

Development and Validation of an Airflow and Heat Transfer Model for Thin Layer Forced-Air Drying of Plums

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ABSTRACT

Solar drying is an important method of maintaining food security and food quality through safe process of lowering the level of moisture content in Horticultural products. Although it works, one of the major problems is to optimize the process to have the energy efficiency and quality of products. The literature in the past, on plum drying has tended to involve taking the thin-layer models that simplify the convective conditions based on the fact that the mass and heat transfer coefficients are constant. This paper fills this gap by creating a more realistic more physics-based model which combines detailed airflow dynamics with product drying kinetics of forced-air plum drying. In a Completely Randomized Design with three repetitions a whole plum were dried in a chamber that was attached to a flat-plate solar collector under three temperatures (45-65 °C) and three velocities of air (0.1-1.0 ms⁻¹). The maximum moisture loss (2.629 % WB) and moisture diffusivity (1.76 x 10⁻⁹ ms⁻¹) was highest at 65d °C and maximum activation energy (46.97 KJ.mol⁻¹) was highest at this temperature. The best model to have explained the drying kinetics was the Modified Page model; (R² = 0.99, RMSE = 0.08, χ^2 = 0.62). The findings clearly indicate that the most significant factor which had a statistically significant bearing on moisture removal was temperature, whereas air velocity did not have a significant influence. This proven model is a sound mechanism of optimizing the mechanics of the processes, which allows the development of more effective solar dryers that do not waste energy and at the same time, they are able to maintain the quality of the product.

Keywords: Heat transfer, forced-air drying, plum drying, drying kinetics model

INTRODUCTION

Plums (*Prunus Domestica* L.) belong to the *Rosaceae* family of angiosperm trees and are distributed throughout the northern temperate regions of the globe. They are part of the same family as nectarines, peaches, cherries, apples, berries, apricots, and

almonds. Plums are medium-sized stone fruits, typically with dark purple or red skin. They contain a fair number of important vitamins and minerals while being relatively low in calories. In addition to their nutritional value, plums offer numerous health benefits; they are rich in vitamins and were historically used to treat gastrointestinal diseases. They are considered one of the first fruits to be domesticated (Ahmadi et al., 2008). It is a temperate fruit and grown in climates with well-differentiated seasons. It requires a moderately high temperature in the spring and early summer and Moderately cold winter (Kurmanov *et al.*, 2015). The plum is a high-cost fruit and consumed mostly in its fresh state with over 70% of the product delivered by the fresh produce market. It is susceptible to mechanical damage, microbial decay and water loss. However, plum is one of the most perishable fruits and in some

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cases, these prevent the product from reaching the consumer at its optimal quality after transport and distribution (Manganaris *et al.*, 2007).

According to FAO statistics (2022), the world's largest producers are Iran, Turkey and Czech Republic, accounting for world production of plums are 23.1, 21.6 and 14.7% respectively, followed by Pakistan, Spain, Italy, Uzbekistan, Algeria, Japan, Morocco, Egypt. It is used for preparation of jellies, jam, marmalades, pulp, juices, nectars and extruded products, and consumed in fresh, dried and frozen forms (Sevil *et al.*, 2019). In Pakistan, there is a high demand of dried plums called Alobukhara. It has a good demand in market and also used in different dishes, juices and consumed as whole dried fruit. It is considered to be a good tonic for weight lost and removing toxic materials from the liver. For this purpose, it is mixed with tamarind (Imlli) and consumed as a syrup called Alobukhara syrup (Hussain, 2018).

Plums are usual fruits that are dried to preserve them, which inhibits the effect of water enhancing the shelf life, as well as less weight and bulk that enhances storage and transportation (Onwude *et al.*, 2016; Ertekin and Firat, 2017). Forced air convective drying is especially appropriate with fruits having a high moisture content, and it can be incorporated in industrial lines with an easy-to-use tunnel or conveyor dryers (Goyal *et al.*, 2007; Menges and Ertekin, 2006; Bardavelidze *et al.*, 2025). Nevertheless, it is a resource-intensive technology prone to the compromise of product quality and requires optimization of drying operations to save time and energy without compromising on the quality (Onwude *et al.*, 2016; Akter *et al.*, 2022; Castro *et al.*, 2018). The heat and mass transfer mathematical modeling of drying kinetics can also be employed as a potent optimization tool in different circumstances without involving intensive experimentation (Onwude *et al.*, 2016; Ertekin and Firat, 2017; Akter *et al.*, 2022; Reverberi *et al.*, 2022).

