient of regression and root mean square error of published equations for drying kinetics of persimmon.

Model's Equation	R ²	Root mean square error
MR = exp (-kt)	0.98	0.0003
MR = exp (-kt ⁿ)	0.79	0.0019
MR = exp (-(kt)) ⁿ	0.89	0.0008
MR = a ¹ exp (-kt) ¹ + a ² exp (-kt) ²	0.99	0.0001
MR = 1 + at+ (at) ²	0.98	0.0003

R² represents the coefficient of regression.

<https://doi.org/10.1371/journal.pone.0265111.t005>

lowest RMSE values described the model as a good-fitted one. The results indicated that two-term exponential model was the best for describing drying kinetics of persimmon, as it has a maximum value of coefficient of regression and minimum value of RMSE (Table 5). Hence, it is recommended to apply a two-term exponential model on the moisture ratio of persimmon to get good results of correlation and regression and best fit.

Correlation analysis

Pearson's correlation analysis showed that moisture loss was positively correlated with drying rate, total soluble sugars, and ash contents, while negatively correlated with drying time, pH, and acidity. Similarly, drying time, drying rate, and total soluble sugars showed a significant positive correlation with acidity, ash contents, and vitamin C. On the other hand, pH was negatively correlated with drying time, drying rate, total soluble sugars, acidity, and vitamin C, while positively correlated with ash contents (Table 6).

Discussion

Preservative solutions and drying treatment significantly influenced all the studied attributes of solar-dried persimmon. Dehydration during drying of fruits is considered a useful term. In the present study the highest moisture loss was recorded in solar dried persimmon fruits under 50°C preserved in citric acid solution. More moisture loss helps the dried commodity to delay the spoilage and prevent microorganisms' growth which means dried fruits can be stored for longer period. Furthermore, increased shelf life through dehydration would help in long distance transport of fruits. Solar drying helps to evaporate most of the moisture where only soluble solids are left. However, very high temperature beyond 50°C would result in more humid condition around the fruits which will expose the fruits to microorganisms [39].

Table 6. Pearson's correlation analysis among different organoleptic quality attributes of persimmon fruit treated with preservatives and dried under different temperatures.

	Moisture loss	Drying time	Drying rate	Total soluble sugars	pH	acidity	Ash contents	Vitamin C
Moisture loss	1	-0.16	0.79**	0.84**	-0.30	-0.05	0.68**	0.20
Drying time		1	0.01	-0.06	-0.12	0.53*	0.14	0.07
Drying rate			1	0.75**	-0.55*	0.25	0.49	0.29
Total soluble sugars				1	-0.44	0.21	0.69**	0.27
pH					1	-0.56*	0.08	-0.78**
Acidity						1	0.11	0.43
Ash							1	-0.18
Vitamin C								1

** and * indicate correlation is significant at the 0.01 and 0.05 level, respectively.

<https://doi.org/10.1371/journal.pone.0265111.t006>

Therefore, optimum drying temperature and preservatives are needed to minimize microorganisms' attack and retain the quality of dried persimmon. Furthermore, fruits preserved in citric acid recorded the highest moisture loss but retained quality attributes like ascorbic acid, TSS, and acidity etc. This might reduced browning of fruits which is an important limiting factor for quality retention of fruits in postharvest biology [40]. The reasons for reduced browning might be decreased activity of Polyphenol oxidase (PPO). Decreased PPO activity would have induced resistance to browning or decay [41]. Moreover, organic acids such as citric acid have been reported as the source of carbon and energy for cells and used in the respiratory cycle and some other biochemical pathway [42] which would have retained the quality of solar dried persimmon fruits and hence prolonged the storage life of persimmon fruits. These results align with Doymaz [9], who noted a significant decrease in moisture loss per hour by increased temperature. Hanif et al. [12] also observed significant effects of preservatives on overall moisture loss by persimmon.

