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A Study of the Comparison of Fluidized Bed Drying of Turkey Berries and Open-Sun Drying

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HIGHLIGHTS

- The quality of dried turkey berries depends mainly on sample preparation and drying methods.
- The pre-treated drying process and the addition of inert materials offered less drying time.
- The combination of the physical pre-treated drying process improves the kinetics and quality.
- Open-sun drying resulted in low quality compared to fluidized bed drying.

Abstract: The primary objective of this investigation, the influence of chemical, combined chemical, hybrid pre-treated samples and the addition of inert material into turkey berry samples through the fluidized bed dryer was studied at processing air temperature of 70 ^{0}C and an inlet air flow of 4.2 m/s, as well as compared to sun drying. Results showed that the Hybrid-II treatments as well as the addition energy carrier method reduced drying time around by 12 times and 10 times compared to open sun-dried samples. The Hybrid-II pre-treatment method resulted in the quickest drying procedure, and it was completed in 330 minutes. In addition, the lowest shrinkage of around 39%, tolerable color change, and the maximum retention of vitamin-C were achieved compared to both OSD and un-treated samples. The Midilli and coauthors (2002) [1] model was fitted, the most preferable model for predicting the drying characteristics of Turkey berry.

Keywords: Color; Effective Moisture Diffusivity; Fluidized bed dryer; Open sun drying; Shrinkage; Turkey berry.

Symbols and abbreviations

Nomenclature

FB	Fluidized Bed	d.b (Dry basis)- kg water / kg dry matter
OSD	Open sun drying	w.b(Wet basis)- kg water /kg total mass
AA	Ascorbic acid	D.R (Drying Rate) -kg water/ kg dry matter x min
TD	Tray dryer	M_s- Moisture content of the sample, (kg water / kg dry matter)
IMM	Mass of Inert materials	M_{in} - Initial moisture content of the sample, (kg water / kg dry matter)
SM	Mass of the sample	D_0 - Pre-exponential factor of the Arrhenius equation, (m^2/s)
R_{in}	Roughness of inert materials	D_{eff}- Effective moisture diffusivity ,(m^2/s)
VFD	Variable frequency drive	M_{eq}- Equilibrium moisture content of the sample (kg water/kg dry matter)
$Na_2S_2O_5$	Sodium Metabisulfite	M_{st} - Moisture content at any time, (kg water/kg dry matter)
$CaCl_2$	Calcium chloride	R_p - Radius of product, (m)
S_1	Slope of the line	t ,t_1, t_2 - Time, (s)
ΔE	Total Color Difference	V_{in} - Initial volume of sample, (m^3)
MR	Moisture ratio	V_f – Final volume of sample, (m3)
VS_P	Shrinkage percentage of product	W_{st} - Sample weight at a specific time (g)
$M_{d.b}$	Moisture content at dry basis	W_{dry} - Sample dry weight (g)
SEM	Scanning electron microscope	

INTRODUCTION

The turkey berry, the scientific name of Solanum Torvum (Solanaceae family) and is a pharmaceutical plant that can be utilized in fresh or dried practice. The vegetables are still used as traditional medicine by people in South India and other Asian countries, particularly in rural areas. This is an essential medicinal plant whose leaves, vegetables, and fruits are utilized as therapeutics for antihypertensive, viral fever, antioxidant, and anti-microbial purposes [2]. In addition, these fruits are also provided in addition to a regular diet. Nonetheless, they have a valuable supply of neutrinos that will decay within a couple of days of post-harvesting, just like any other foodstuff. To prolong its lifespan, it must consequently be stored in a cold storage room/freezer or dried. Furthermore, the dried foodstuffs are easier to move from one place to another and store in small places [3-4].

One of the most common methods of preserving agricultural products is drying. The primary reason for the drying of foodstuffs is to hinder the reproduction of microorganisms and bacteria. The growth of these bacteria can indeed be restricted without the existence of water, and food can be kept for longer periods of time [3-4]. Many types of dryers were widely accessible in the food industry including oven dryers, fluidized bed dryers, microwave dryers, drum dryers, freeze dryers, indirect solar dyers, and infrared radiation dryers. Among the different kinds of dehydration methods, fluidized bed dryers (FBD) are employed all over the world for the dehydration of agro-food products [3-4]. The FBD is known for its consistent dehydration as well as its effective heat and mass transfer phenomena, which effectively removes the moisture from foodstuffs within a short period of time. Furthermore, FBD is a convenient way for avoiding overheating heat-sensitive fruits and vegetables [5-7].

A waxy covering on the exterior surface of turkey berry fruits, similar to grapes, Cape gooseberry, plumes, and cheery fruits, inhibits moisture from flowing through the peel and slows the dehydration rate. Numerous studies report that many number of agro- foodstuffs having wax layer and it can be removed simply by pre-treatment technique includes that the physical, chemical, non-thermal and combined or hybrid techniques [8-10]. Similarly, the existence of inert materials in the fluidized drying chamber would enhance the fluidization behavior and food quality as well as increasing heat and mass transfer phenomena [11-15].

Murthy and Joshi [15] experimentally studied, the drying characteristics of Indian gooseberries in the FBD, Tray dryer and OSD. The greatest dehydration period was required by the OSD, whereas the minimum dehydration period was taken by the FBD. The AA content retention is better in the FB dried samples than in the OSD and TD dried samples. Similarly, the fluidized bed dryer was compared to the OSD for a variety of agro-food crops, including kaffir lime leaves [14], bird's chili [16], green peas [17], ginger and turmeric [18]. Furthermore, numerous studies and research been published comparing the OSD and solar-based dryers for agro foodstuffs such as turkey berries [19], red chili [20], Indian cucumber [21], Ghost-Chili pepper [22], green chilies [23], pineapples [24],

As per the review of extant literature, no research has been conducted on the drying behavior of turkey berries in a FBD, and there has not been a comparative study of the FBD and the OSD of turkey berries. Based on previous studies, the pre-treated samples, as well as the addition of inert materials into the FBD chamber, improve the drying kinetics and product quality. A study was carried out to compare the drying properties of turkey berries in a fluidized bed dryer and in the traditional drying method. The drying effect on the turkey berry color, Vitamin C retention, and shrinkage were all investigated.

MATERIAL AND METHODS

Sample Preparations

The raw turkey berries were gathered from a nearby market. The sample choosing, preparation and handling details described by previous author [6].

Figure 1. Drying of the turkey berries in the OSD

The mean sample size examined was 13.0±0.5 mm. To conduct the course of initial water content of the sample test, around 10 g of raw samples were collected, and their single berry weight was 2.1 ± 0.4 g (3 trials). According to the AOAC standard [25], the mean initial water content of the raw fruit was about 83.8 ±1.2% on a wet basis (w.b).