In the case of plums and other produce, when dried, the diffusion between the inside and the outer part of the produce takes charge than evaporation at a constant rate (Goyal *et al.*, 2007; Menges and Ertekin 2006; Togrul and Pehlivan 2004). The moisture content is associated with drying time through thin-layer models, common models that are used in many industries. Research on plum drying has demonstrated that such models as the logarithmic form, the Midilli *et al.* one, and modified Henderson-Pabis form can be used to explain the drying behavior and the parameters of these models are also dependent on air temperature and velocity (Goyal *et al.*, 2007; Menges and Ertekin, 2006; Togrul and Pehlivan, 2004). The effective moisture diffusivity can also be estimated using these

models (Goyal *et al.*, 2007; Menges and Ertekin, 2006; Tzempelikos *et al.*, 2015).

In traditional thin-layer models the constant convective coefficients are generally taken as simple in the approach to airflow. More recent developments in conjugate and CFD modeling evidences that spatial and temporal changes in the airflow generate heterogeneous local transfer coefficients, which results in local disparity between temperatures, moisture, and quality in the fruit (Defraeye & Radu, 2017; Defraeye and Radu, 2018; Tzempelikos *et al.*, 2015; Zhao *et al.*, 2021). An approach that is more precise involves product drying models with detailed airflow modeling to better examine the areas of influence of the design of the dryer and its operating conditions (Defraeye & Radu, 2017; Defraeye & Radu, 2018; Maphosa *et al.*, 2025; Akter *et al.*, 2022; Castro *et al.*, 2018). In the case of plums, outlet conditions have been predicted using integrated dynamic models, which prove to be effective and promising to enhance the control of processes and energy efficiency (Bardavelidze *et al.*, 2025).

Recent advances in drying science have emphasized the importance of accurate thin-layer drying models for predicting moisture behavior under variable solar drying conditions. Recent work has shown that these models—especially Page-type and Midilli-type—remain highly reliable for agricultural products dried using solar-assisted systems (Kidane *et al.*, 2025).

This means that a coordinated airflow and heat transfer model of thin-layer plum drying is a significant unfinished stage toward a mechanistic insight and optimistic industrial drying. Onwude *et al.* (2016), Ertekin and Firat (2017) and Defraeye and Radu (2017) point out that such a model, incorporating justified kinetic models, with realistic convective transfer physics can inform the design of more efficient dryers, use less energy, and improve the quality of dried plum products.

MATERIALS AND METHODS

Site Description

The research study was performed in the Department of Agricultural Mechanization and Renewable Energy Technologies in the year 2020. The University of Agriculture, Peshawar, Pakistan. The study area is located at 34.01° N latitude and 71.35° E longitude at an altitude of 350 m above sea level in Peshawar valley, Pakistan, with a sub-tropical climate (Ahmad *et al.*, 2019). Peshawar is located approximately 1600 km north of the Indian Ocean (Alam *et al.*, 2020). The Indus River also enters the city in the northwest and then splits into various other small channels. Generally, its subsoil strata are composed of boulders and gravel and are overlain by sand, clay, and silt. The valley of Peshawar is covered with split-up deposits of sand, silt, and pebbles from recent geological times

(Basit et al., 2022). Both summer and winter weather are extreme (Basit et al., 2019), characterized by severe winter and hot prolonged summer, where the average minimum temperature during winter is 5 °C, while during summer, the average maximum temperature reaches up to 45 °C. The wettest month (with the highest rainfall) is March (78 mm), and the driest month (with the lowest rainfall) is June (7 mm) (Gilani et al., 2021; Sajid et al. 2020).