Drying time and rate were significantly affected by drying temperature and preservatives in the current study. The increase in drying time and rate with drying temperature at 50°C might be due to the increased metabolic activities and reactions within the fruits which would have contributed to early and fast drying of persimmon fruits [14]. On one side drying temperature fastens the rate of drying, while on the other side, citric acid retained the quality of dried persimmon which was needed to prolong the shelf life [1]. Treatment of dried persimmon fruits with preservatives could change the activity of enzymes, increase surface pores, and retain some active substances. The expansion fruit pores accelerated heat and mass transfer rate between fruit surface and the air, thereby reduced drying time consumption [43]. These results are in line with the previous experiments, where a significant decrease in drying time was recorded with increased temperature [14], and a significant increase in drying time was noted by the application of the preservative in persimmon. These results are supported by the previous study of del Río et al. [44], who recorded a significant decrease in drying rate by increased temperature and significant effects of preservatives on the increase in drying rate, respectively. The present results also showed that all the quality attributes (TSS, acidity, ascorbic acid, pH) were significantly retained by preserving solar dried persimmon fruits at 50°C in citric acid. Many studies reported that biochemical and phytochemicals could be easily affected by drying time, method, temperature and light conditions which can convert these into other compounds [45]. Thus appropriate drying methods and temperature play a vital role to get high biochemical and phytochemicals content and composition of dried agriculture materials [46]. High drying temperature may cause quality attributes and phytochemicals rupture at the initial stages and dissolve some heat-sensitive compounds [47]. Furthermore, it was found that the water evaporation could act as a carrier to bring volatile compounds to the environment in drying [48]. The more evaporation results in more volatile compounds' loss; thus, retaining the quality of dried persimmon fruits. As mentioned earlier, rapid evaporation of moisture from dried fruits during drying helps to prevent the support of microorganism and help to retain quality of dried fruits [39]. These results align with the previous experiments [26], who recorded a significant change in total soluble sugars and pH of persimmon at a higher temperature. Likewise, Park et al. [14], Kim et al. [25], Hanif et al. [12] and Hanif et al. [11] recorded a significant effect of preservatives on quality attributes during drying of persimmon at high temperature.

Conclusions

Drying temperatures and preservatives significantly affected the quality and drying kinetics of persimmon fruits. It is concluded that citric acid treatment and drying persimmon fruits at 50°C is promising. Hence, it could be used to extend the storage period of persimmons.

Supporting information

S1 Dataset. Minimal dataset of the study.
(XLSX)

Author Contributions

Conceptualization: Wen-Fang Li, Shahbaz Ali, Syed Tanveer Shah, Zong-Huan Ma, Juan Mao, Yasir Niaz, Bai-Hong Chen, Inzamam Ul Haq, Rashid Al-Yahyai, Mohamed A. A. Ahmed, Abdullah Ahmed Al-Ghamdi, Mohamed S. Elshikh, Ali Tan Kee Zuan.

Data curation: Zong-Huan Ma, Inzamam Ul Haq.

Formal analysis: Abdul Khaliq, Juan Mao, Inzamam Ul Haq.

Funding acquisition: Syed Tanveer Shah, Rashid Al-Yahyai, Mohamed A. A. Ahmed, Abdullah Ahmed Al-Ghamdi, Mohamed S. Elshikh, Ali Tan Kee Zuan.

Investigation: Wen-Fang Li.

Project administration: Wen-Fang Li, Syed Tanveer Shah, Bai-Hong Chen.

Resources: Juan Mao.

Software: Abdul Khaliq.

Supervision: Wen-Fang Li, Bai-Hong Chen.

Validation: Abdul Khaliq.

Visualization: Abdul Khaliq, Shahbaz Ali.

Writing – original draft: Inzamam Ul Haq.

Writing – review & editing: Wen-Fang Li, Shahbaz Ali, Syed Tanveer Shah, Zong-Huan Ma, Juan Mao, Yasir Niaz, Bai-Hong Chen, Rashid Al-Yahyai, Mohamed A. A. Ahmed, Abdullah Ahmed Al-Ghamdi, Mohamed S. Elshikh, Ali Tan Kee Zuan.

References

1. Karakasova L, Babanovska-Milenkovska F, Lazov M, Karakasov B, Stojanova M. Quality properties of solar dried persimmon (*Diospyros kaki*). *Journal of Hygienic Engineering and Design*. 2013; 4(1):54–59.
2. González CM, Gil R, Moraga G, Salvador A. Natural Drying of Astringent and Non-Astringent Persimmon “Rojo Brillante”. *Drying Kinetics and Physico-Chemical Properties*. *Foods*. 2021; 10(3):647. <https://doi.org/10.3390/foods10030647> PMID: 33803816
3. Bolek S, Obuz E. Quality characteristics of Trabzon persimmon dried at several temperatures and pre-treated by different methods. *Turkish Journal of Agriculture and Forestry*. 2014; 38(2):242–249.
4. Kaya A, Kamer M, Şahin H. Experimental investigation of drying kinetics of Trabzon persimmon (*Diospyros kaki* L.). *GIDA-Journal of Food*. 2015; 40(1):15–21.
5. Suzuki T, Someya S, Hu F, Tanokura M. Comparative study of catechin compositions in five Japanese persimmons (*Diospyros kaki*). *Food Chemistry*. 2005; 93(1):149–152.
6. Luo Z. Effect of 1-methylcyclopropene on ripening of postharvest persimmon (*Diospyros kaki* L.) fruit. *LWT-Food Science and Technology*. 2007; 40(2):285–291.
7. Butt MS, Sultan MT, Aziz M, Naz A, Ahmed W, Kumar N, et al. Persimmon (*Diospyros kaki*) fruit: hidden phytochemicals and health claims. *EXCLI journal*. 2015; 14:542. <https://doi.org/10.17179/excli2015-159> PMID: 27047315
8. Cárcel J, García-Pérez J, Riera E, Mulet A. Influence of high-intensity ultrasound on drying kinetics of persimmon. *Drying Technology*. 2007; 25(1):185–193.
9. Doymaz İ. Evaluation of some thin-layer drying models of persimmon slices (*Diospyros kaki* L.). *Energy conversion and management*. 2012; 56:199–205.