The combined chemical and hybrid pre-treatments, as well as the aluminum inert materials and untreated samples used in these tests, are given in Table 1. The combined chemical (T3) and hybrid pre-treatments (T4 & T5) sample preparations were briefly explained by the previous author [26] and their chemical composition modified for these studies. The aluminum (Al) inert materials preparations (T2) were described by the previous author and their surface roughness was modified for these studies [7].

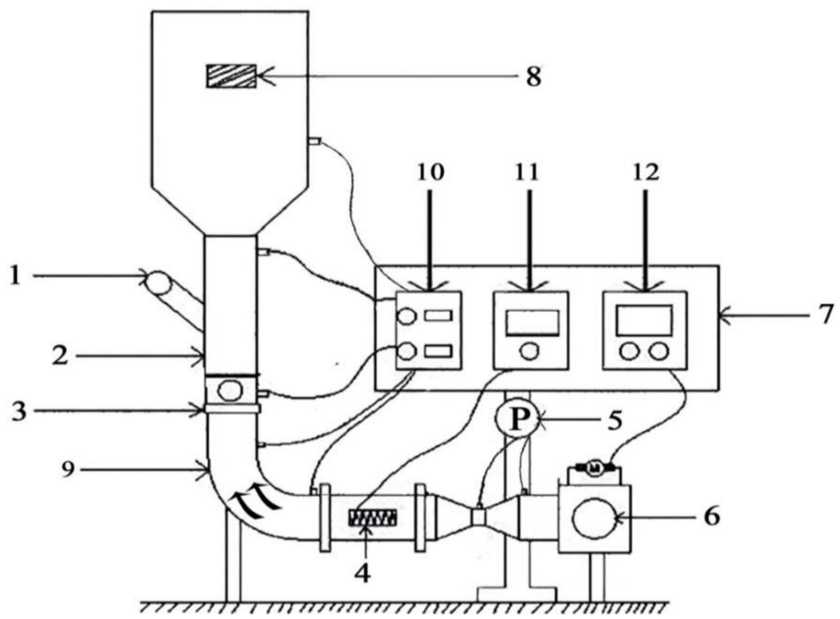
Table 1. Test conditions of the experiments for comparative studies of the FBD and OSD

Test	Ti (^{0}C)	U (m/s)	Sample preparations
T1	70	4.2	Untreated- sample
T2	70	4.2	Al-Inert material +Untreated samples (R_{in}=1.5 mm, IMM/SM=1)
T3	70	4.2	Combined Chemical treatments (Sesame oil (9.5%) + $Na_2S_2O_5$ (0.5 %) + $CaCl_2$(1.5%) ; soaking time- 60 min
T4	70	4.2	Hybrid –I Treatments (Sesame oil (5%) + $Na_2S_2O_5$ (0.5 %) + $CaCl_2$ (1.5%) 90^{0}C 20s)
T5	70	4.2	Hybrid-II Treatments (T4 + Abrasive treatment)
OSD	29-36	0.3-1.2	Untreated- sample

The samples for the open sun drying studies were simply placed on 0.35m x 0.25m plastic sheet trays and dried in direct sunlight in April at temperatures ranging from 28 to 37 ^{o}C as shown in Figure 1. Every day, from 9 a.m. to 6 p.m., the OSD experiment was carried out to observe the drying properties of the samples. On every assessment, 100 g of berries were collected, and the dried berries were conserved in tightly sealed plastic containers to prevent changes in water content during subsequent tests. Three exams were carried out for each experimental condition to establish the reproducibility of the analysis.

Experimental set-up

A batch method of FBD, as displayed in Figure 2, was built to evaluate the dehydration behavior of turkey berries. The research setup includes a blower, 2 HP- electric motor with a VFD, an electric heater, a drying cabinet, an air filter, and other equipment, which are described in full in Barathiraja and coauthors, [7].



(1) Sample input
(2) Drying *cabinet*
(3) Air plenum
(4) Heater
(5) Pressure sensor
(6) Air-blower
(7) Control unit
(8) Filter-bag
(9) Plenum cabinet
(10) Temperature sensor
(11) Power meter
(12) VFD controller

Figure 2. Schematic picture of the experimental setup of FBD

Experimental Methods

The drying behavior and physicochemical properties of turkey berries were investigated in this study at a constant temperature and air flow of 70 ^{0}C and 4.2 m/s, respectively, using various pre-treated and untreated samples. Table 1 describes the details of six different sample preparations. Every half hour, the entire sample was emptied from the bed, and the weight was recorded using an electronic weighing scale with a precision of 0.01g. Following the weight recording, the fruits were loaded into the drying chamber for an additional 30 minutes to further reduce their moisture content. Similarly, in traditional drying (OSD), every 30 minutes ones weight was recorded. The fruits were loaded till the moisture level was less than 0.14±0.05 (d.b).

THEORETICAL CONCEPT

Drying Kinetics

The weight loss of a product as a function of time is used to evaluate drying parameters systematically. The water content of berries was calculated on a dry basis (d.b) by the given Equation (1) [5-7].

$$M_{db} = \left(\frac{W_{st} - W_{dry}}{W_{dry}} \right) \tag{1}$$

The moisture ratio (MR) of beery during the dehydration process in a fluidized bed is determined by the formula below.

$$MR = \left(\frac{M_{st} - M_{eq}}{M_{in} - M_{eq}} \right) \tag{2}$$

The equation (2) changed in the form of $MR = M_{st} / M_{in}$ and moisture ratio is a non-dimensional unit. The drying rate ($D.R$) of the berry in the time of drying was estimated by the following equation (3) [7].

$$D.R = \left(\frac{M_{s,t_1} - M_{s,t_2}}{t_2 - t_1} \right) \tag{3}$$

Evaluation of the mathematical models

An attempt has been made to identify a suitable model which predicts the drying behavior of turkey berry from the available drying models as presented in Table 2.