Experimental Design

The research was carried out in completely randomized design (CRD) with temperature and air velocity as factors having three levels with three replications. The total number of treatments was 9 in the study.

Table 1. Experimental Factors and their Levels

Factor 1 T1 T2 T3	Temperature 45±1 °C 55±1 °C 65±1 °C
Factor 2 V1 V2 V3	Air Velocity 0.1 ms ⁻¹ (Natural) 0.5 ms ⁻¹ 1.0 ms ⁻¹

Solar Irradiance

Solar irradiance was determined by using sun power meter during sunshine in experimental time.

Sample Preparation

Approximately uniform size of plums was selected and used (50±5 grams). The collected samples were stored at 3±0.5 °C for 1 hour before using in experiments. Moisture content of plums was determined with oven drying method at 100 °C in a vacuum oven (model EV 018, Nuve laboratory and sterilization Tech.) for 24 hours. The initial moisture content of plums samples was 87±1.0 % (Bano et al., 2015).

Drying Process

Drying experiments were performed in a flat plate solar collector (FPSC) with dryer. The dryer consists of centrifugal fan to supply the air flow and an electronic proportional controller (ENDA, EUC442). Prior to drying of plums samples were blanched by dipping in hot water at 80 °C for 5 minutes. These samples were immediately cooled down in tap water at room temperature to avoid excess heat and placed on tissue paper to absorb the excess surface water prior to drying. The plums were immersed in 2% potassium metabisulfite solution at 35 °C for 10 minutes (Lopez et al., 2018). The dryer was turned on about 1 hour before the drying process to reach steady-state or equilibrium conditions before each drying experiment. After the steady state conditions for the operation temperature, Plums were placed on the tray of the dryer and dried simultaneously. The drying experiments were performed at 45,55 and 65 °C air temperature. The air velocity was kept at 0.1,0.5 and 1.0 ms⁻¹ in drying chamber. During drying the samples were taken after 2 hours intervals and

weighed, before being returned to the dryer (Hanif et al., 2018).

At the end of each drying experiment, the final moisture content of the samples was determined. Samples were dried with approximately 15% final moisture content. Moisture content was given in wet basis. The amount of dry matter was calculated by using the mean final moisture content and weight of the dried plums (Khattak et al., 2019). The moisture contents were also expressed in dry basis. All the experiments were replicated three times at each air temperature and average value.

Mathematical Modeling of Drying Curves

Mathematical models that describe drying mechanisms of plums provide the required temperature and moisture information. The best model describing the drying behavior of plums is selected by testing the five commonly used thin layers drying models given in Table 1. However, the moisture ratio (MR) was simplified to M/Mo instead of the (M – Me) / (Mo – Me)

To develop and test the physical applied model for the moisture loss ratio .

The coefficient of determination (R²), Root means square error (RMSE) and reduced chi square (X²) obtained from these equations were used to compare the relative goodness of fit of experimental data. These parameters can be calculated as follows.

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

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

$$X^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - Z} \dots \dots \dots [3]$$

Table 2. Mathematical models applied to drying curves

Model name	Model Equation	References
Logarithmic	MR = α exp (-kt) + c	Onwude <i>et al.</i> , 2016
Lewis	MR = exp (-kt)	Agbossouet <i>et al.</i> , 2016 Henderson and Pabis
Page	MR = α exp (-kt)	Olabinjo <i>et al.</i> , 2017
Modified Page	MR = exp (-ktn)	Hichamet <i>et al</i> 2018
	MR = exp[-(kt)n]	Hanif <i>et al.</i> , 2015

Variations of moisture content with drying time of blanched (B) and immersed in 2 % potassium metabisulfite solution (I) plums at different air temperatures. MR_{exp, i} is the ith experimentally observed moisture ratio, MR_{pre, i} is the ith predicted moisture ratio. N is the number of observation and Z is the number of constants.

The best model describing the drying behavior of plums were chosen as the one with the highest coefficient of determination and the least mean relative percent error and the least root mean square error. In addition, reduced Chi square was used to determine the goodness of the fit. The lower values of reduce Chi square, the better goodness of the fit (Agbossou *et al.*, 2016).