10. Mohamed AH, Ragab M, Siliha H, Haridy LA. Physicochemical, microbiological and sensory characteristics of persimmon fruit leather. *Zagazig Journal of Agricultural Research*. 2018; 45(6):2071–2085.
11. Hanif M, Khattak MK, Ali SA, Khan M, Ramzan M, Amin M, et al. Impact of drying temperature and slice thickness on retention of vitamin c in persimmons (*Diospyros kaki* L.) dried by a flat plate solar collector. *Pak J Food Sci*. 2015; 25:66–70.
12. Hanif M, Khattak MK, Rehman MU, Ramzan M, Amin M, Aamir M, et al. Effect of drying temperature and natural preservatives on reducing aflatoxins in solar dried persimmon (*Diospyros kaki* L.). *Proc Pak Acad Sci*. 2015; 52:361–365.
13. Çelen S. Effect of microwave drying on the drying characteristics, color, microstructure, and thermal properties of Trabzon persimmon. *Foods*. 2019; 8(2):84.
14. Park Y-S, Jung S-T, Kang S-G, Delgado-Licon E, Ayala ALM, Tapia MS, et al. Drying of persimmons (*Diospyros kaki* L.) and the following changes in the studied bioactive compounds and the total radical scavenging activities. *LWT-Food Science and Technology*. 2006; 39(7):748–755.
15. Adiletta G, Russo P, Proietti N, Capitani D, Mannina L, Crescitelli A, et al. Characterization of pears during drying by conventional technique and portable non invasive NMR. *Chemical Engineering Transactions*. 2015; 44:151–156.
16. Alibas I, Köksal N. Convective, vacuum and microwave drying kinetics of mallow leaves and comparison of color and ascorbic acid values of three drying methods. *Food Science and Technology*. 2014; 34(2):358–364.
17. Khademi O, Farrokhzad Y, Khangholi S. Impact of different pre-treatments and drying methods on quality and antioxidant properties of dried persimmon (*Diospyros kaki* L.) slices. *International Journal of Postharvest Technology and Innovation*. 2019; 6(2):137–150.
18. Prosapio V, Norton I. Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance. *Lwt*. 2017; 80:401–408.
19. Baeghbal V, Ngadi M, Niakousari M. Effects of ultrasound and infrared assisted conductive hydro-drying, freeze-drying and oven drying on physicochemical properties of okra slices. *Innovative Food Science & Emerging Technologies*. 2020; 63:102313.
20. Seerangurayar T, Al-Ismaili AM, Jeewantha LJ, Al-Nabhani A. Experimental investigation of shrinkage and microstructural properties of date fruits at three solar drying methods. *Solar Energy*. 2019; 180:445–455.
21. Khanlari A, Sözen A, Afshari F, Şirin C, Tuncer AD, Gungor A. Drying municipal sewage sludge with v-groove triple-pass and quadruple-pass solar air heaters along with testing of a solar absorber drying chamber. *Science of The Total Environment*. 2020; 709:136198. <https://doi.org/10.1016/j.scitotenv.2019.136198> PMID: 31887496
22. Rabha D, Muthukumar P, Somayaji C. Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger. *Renewable Energy*. 2017; 105:764–773.
23. Senadeera W, Adiletta G, Önal B, Di Matteo M, Russo P. Influence of different hot air drying temperatures on drying kinetics, shrinkage, and colour of persimmon slices. *Foods*. 2020; 9(1):101.
24. Park H-W, Oh S-I, Cho M-G, Kim C-W, Lee U. The comparison of quality characteristics of dried persimmons manufactured by solar drying method in Yecheon. *Journal of Korean Society of Forest Science*. 2018; 107(4):422–427.
25. Kim I-D, Lee J-W, Kim S-J, Cho J-W, Dhungana SK, Lim Y-S, et al. Exogenous application of natural extracts of persimmon (*Diospyros kaki* Thunb.) can help in maintaining nutritional and mineral composition of dried persimmon. *African Journal of Biotechnology*. 2014; 13(22).
26. Bibi N, Khattak AB, Mehmood Z. Quality improvement and shelf life extension of persimmon fruit (*Diospyros kaki*). *Journal of food engineering*. 2007; 79(4):1359–63.
27. Ucar A, Inalli M. Thermal and exergy analysis of solar air collectors with passive augmentation techniques. *International communications in heat and mass transfer*. 2006; 33(10):1281–1290.
28. Song X-D, Mujumdar AS, Law C-L, Fang X-M, Peng W-J, Deng L-Z, et al. Effect of drying air temperature on drying kinetics, color, carotenoid content, antioxidant capacity and oxidation of fat for lotus pollen. *Drying Technology*. 2020; 38(9):1151–1164.
29. Ouaabou R, Nabil B, Hidar N, Lahnine L, Idlimam A, Lamharrar A, et al. Valorization of solar drying process in the production of dried Moroccan sweet cherries. *Solar Energy*. 2018; 172:158–164.
30. Bozkir H, Ergün AR, Serdar E, Metin G, Baysal T. Influence of ultrasound and osmotic dehydration pre-treatments on drying and quality properties of persimmon fruit. *Ultrasonics sonochemistry*. 2019; 54:135–141. <https://doi.org/10.1016/j.ultsonch.2019.02.006> PMID: 30765216
31. International A. Official methods of analysis. Moisture in sugars. 2000.