Table 2. Mathematical models applied to drying curves of turkey berry

Name of model	Model equation	Reference
Newton	$MR = \exp(-kt)$	[22, 31]
Page	$MR = \exp(-kt^n)$	[5, 8, 22, 29,31]
Henderson and Pabis	$MR = a\exp(-kt)$	[8, 22, 28]
Logarithmic	$MR = a\exp(-kt) + b$	[5, 8, 22, 28, 31]
Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	[1, 5, 8, 28, 29]
Logestic	$MR = a/(1 + b\exp(kt))$	[5]

a, b, k, and *n* are model coefficients

Computation of effective moisture diffusivity (D_{eff})

Fick's second law of diffusion equation was employed to examine drying kinetic parameter and predict the D_{eff} of the materials with spherical geometry

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2}{\partial t} \tag{4}$$

Considering that the sample of the turkey berry is almost spherical and the phenomenon of moisture migration occurs solely through diffusion and the MR can be determined by the given equation (5) [5-7];

$$MR = \frac{M_{st} - M_{eq}}{M_{in} - M_{eq}} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(\frac{-D_{eff} n^2 \pi^2 t}{R_p^{\ 2}} \right) \tag{5}$$

During the dehydration periods where the moisture ratio seems to be beyond 0.6, the first part of their sequence of equations is evaluated, and the equation 5 can thus be reformulated as equation 6.

$$MR = \left(\frac{6}{\pi^2}\right)\exp\left(\frac{-D_{eff}\pi^2 t}{R_p{}^2}\right) \tag{6}$$

Using natural log on both the left and right hand sides of Eq. (6), the first-degree equations such as linear equations are formed and re-written as Equation (7).

$$\ln MR = \ln\left(\frac{M_{st} - M_{eq}}{M_{in} - M_{eq}}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{D_{eff}\pi^2 t}{R_p{}^2}\right) \tag{7}$$

By graphing, the drying time against natural logarithmic of moisture ratio data of *ln (MR),* the linear slope S_1 was obtained

$$S_1 = \left(\frac{D_{eff}\pi^2}{R_p{}^2}\right) \tag{8}$$

Computation of the volumetric shrinkage (*VS_p*)

The berry dimensions were determined using a digitized Vernier caliper and compute their initial volume. Furthermore sample was measured multiple times along the relevant axis. After dehydration of the sample, selected any 3 samples from each test and measured their dimensions. With the help of equation (12), the change in volume percentage was calculated as a ratio of the volume of dehydrated berries (V_{fi}) to the volume of raw berries (V_{in}) [5, 7].

$$VS_p = \left(\frac{V_{in} - V_{fi}}{V_{in}}\right) \times 100 \tag{9}$$

Computation of total color change

A Tristimulus Colorimeter (Model: VT-10) was measured to assess the skin color of turkey berries under a D65 light lamp at a 10 0 camera angle. On the Hunter scale, color values were expressed as L- ranging from brightness to darkness (100–0), "a" ranging from redness to greenness (positive to negative), and "b" ranging from yellowish color to blueness (positive to negative), with the subscripts 'fi' and 'in' denoting final and initial intensity of color. For every sample, three data points were measured in three distinct locations, and the mean reading was calculated. Total Color Difference (ΔE) values were determined from the variables "L", "a", and "b" [8-9];

$$\Delta E = \sqrt{(L_{fi} - L_{in})^2 + (a_{fi} - a_{in})^2 + (b_{fi} - b_{in})^2} \tag{10}$$

Vitamin -C Retention

The vitamin-C concentration was determined using the colorimetric approach described by "2, 4-dinitrophenyl hydrazine" [26]. Ascorbic acid (AA) was extracted, refined, and dosed in extracts with standard AA using 0.5 percent oxalic acid. The data was collected using a spectrophotometer at 510 nm, and the experiments were repeated three times; the levels are given in mg/100 g.

Microstructure analysis

A scanning electron microscope was employed to analyze the morphology of dried turkey berries (FEI Quanta 200 F SEM, Netherland). To get SEM micrographs, miniscule pieces of fruit skin were collected and coated with a thin layer of Nano-gold under a vacuum environment to provide an illumination surface for the electron gun. Gold coat was done with an argon gas, at a pressure smaller than the ambient pressure on a sputter coater (HV-DSR1, Sputter Coater).

Data Analysis

MATLAB (MathWorks Inc.) software was used to develop empirical models for moisture ratio. Three indices namely sum of squared errors (SSE), root mean square error (RMSE), and coefficient of determination (R^2) were used for selecting the best model to represent the drying characteristics of turkey berry. A model can be selected as the best when the R^2 value is at its maximum and the SSE and RMSE values are at their minimum according to Amiri Chayjan & Kaveh 2013 [5], Sivakumar et al. 2022 [19]. Equations of the comparative indices are as follows:

$$SSE = \left[\sum_{i=1}^{N} \frac{\left(MR_{\exp,i} - MR_{pre,i} \right)^2}{N-n} \right]^{\frac{1}{2}} \quad (12)$$

$$R^2 = 1 - \frac{\sum_{i=0}^{N} \left(MR_{pre,i} - MR_{\exp,i} \right)^2}{\sum_{k=1}^{N} \left(\overline{MR_{pre,i}} - MR_{\exp,i} \right)^2} \quad (13)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{pre,i} \right)^2 \right]^{\frac{1}{2}} \quad (14)$$

Where MR $_{\exp,i}$ is the experimental moisture ratio of ith data, MR $_{pre,i}$ is the predicted moisture ratio of i^{th} data, is the average predicted moisture ratio, N is the number of observations and n is the number of constant in the model equation.

RESULTS AND DISCUSSION

Drying kinetics

As shown in Figure 3, the rate of dehydration of fruits with respect to drying period and the water evaporation rate were reduced steadily during the dehydration of the samples. According to the investigational findings, the declining rate of drying was discovered throughout for all circumstances, as well as the water transport from the inner core of the sample to the outermost peel is predominantly regulated by the diffusivity phenomenon. Also, a large amount of evaporation of moisture was recorded in the early stages of drying of berry, but the final stage had a lower rate. At the initial stage (1 hour) of drying of the turkey berries in FBD, the highest and lowest drying rates are observed and estimated as 19.2 and 15.7 g of H_2O at 70 ^{0} C along with a constant air velocity of 4.2 m/s. The superior drying rate was observed for pre-treated samples and added inert materials in the samples in the fluidized bed, compared to the OSD, and it can be seen in Figure 3.

During the dehydration of samples (T1-T5) at 70 ^{0}C, the vapor pressure vigorously developed on the cell walls of interior of the fruit structures, so a considerable amount of the turgor pressure of the fruit structure was reduced. In addition, pre-treatment of the samples and the existence of the inert materials are both phenomena that modify the cell structure of the samples. As a result of the preceding, the porous structure of the sample increases dramatically and has the proclivity to generate additional micro-pores and facilitate water movement from the center to the surface of the fruits, as shown in Figures 5, 6 [5, 26].