Calculation of Effective Moisture Diffusivity

The experimental drying data for the determination of moisture diffusivity was interpreted by Fick’s Second law of diffusion. The solution of Fick’s second law in spherical coordinates is given below (Eq. 4), with the assumption of moisture migration being by diffusion, negligible shrinkage, constant diffusion coefficients and temperature (Hicham *et al.*, 2018).

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(- \frac{n^2 \pi^2 D_{eff} t}{R^2} \right) \dots \dots \dots [4]$$

$$\ln (MR) = \ln \left(\frac{6}{\pi^2} \right) - \left(\frac{\pi^2 D_{eff} t}{R^2} \right) \dots \dots \dots [5]$$

The effective moisture diffusivity was calculated by using the method of slopes. Diffusion coefficients are typically determined by plotting experimental drying data in terms of ln (MR) versus time as given in Eq. (5) From Eq. (5), (Hanif *et.*, 2016) a plot of ln (MR) versus time gives a straight line with a slope of

$$\text{Slope} = \frac{\pi^2 D_{eff}}{R^2} \dots \dots \dots [6]$$

Calculation of Activation Energy

Arrhenius type equation is using to calculate the activation energy (Ea) (Onwude *et al.*, 2016)

$$D_{eff} = D_o \exp \left(\frac{-E_a}{RT} \right) \dots \dots \dots [7]$$

Where D_o is the pre-exponential factor of the Arrhenius equation (m²s⁻¹), E_a is the activation energy (KJ.mol⁻¹), R is the universal gas constant (kJmol⁻¹ K⁻¹), and T is the absolute air temperature (K). The activation energy is determined from the slope of the Arrhenius plot, ln (D_{eff}) versus T⁻¹.

Parameters studied

The study focused on evaluating key parameters influencing the drying process, including solar irradiance, temperature, and humidity of both the dryer and ambient air. Changes in moisture content were monitored to determine moisture loss and drying rate throughout the process. Moisture diffusivity was calculated to understand internal moisture movement, while activation energy was estimated to describe the temperature dependence of moisture diffusion. In addition, the applicability of various thin-layer drying models was assessed based on their ability to accurately predict the moisture loss ratio during drying.

Statistical Analysis

The research was carried out in completely randomized design (CRD). The significance of differences among the treatments were analyzed with the help of ANOVA. Statistical significances were set at P-value of <0.05 (Liu *et al.*, 2011).

RESULTS

Solar Irradiance

The solar irradiance data of the site is given in figure (1) . The results show that solar irradiance was received by the solar collector from 6:00 am to 7:00 pm. There were 11 hours of sunshine duration in total. At 6 am the solar radiance was 100 w.m⁻², which increased with time and at noon 12:00 maximum solar irradiance of 890 w.m⁻² was recorded. The fluctuation then began to decrease and at 7:00 pm it was recorded that 120 w.m⁻² of solar irradiance was available, which became zero at 8:00 pm.