32. Hernández Y, Lobo MG, González M. Determination of vitamin C in tropical fruits: A comparative evaluation of methods. *Food chemistry*. 2006; 96(4):654–664.
33. Roberts JS, Kidd DR, Padilla-Zakour O. Drying kinetics of grape seeds. *Journal of Food Engineering*. 2008; 89(4):460–465.
34. Vega-Gálvez A, Lemus-Mondaca R, Bilbao-Sáinz C, Fito P, Andrés A. Effect of air drying temperature on the quality of rehydrated dried red bell pepper (var. Lamuyo). *Journal of food engineering*. 2008; 85(1):42–50.
35. Hanif M, Ramzan M, Aamir M. Drying of grapes using a dish type solar air heater. *J Agric Res*. 2012; 50(3):423–432.
36. Miranda M, Maureira H, Rodriguez K, Vega-Gálvez A. Influence of temperature on the drying kinetics, physicochemical properties, and antioxidant capacity of Aloe Vera (*Aloe Barbadensis* Miller) gel. *Journal of Food Engineering*. 2009; 91(2):297–304.
37. Aktaş M, Ceylan İ, Yılmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. *Desalination*. 2009; 239(1–3):266–275.
38. Ceylan I. Energy analysis of PID controlled heat pump dryer. *Engineering*. 2009; 1(3):188.
39. Mercer DG. An introduction to the dehydration and drying of fruits and vegetables: Donald G. Mercer; 2014.
40. Pareek S, Yahia EM, Pareek O, Kaushik R. Postharvest physiology and technology of Annona fruits. *Food Research International*. 2011; 44(7):1741–1751.
41. Zheng X, Ye L, Jiang T, Jing G, Li J. Limiting the deterioration of mango fruit during storage at room temperature by oxalate treatment. *Food Chemistry*. 2012; 130(2):279–285.
42. Darandeh N, Hadavi E. Effect of pre-harvest foliar application of citric acid and malic acid on chlorophyll content and post-harvest vase life of *Lilium* cv. Brunello. *Frontiers in plant science*. 2012; 2:106. <https://doi.org/10.3389/fpls.2011.00106> PMID: 22639626
43. Toğrul İT, Pehlivan D. Modelling of thin layer drying kinetics of some fruits under open-air sun drying process. *Journal of food engineering*. 2004; 65(3):413–425.
44. del Río M, Navarro LA. Quality of persimmon fruit cv. Rojo brillante during storage at different temperatures. *Spanish Journal of Agricultural Research*. 2004;(2):243–248.
45. Turek C, Stintzing FC. Stability of essential oils: a review. *Comprehensive reviews in food science and food safety*. 2013; 12(1):40–53.
46. Chua LY, Chong CH, Chua BL, Figiel A. Influence of drying methods on the antibacterial, antioxidant and essential oil volatile composition of herbs: a review. *Food and Bioprocess Technology*. 2019; 12(3):450–476.
47. Argyropoulos D, Müller J. Changes of essential oil content and composition during convective drying of lemon balm (*Melissa officinalis* L.). *Industrial Crops and Products*. 2014; 52:118–124.
48. Figiel A, Szumny A, Gutiérrez-Ortiz A, Carbonell-Barrachina ÁA. Composition of oregano essential oil (*Origanum vulgare*) as affected by drying method. *Journal of Food Engineering*. 2010; 98(2):240–247.