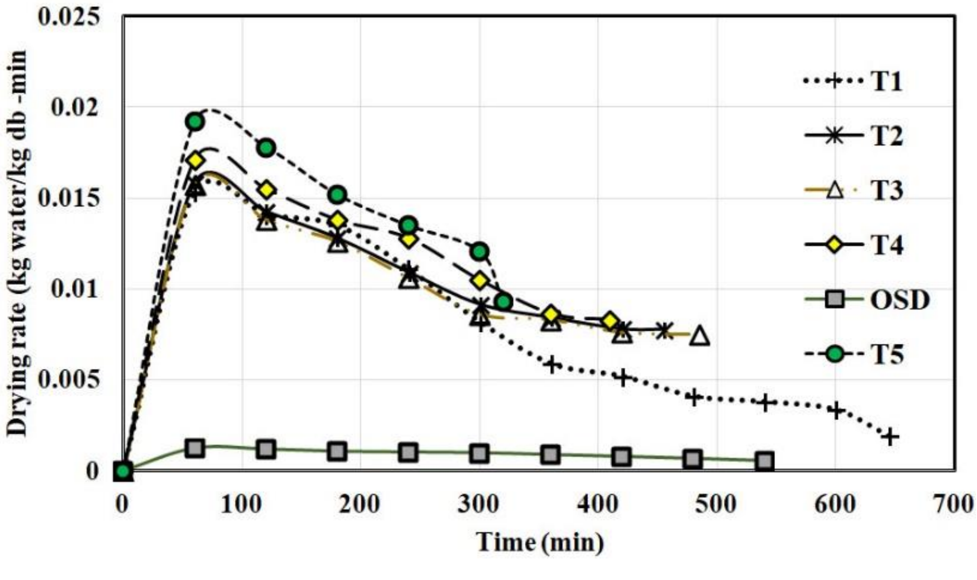


Figure 3. Drying with respect to time under various testing conditions

During the first day of the open sun drying (OSD), the outdoor conditions, such as atmospheric air temperature, varied from 29.2 to 36.5 ^{0}C, and the solar energy ranged from 420 to 1030 W/m^2. The highest temperature and sun irradiance were detected at 1.00 PM, and the following 7 days showed essentially identical tendencies. The Relative humidity and dry-bulb temperatures (D.B.T) of atmospheric air are measured by psychrometers, and their values are shown in Table 3. Similar to a thermometer, a pyranometer measures the availability of solar radiation, and Table 3 lists their values. The remaining six days' data also showed similar tendencies, thus it is not reported here. During the OSD, the highest and lowest evaporation rates were recorded and calculated to be 0.39 and 1.09 g of H_2O at the completion of the first day of investigation, respectively, and for the rest of the days, the same tendencies were observed. There is no substantial effect on cell structure at the OSD of the turkey berries; pore formation is inhibited by the wax layer, as seen in Figure 7. As low water migratory was transferred from the inner core to the outer surface of the berries [26], it can be seen in Figure 3. From this study, it can be inferred that the dehydration of turkey berries through pre-treatments such as combined physical treatments as well as the addition of energy carrier (Al) method enhances the evaporation rate positively.

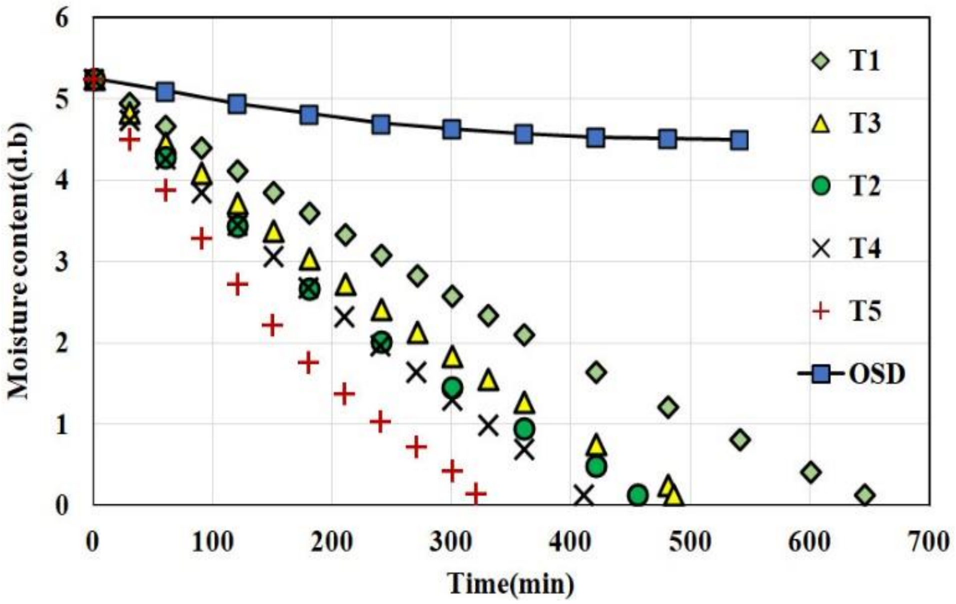


Figure 4. Moisture content with respect to time under various testing conditions

Figure 4 depicts the change in moisture level of the berries at various input parameters, and every line represents the amount of duration required to reduce the water potential from a beginning moisture content of 5.22 (d.b) or 84 % (w.b) to a final value of 0.14 (d.a). The change in water content of the berries at various pre-treated and un-treated conditions with a constant fluidized bed was seen in Figure 4. It is demonstrated that the water level of the berries progressively diminished with regard to time in all experiments, and that the dehydration period is significantly shorter in fluidized test conditions, irrespective of different pre-treatment methods, as shown in Figure 4.

Table 3. Average temperature and solar radiation values during open sun drying of turkey berries.

	Ambient conditions			
	Time (hr)	**Dry Bulb Temperature, T (^{0}C)**	**Relative Humidity, R.H (%)**	**Solar radiation, I (W/m^2)**
Day 1	9	31.2	62.1	830
	10	32.4	60.5	910
	11	33.5	58.2	970
	12	34.6	50.4	1000
	13	36.5	50.1	1030
	14	34.2	56.5	980
	15	32.1	59.5	950
	16	31.2	61.2	845
	17	30.1	67.6	610
	18	29.2	67.8	420

Cont Table 3

Day 2	9	30.8	61.9	825
	10	32.6	60.8	915
	11	33.8	59.2	965
	12	35.0	51.4	1005
	13	36.2	50.8	1020
	14	34.2	56.8	970
	15	31.8	60.2	945
	16	30.8	61.8	850
	17	29.9	68.0	600
	18	29.4	68.8	425

The drying period of untreated (T1), T2, T3, T4, and T5 samples was found to be 635, 455, 485, 410 and 320 min respectively, in FBD at constant drying conditions, as demonstrated in Figure 4. This can be deduced that when the samples are pre-treated by Hybrid-II method and the use of the energy carrier technique (Al), the dehydration period is diminished by approximately 50% compared to untreated samples.