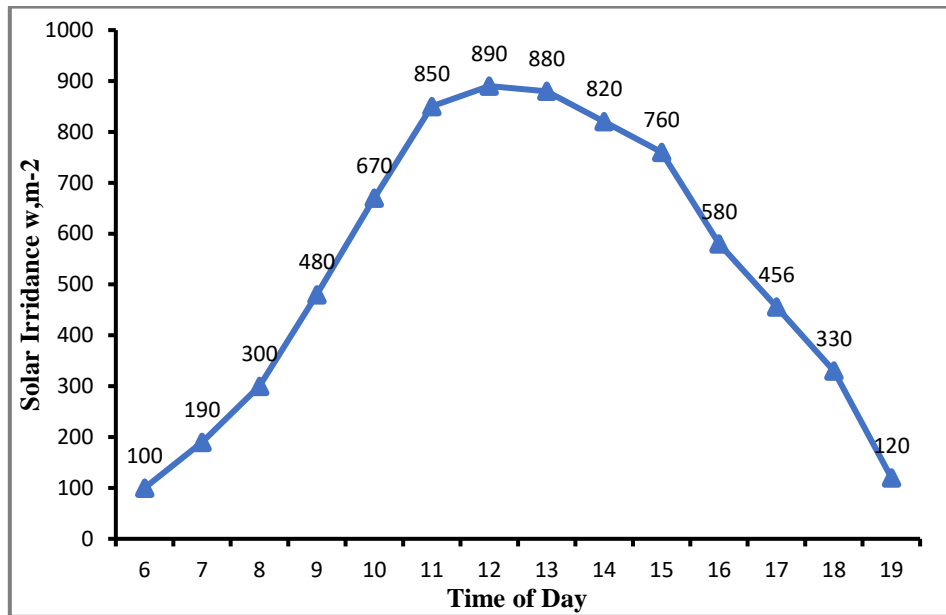


Figure 1. Solar Irradiance at different day timings during the experimental period

Temperature and Humidity of dryer and ambient air

Temperature and humidity data of the dryer assembly of the solar collector is given in Figure 2. The ambient temperature data shows that at 6:00 am the recorded ambient temperature was 32 °C which gradually rose to 34 °C at 10:00 am and reached the maximum at 1:00 pm. It again decreased gradually and reached 35 °C at 7:00 pm similarly the dryer temperature shows that it was

40 °C at 6:00am, which gradually increased to 44 °C at 10:00 am and reached a maximum of 52 °C at 1:00 pm. It again started decreasing gradually and reached 35 °C at 7:00 pm. The humidity data of the dryer showed that relative humidity of the dryer was 60 % at 6:00 am which gradually decreased to 26 % at 10:00 am and reached a maximum of 19 % at 2:00 pm. It again increased and reached 39 % at 7:00 pm (Figure 2).

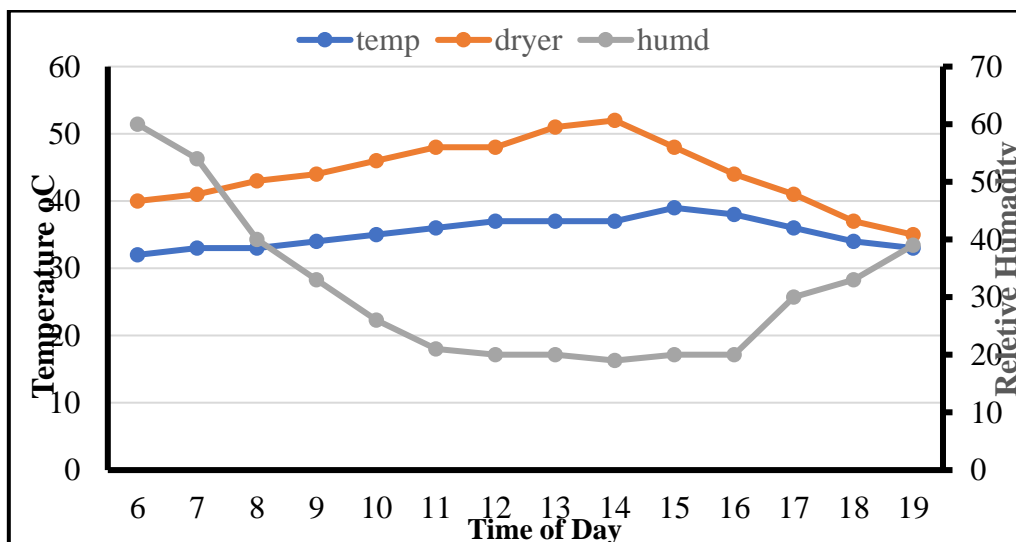


Figure 2. Temperature and Humidity of the dryer at different day timings during the experimental period.

Moisture Loss per hour

The results of moisture loss per hour by plums under different velocities at 45 °C temperature are

given in Figure 3. The initial moisture content was 85%, which was reduced to less than 10 %. It took almost 26 hours during drying to achieve this

moisture at air velocity of 0.1 ms⁻¹. Moisture content was reduced to 81 % after two hours of drying and reached 51 % at 13 hours of drying

interval. It reached 28 % after 20 hours of drying and reached 9 % after 26 hours of drying.

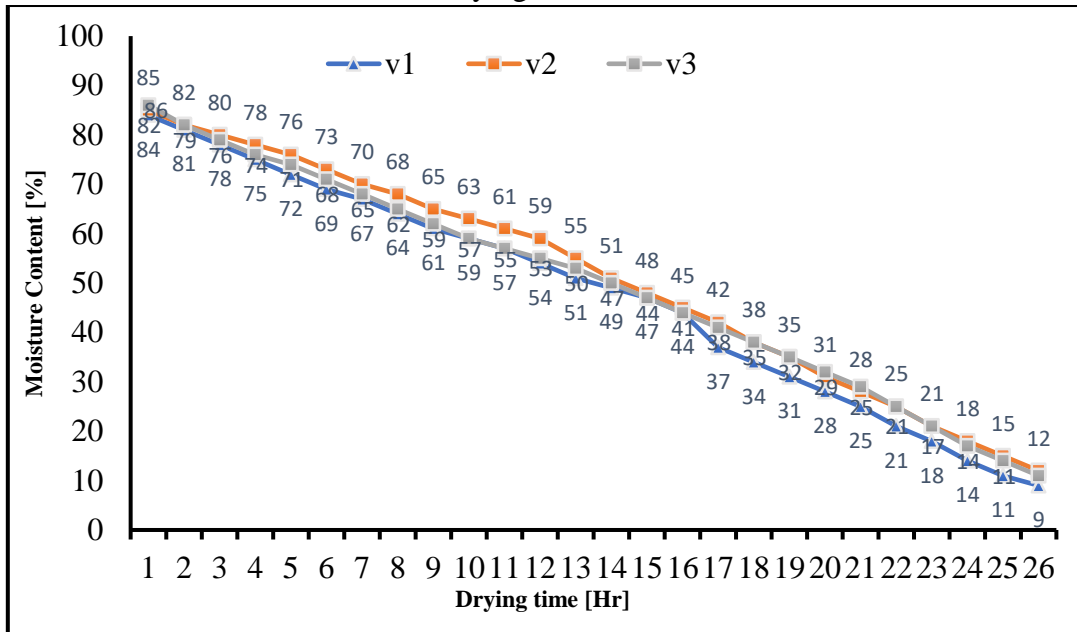


Figure 3. Moisture Loss per hour at 45°C

The results of moisture loss per hour by plums under different velocities at temperature 55 °C are given in Figure 4. The initial moisture content was 85 % which reduced to less than 10 % . It took almost 23 hours

during drying to achieve this moisture at Air velocity 0.5 ms⁻¹. Moisture content reduced to 81 % after two hours of drying and reached 42 % at 13 hours of drying interval. It reached 16 % after 20 hours of drying and reached 9 % after 23 hours of drying.