As open sun drying is carried out from 9 a.m. to 6 p.m. per day, the water level of the samples minimizes gradually with respect to drying duration. The drying rates were slightly increase every an hour from morning to mid-day and higher drying rate observed mid-day (12-13.00 p.m) because of the solar radiation as well as higher D.B.T and low R.H values are recorded. After mid-day of drying process, the drying rate was decreased because of decreasing D.B.T and solar radiation of nature. Furthermore, the OSD took a total drying period of 72 hours to diminish water content from the approximate 84% (w.b) to a determined value of around 14%. At the completion of the day one, the water content of the berries was reduced to just 5.2 to 4.49 kg of H2O / kg of dry matter (d.b), as shown in Figure 4. From this study, it can be inferred that the dehydration of turkey berries through pre-treatments such as Hybrid-II treatment as well as the addition energy carrier method reduced drying time by 12 times and 10 times compared to open sun-dried samples. Pochont and coauthors, [20, 27] reported the same findings.

Mathematical modelling and statistical analysis

The statistical data including the values of the coefficient of determination (R^2), root mean square error (RMSE) and the sum of squared errors (SSE) of different models used are given in Table 4.

Table 4. Results of mathematical modelling and statistical analysis of the experimental moisture ratio data.

Model Name	Model coefficients	Different Experimental conditions					
		T1	**T2**	**T3**	**T4**	**T5**	**OSD**
Newton	R^2	0.9476	0.9632	0.9548	0.9561	0.9716	0.9161
	SSE	0.0602	0.0338	0.0389	0.0357	0.0220	0.0017
	RMSE	0.0740	0.0650	0.0697	0.0714	0.0605	0.0145
	Constants	k = 0.0028	k = 0.0043	k = 0.0037	k = 0.0045	k = 0.0065	k = $3.75x10^{-4}$
Page	R^2	0.9894	0.9930	0.9880	0.9896	0.9936	0.9845
	SSE	0.0121	0.0064	0.0103	0.0085	0.0049	0.0003
	RMSE	0.0348	0.0302	0.0384	0.0376	0.0314	0.0067
	Constants	k = 0.0002 n = 1.4881	k = 0.0005 n = 1.4071	k = 0.0003 n = 1.4291	k = 0.0004 n = 1.4448	k = 0.0010 n = 1.3654	k = 0.0025 n = 0.6768
Henderson &Pabis	R^2	0.9573	0.9692	0.9613	0.9619	0.9745	0.9458
	SSE	0.0491	0.0282	0.0333	0.0310	0.0197	0.0011
	RMSE	0.0701	0.0635	0.0690	0.0718	0.0628	0.0125
	Constants	a = 1.0758 k = 0.0030	a = 1.0603 k = 0.0045	a = 1.0589 k = 0.0039	a = 1.0566 k = 0.0047	a = 1.0418 k = 0.0067	a = 0.9844 k = 0.0033

Cont. Table 4

Logarithmic	R^2	**1**	**0.9992**	**0.9998**	**0.9997**	**0.9997**	**0.9974**
	SSE	**0.0000**	**0.0008**	**0.0002**	**0.0002**	**0.0002**	**0.0001**
	RMSE	**0.0022**	**0.0113**	**0.0054**	**0.0069**	**0.0072**	**0.0030**
	Constants	**a = 2.7307 k = 0.0007 b = -1.7291**	**a = 1.7458 k = 0.0018 b = -0.7404**	**a = 2.5339 k = 0.0010 b = -1.5372**	**a = 2.2721 k = 0.0013 b = -1.2734**	**a = 1.5105 k = 0.0032 b = -0.5104**	**a = 0.1759 k = 0.0037 b = 0.8268**
Midilli. *et al.*	R^2	**1**	**0.9993**	**0.9999**	**0.9997**	**0.9998**	**0.9995**
	SSE	**0.0000**	**0.0007**	**0.0001**	**0.0002**	**0.0002**	**0.0000**
	RMSE	**0.0019**	**0.0114**	**0.0041**	**0.0074**	**0.0080**	**0.0014**
	Constants	**a = 0.9989 k = 0.0010 n = 1.0562 b = -0.0006**	**a = 1.0014 k = 0.0018 n = 1.0827 b = -0.0005**	**a = 1.0010 k = 0.0023 n = 0.9274 b = -0.0010**	**a = 1.0002 k = 0.0023 n = 0.9876 b = -0.0009**	**a = 1.0003 k = 0.0039 n = 1.0194 b = -0.0007**	**a = 1.0003 k = 0.0011 n = 1.0405 b = 0.0007**
Logestic	R^2	0.9933	0.9692	0.9613	0.9925	0.9949	0.9214
	SSE	0.0077	0.0282	0.0333	0.0061	0.0039	0.0016
	RMSE	0.0292	0.0686	0.0745	0.0350	0.0314	0.0162
	Constants	a = 1.1852 k = 0.0063 b = 0.2175	a = -6933.1 k = 0.0045 b = -6540.3	a = -7816.6 k = 0.0039 b = -7383.6	a = 1.2477 k = 0.0095 b = 0.2716	a = 1.3917 k =-0.0118 b = 0.4068	a = 116.76 k = -2.8585 b = 119.33

Based on the criteria of highest R^2, lowest RMSE, and SSE values, the most suitable model describing the drying characteristics of turkey berries is identified as the Midilli et al. (2002) model [1], among other models. Among the six models, both the Logarithmic and Midilli et.al., [1] models are better fitting. However, among both of these, Midilli et.al. (2002), better than the Logarithmic model. The calculated R^2 value is ranging from 0.9993 to 1, RMSE value ranging from 0.0014 to 0.0114 and SSE value varying from 0000 to 0.0007 as given Table 4. Similarly the coefficient values of the Midilli et al. [1] model were calculated and are presented in Table 4.

Effective Moisture Diffusivity

Figure 5 depicts the variation of *Ln* (*MR)* as a function of drying time at the OSD and FBD conditions. The fruit's D_{eff} values were calculated using Eq. 7, and its R-squared (R^2) was estimated using the linear equation, as listed in Table 5. For untreated samples (T1), the D_{eff} value was estimated as 2.928×10^{-10} m^2s^{-1}, whereas open sun drying achieved only 5.78×10^{-11} m^2s^{-1}. Similarly, the D_{eff} values of the chemical pre-treated (T3) samples, hybrid pre-treated samples (T4), and (T5) were calculated as listed in Table 5. Further details of the D_{eff} of samples (T1-T5) are described by the previous author [7, 26].