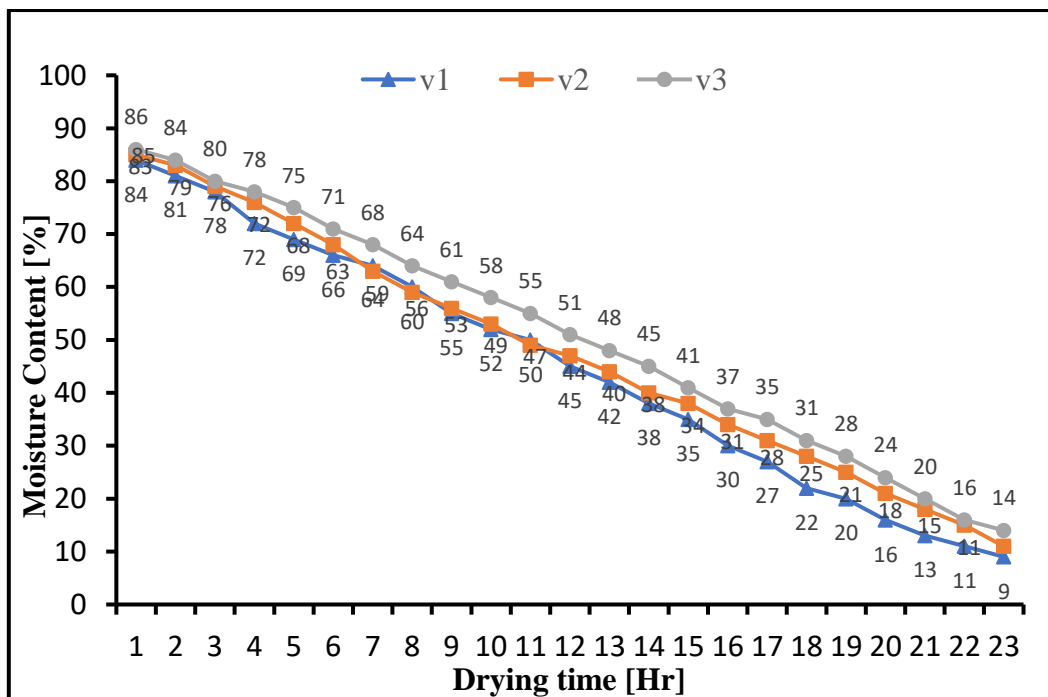


Figure 4. Moisture Loss per hour at 55°C

The results of moisture loss per hour by plums under different velocities at temperature 65 °C are given in Figure 5. The initial moisture content was 85 % which

reduced to less than 10 % . It took almost 19 hours during drying to achieve this moisture at air velocity 1 ms⁻¹. Moisture content reduced to 79 % after two

hours of drying and reached 31 % at 13 hours of drying interval. It reached 21 % after 15 hours of drying and reached 10 % after 19 hours of drying.

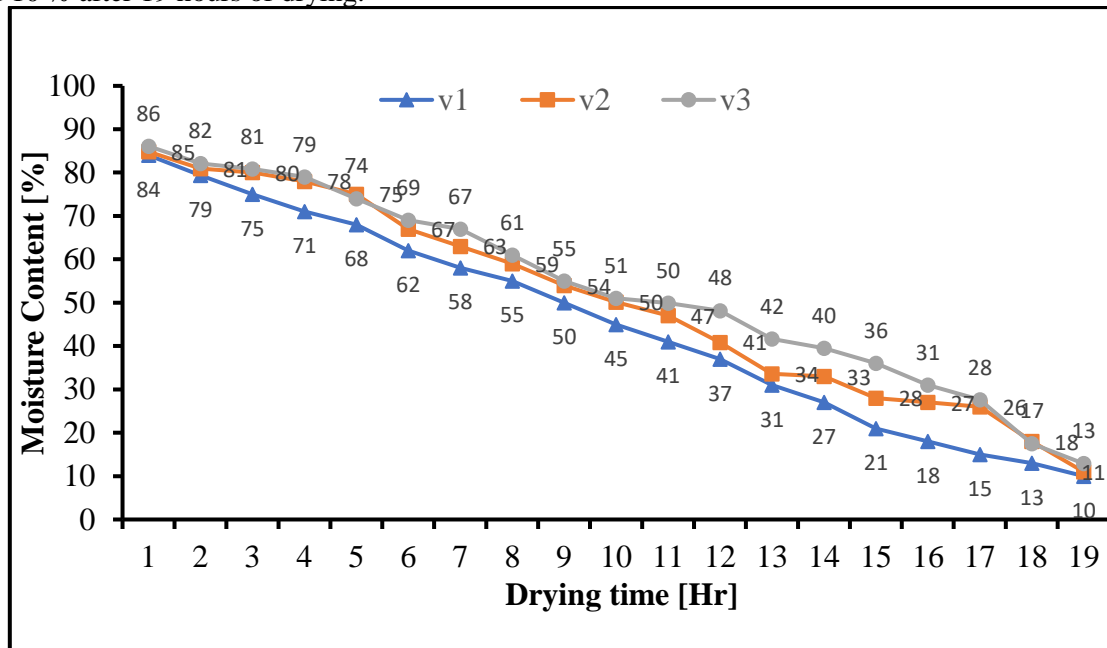


Figure 5. Moisture Loss per hour at 65°C

Drying Rate on Wet basis (%)