Table 5. Values of moisture diffusivity and physiochemical quality at different drying conditions

Test methods	**D_{eff} (m^2/s)**		**Volumetric Shrinkage (%)**	**Total Color change(ΔE)**	**Vitamin-C content (mg/100g d.m)**
	x 10^{-10}	**R^2**			
T1	2.928	0.9248	55.3	14.68	1.13
T2	4.823	0.9876	39.8	9.14	1.39
T3	4.446	0.9599	47.1	8.26	1.43
T4	5.342	0.9589	41.8	9.04	0.99
T5	6.126	0.9628	39.4	8.31	1.36
OSD	0.578	0.9555	72.3	22.38	0.45

The D_{eff} value of T5 rises dramatically as a result of more micro-pores or cracks forming on the skin of the turkey berries as a result of better convective heat and mass transport occurring during the dehydration of the samples. The D_{eff} the value of turkey berry lay down within the limit of 10^{-8} to 10^{-11} m^2/s, as the range of D_{eff} values of most of the food commodities, reported by Tasirin and coauthors [14]. Untreated and pre-treated turkey berries are dried at 70 ^{0}C in the FBD. The higher processing air temperature (70 ^{0}C) and pre-treatment methods used to produce vapor pressure on the fruit's cellular structure significantly reduced the turgidity of the cell membrane and increased the porous structure of the sample, thereby enhancing porosity. Whereas in the OSD, the D_{eff} value was lower than in fluidized bed drying conditions because of the atmospheric conditions like low wind speed and fluctuating temperature. The test results reveal that increased evaporation rates and D_{eff} values are directly proportional and the same results reported by Aral & Beşe [29-31].

Volumetric Shrinkage

Table 5 shows the change in volumetric shrinkage (%) at various tests, and the change in dimensions of the berries was calculated by Eqn. 9. The experimental results undoubtedly show that the drying method and pre-treatment technique have a substantial effect on the samples' shrinkage. Table 5 reveals that T5 treated samples had 39.4 % less volumetric shrinkage. Open sun drying, on the other hand, resulted in a higher volumetric shrinkage of 72.3%. According to Figure 7, the turkey berries dehydrated at OSD have significantly altered their shapes, making them undesirable compared to berries dried under the FBD. The largest dimension variations were noticed once the samples were dried at the OSD, low flow rate of air, and low atmospheric air temperature due to minimal permeability, smaller moisture differences on the inner and outer surfaces, and minimal vapor tension development on the cell structure [13, 29-30].As a result, it is possible to deduce that the processing temperature, pre-treatment methods and drying methods has a substantial impact on differ the shape/ volume of the fruits. According to Hatamipour and Mowla [13], reduction in volume/shape of the product is negatively related to the evaporation rate of moisture.

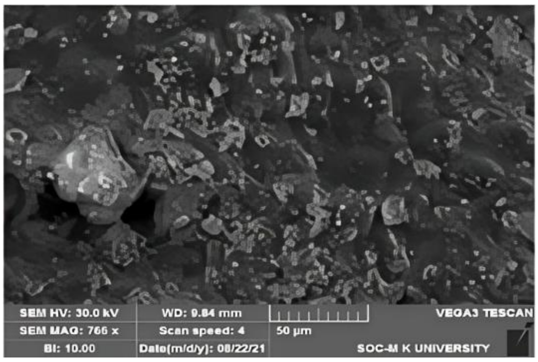
Total Color Change

In the food sector, color is one of the most important quality indicators of food attributes, and color degradation is undesirable. The method of drying and sample preparation were both more influenced by the change in color of the product and the equation (Eq.10) was used to compute the total color change of the products. The brightness (L_i) of 71.2, greenness (a_i) of -7.83, and yellowish color (b_i) of 25.96 were used to calculate the fresh fruit color values in this investigation. The total color difference (TCD or ΔE) between dehydrated samples was determined to be substantively different as indicated in Table 5. At different test conditions (T1-T5), the estimated TCD scores for dehydrated samples ranged from 8.26 to 14.68, where as in open sun drying, it was measured as 22.38. The TCD values of traditional drying are 3 times higher than per-treated samples (T5) dried in FBD. When the sample dried under the open sun, it took 72 hours for the specified final moisture content to be attained. As a result, both low-temperature and prolonged drying periods negatively affected the skin color of the products. Consequently, both caramelization and enzymatic browning reactions occurred. Table 5 and Figures (6-7) shows that both parameters like brightness and yellowish color were dramatically lowered, resulting in greater change in to darkness as well as decreased greenness. Table 5 and Figures 6-7 illustrate the influence of the changes in the surface color of the berries when dried under the FBD and traditional drying (OSD). Commonly, when the foodstuffs are subjected to high-temperature settings, total phenolic acids are oxidized, and carbohydrates or amino acids undergo chemical reactions. According to Deng and coauthors [10] and Vásquez-Parra and coauthors [9], the amount of color deviations was affected by drying air temperature and processing duration, as well as the amount of oxygen present in flow of inlet air.

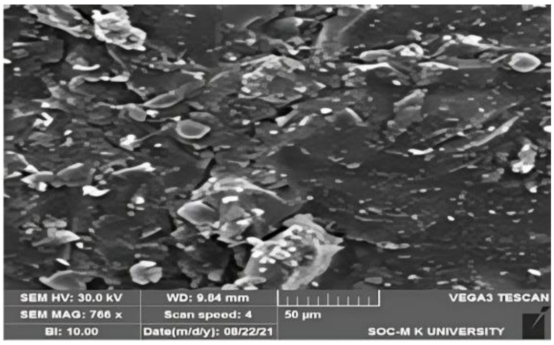
Vitamin -C Retention

The Vitamin-C content of dried turkey berries is shown in Table 5. The vitamin-C level of raw fruit was 3.83 ± 0.27 mg / 100 g d.m, which is almost identical to Lim's data [2]. Table 5 shows that the vitamin-C degradation of dried samples from the FBD and conventional drying (OSD) differ substantially. According to research observations, Vitamin-C level retention was around 1.13 of T1, 1.39 of T2, 1.43 of T3, 0.99 of T4, and 1.36 mg/100g d.m of T5 under fluidized bed conditions, while in OSD it was only around 0.45 mg/100g dm. Because vitamin-C is a sensitive component that is affected by light and heat, it is lost unavoidably during the dehydration of fruits. Because the samples are exposed to prolonged solar radiation and oxidation processes are involved in the OSD.

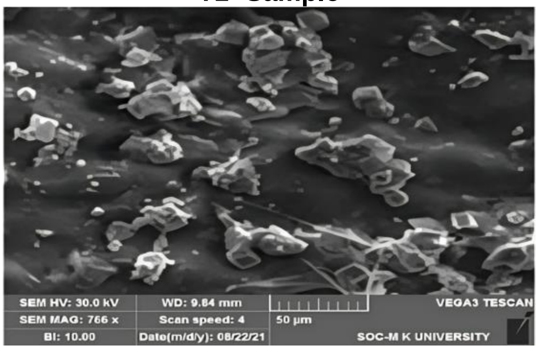
Evaluation of the micro-structure of the berry



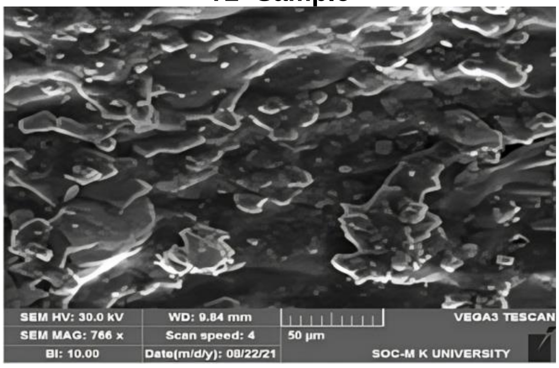
T1- Sample



T2- Sample



T3- Sample



T4- Sample

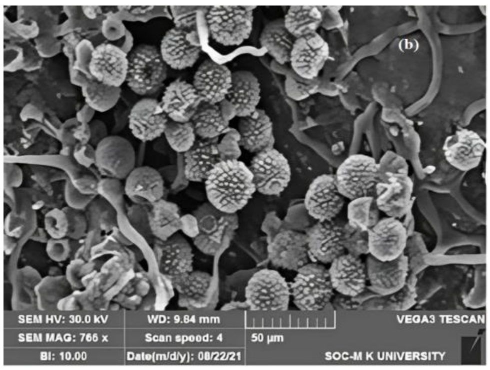
Figure 5. SEM images of dried samples at the FBD

Figure 5-7 shows the pictures and SEM images of the dried samples under the FBD and OSD conditions. The SEM image of a raw turkey berry, seen in the previous published article [7, 26], reveals the waxy covering on its skin. According to previous author reports [7, 26], whenever the berries are dehydrated at hot air inlet temperatures (above 60 ^{0}C), the waxy-covered surface begins to disintegrate or break, allowing pores to develop.

Both Figures 5 and 6 reveal a decomposed waxy surface layer, as well as micro-pores and tiny tears upon that peel of the beery depicted in Figure 6. It is reasonable to conclude that the superior drying rate was achieved because of the numerous micro-pores created by the Hybrid-II pre-treatment on the samples (T5).

The surface of the pre-processed berries exhibits higher porous structures that are formed as a result of the high evaporation rate that occurred. The photo and SEM images of the berry skin dried in the OSD are shown in Figure 7. The wax covering on the surface of the beery is slightly or partially removing when they are dried at OSD, as seen in Figure 7 (b).

(a) T5- Dried sample



(b)T5- SEM image

Figure 6. Hybrid pre-treated dried samples (a) photo image (b) SEM image

Finally, it can be concluded from the results that the pre-treatment method as well as the inlet temperatures of processing air (70 ^{0}C) consequently increase the internal stress on the cell wall and alter the cell structure. This may cause enhanced vapor pressure and result in greater water permeability from the interior of the sample. Aral and Beşe [29], Adiletta and coauthors [8] and Vásquez-Parra and coauthors [9], noticed the same tendency. Furthermore, higher volumetric shrinkage was found under traditional drying (OSD) compared to fluidized bed drying conditions.

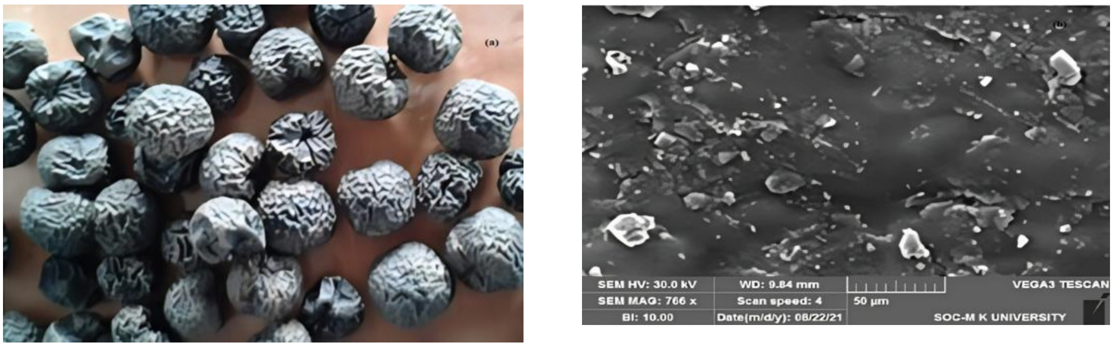


Figure 7. Dried samples of OSD (a) photo image (b) SEM image

CONCLUSIONS

The result shows the effects of different method of pre-treatments, like chemical, combined chemical, and hybrids as well as addition of inert material on the drying behavior and quality of turkey berry samples were studied through the FBD and compared with OSD. Taking all the research observations into account, the main results can be taken from the investigations. The highest evaporation rate was achieved when the samples were dried under pre-treated and inert material conditions because the wax layer of the berries was disintegrated or removed and enhancing the phenomena of the heat and mass transfer mechanism. The samples were dried at constant drying conditions in the FBD, the T4 and T5 pretreated methods, resulting in greater wax removal and micro-cracks than when the fruits were exposed to other pre-treatment methods. At constant drying conditions in the FBD, higher effective moisture diffusivity was obtained at Hybrid-II pre-treated methods of 6.126 x 10^{-10} m^2/s, while in the OSD it was only 0.578 x 10^{-10} m^2/s. When the OSD and un-treated samples were compared with T5 dried samples, the Hybrid-II pre-treatment methods achieved results such as the shortest drying period, the lowest shrinkage, acceptable color change, and the second greatest retention of vitamin C. When the samples were dried after the addition of inert materials in FBD, the maximum retention of vitamin C was achieved. When the OSD and un-treated samples were compared with Al-inert materials (T2) drying conditions, the dried samples resulted in the least color degradation and Vitamin C losses. The most undesirable color change and the least amount of fruit quality retention were noticed when the samples were dried in the OSD compared with the FBD conditions. The most effective model for estimating the drying characteristics of turkey berries was predicted, the Midilli et al., (2002) model better than the other five models.

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REFERENCES

1. Midilli AD, Kucuk HA, Yapar Zİ. A new model for single-layer drying. Drying Technol. 2002 Jul 23; 20(7):1503-13.
2. Lim TK, Lim TK. Solanum torvum. Edible Medicinal And Non-Medicinal Plants: Volume 6, Fruits. 2013:429-41. https://doi.org/10.1007/978-94-007-5628-1_48
3. Mujumdar AS. Hand book of industrial drying. 3rd edition. New York, Marcel Dekker; 2006.
4. Smith PG. Applications of fluidization to food processing. Oxford, UK, Blackwell Science; 2007.
5. Amiri Chayjan R, Kaveh M. Physical Parameters and Kinetic Modeling of Fix and Fluid Bed Drying of Terebinth Seeds. J. Food Process. Preserv. 2013 Mar 14; 38(3):1307–20.
6. Khanali M, Banisharif A, Rafiee S. Modeling of moisture diffusivity, activation energy and energy consumption in fluidized bed drying of rough rice. Heat Mass Transfer. 2016 Jan 25; 52(11): 2541–9.

7. Barathiraja R, Thirumal P, Saraswathy G, Rahamathullah I. Drying of turkey berry in a fluidized bed dryer with mild steel, copper and aluminum inert materials: kinetics and quality determination. J Mech Sci Technol. 2021, May 22; 35(6): 2707–17.
8. Adiletta G, Russo P, Senadeera W, Di Matteo M. Drying characteristics and quality of grape under physical pretreatment. J. Food Eng. 2016 Mar 1; 172: 9–18.
9. Vásquez-Parra JE, Ochoa-Martínez CI, Bustos-Parra M. Effect of chemical and physical pretreatments on the convective drying of Cape gooseberry fruits (Physalis peruviana). J. Food Eng. 2013 Dec; 119(3): 648–54.
10. Deng LZ, Mujumdar AS, Zhang Q, Yang XH, Wang J, Zheng ZA, et al. Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes–a comprehensive review. Crit. Rev. Food Sci. Nutr. 2017 Dec 20; 59(9): 1408-32.
11. Puspasari I, Talib MZM, Daud WRW, Tasirin SM. Drying Kinetics of Oil Palm Frond Particles in an Agitated Fluidized Bed Dryer. Drying Technol. 2012 May; 30(6): 619–30.
12. Yun MT, Puspasari I, Tasirin MS, Talib MZM, Daud WRW, Yaakob Z. Drying of oil palm frond particles in a fluidized bed dryer with inert medium. Chem. Ind. Chem. Eng. Q. 2013 Jan 1; 19(4): 593-603.
13. Hatamipour MS, Mowla D. Drying behaviour of maize and green peas immersed in fluidized bed of inert energy carrier particles. Food Bioprod. Process. 2006 Sep; 84(3): 220-6.
14. Tasirin SM, Puspasari I, Lun AW, Chai PV, Lee WT. Drying of kaffir lime leaves in a fluidized bed dryer with inert particles: Kinetics and quality determination. Ind. Crops Prod. 2014 Nov; 61: 193-201.
15. Murthy ZVP, Joshi D. Fluidized bed drying of aonla (Emblica officinalis). Drying Technol. 2007 Jun; 25(5): 883-9.
16. Tasirin SM, Kamarudin SK, Jaafar K, Lee KF. The drying kinetics of bird's chillies in a fluidized bed dryer. J. Food Eng. 2007 Mar 1; 79(2): 695-705.
17. Jadhav DB, Visavale GL, Sutar N, Annapure US, Thorat BN. Studies on solar cabinet drying of green peas (Pisum sativum). Drying Technol. 2010 May 13; 28(5): 600-7.
18. Borah A, Sethi LN, Sarkar S, Hazarika K. Effect of drying on texture and color characteristics of ginger and turmeric in a solar biomass integrated dryer. J. Food Process Eng. 2017 Feb; 40(1): e12310.
19. Sivakumar DS, Subramani S, Thirumalai NV, Marimuthu MK, Arockiaraj GA. Mathematical modeling of thin layer drying characteristics and proximate analysis of Turkey berry (Solanum torvum). Therm. Sci. 2022 Dec; 26(2):825-34.
20. Pochont NR, Mohammad MN, Pradeep BT, Kumar PV. A comparative study of drying kinetics and quality of Indian red chilli in solar hybrid greenhouse drying and open sun drying. Mater. Today: Proc. 2020 Jan 1; 21: 286-90.
21. Kumar Natarajan S, Sankaranarayanasamy K, Ponnusamy S, Kavya Chowdary V, Kumar J, Rahul D, et al. Experimental comparative study on reduction in the moisture content of cucumber in a double slope solar dryer with open sun drying method. J. Phys. Conf. Ser,2019 Aug; 1276(1):012054. IOP Publishing.
22. Rabha DK, Muthukumar P, Somayaji C. Experimental investigation of thin layer drying kinetics of ghost chilli pepper (Capsicum Chinense Jacq.) dried in a forced convection solar tunnel dryer. Renewable energy. 2017 May 1;105:583-9.
23. Kumar A, Rai AK. Comparative Study of Open Sun Drying & Solar Cabinet Drying Techniques for Drying of Green Chilies. Int. J. Prod Technol Manag. 2016;7(1):18-26.
24. Gwala W, Padmavati R. Comparative study of degradation kinetics of ascorbic acid (vitamin C) in tray drying, solar drying and open sun drying of pineapple slices, Austin J Nutr Metab. 2015 May 20; 2(1): id1014.
25. Association of Official Analytical Chemists (AOAC). Official methods of analysis Vol. 11, 16th edn. AOAC, Arlington, VA; 1995.
26. Barathiraja R, Thirumal P, Saraswathy G, Rahamathullah I. Effects of pretreatments on drying of Turkey berry (Solanum torvum) in fluidized bed dryer. Chem. Ind. Chem. Eng. Q. 2022 May 25; 28(3):169-78.
27. Kebede BH, Forsido SF, Tola YB, Astatkie T. Effects of Variety and Curing and Drying Methods on Quality Attributes of Turmeric (Curcuma domestica) Powder. Braz. Arch. Biol. Technol. 2021 Nov 19; 64: e21200697.
28. Martins TS, Sousa TS, Sales VH, Bandeira MD, Higuita DM, Vélez HA. Comparison between thin-layer models and non-traditional methods in the modelling of drying kinetics of crustacean wastes. Braz. Arch. Biol. Technol. 2021 Jul 5; 64: e21210130.
29. Aral S, Beşe AV. Convective drying of hawthorn fruit (Crataegus spp.): Effect of experimental parameters on drying kinetics, color, shrinkage, and rehydration capacity. Food Chem. 2016 Nov 1; 210: 577-84.
30. Altino HO, Locatelli KM, Cunha RN. Influence of Drying Conditions on the Final Quality of Cherry and Grape Tomatoes. Braz. Arch. Biol. Technol. 2018 Nov 14; 61: e18180054.
31. Beşir A, Gökmen S, Gül LB, Yazıcı F, Gül O. Evaluating of microwave drying for hawthorn slice as alternative to convective drying. Braz. Arch. Biol. Technol. 2022 Jun 27; 65: e22210614.