The result of moisture loss on wet basis as affected by different temperatures and air velocities inside the dryer are given in Table 1. The analysis of variance showed that dryer temperature showed significant results on the moisture loss per hour while air

velocities and the interaction between air velocities and drying temperature showed a non-significant result. The means of Air velocities showed that maximum moisture loss of 2.550 gm.g⁻¹.H₂O was

recorded at 0.5 ms⁻¹ velocity followed by 2.549 % at 1.0 ms⁻¹ air velocity while minimum moisture loss of 2.521 % was recorded at 0.1 ms⁻¹ air velocity in the dryer. The means of dryer temperature showed that maximum moisture loss of 2.629 % was recorded at 65°C while minimum of 2.459 % was recorded at 45°C. The interaction effect showed that maximum moisture loss of 2.647 % was recorded at 65 °C and 0.5 ms⁻¹ air velocity while minimum of 2.443 % was recorded at 45°C dryer’s temperature and 01 ms⁻¹ air velocity inside the dryer.

Table 1. Moisture lost wet basis (%) as affected by different drying temperatures (°C) and air velocities (ms⁻¹) in the dryer

Temperature (°C)	Air Velocity (ms ⁻¹)			Mean
	1.0	0.5	0.1	
65±1	2.633	2.647	2.607	2.629a
55±1	2.543	2.540	2.513	2.532b
45±1	2.470	2.463	2.443	2.459c
Mean	2.549	2.550	2.521	

Cv 11.56

LSD for Temperature (T) = 0.015

Drying Rate on Dry Basis (gH₂O.g_{DM}⁻¹.hr⁻¹)

The means of air velocities showed that maximum moisture loss of 0.142 gH₂O.g_{DM}⁻¹.hr⁻¹ was recorded at 1.0 ms⁻¹ air velocity followed by 0.142 gH₂O.g_{DM}⁻¹.hr⁻¹ at 0.5 ms⁻¹ air velocity while minimum moisture loss of 0.140 gH₂O.g_{DM}⁻¹.hr⁻¹ was recorded at 0.1 ms⁻¹ air velocity in the dryer. The means of dryer temperature

showed that maximum moisture loss of 0.147 gH₂O.g_{DM}⁻¹.hr⁻¹ was recorded at 65°C while minimum of 0.136 gH₂O.g_{DM}⁻¹.hr⁻¹ was recorded at 45°C. The interaction effect showed that maximum moisture loss of 0.150 gH₂O.g_{DM}⁻¹.hr⁻¹ was recorded at 65°C and 0.5 ms⁻¹air velocity while minimum of 0.133 gH₂O.g_{DM}⁻¹

¹.hr⁻¹ was recorded at 45°C dry temperature and 0.5 ms⁻¹ air velocity in the dryer.

Table 2. Moisture lost Dry basis (g_{H₂O}·g_{DM}⁻¹·hr⁻¹) as affected by different drying temperatures (°C) and air velocities (ms⁻¹) in the dryer.

Temperature (°C)	Air Velocity (ms ⁻¹)			Mean
	1.0	0.5	0.1	
65±1	0.147	0.150	0.143	0.147a
55±1	0.143	0.143	0.140	0.142b
45±1	0.137	0.133	0.137	0.136c
Mean	0.142	0.142	0.140	

Cv 11.62

LSD for Temperature (T) = 0.001

Moisture Diffusivity (m²·s⁻¹)

The means of air velocities showed that maximum moisture diffusivity of 1.39×10⁻⁹ was recorded at 1.0 ms⁻¹ air velocity followed by 1.29×10⁻⁹ at 0.1 ms⁻¹ air velocity while minimum moisture loss of 1.24×10⁻⁹ was recorded at 0.5 ms⁻¹ air velocity in the dryer. The means of dryer temperature showed that maximum

moisture diffusivity of 1.76×10⁻⁹ was recorded at 65°C while minimum of 0.91×10⁻⁹ was recorded at 45°C.

The interactive effect showed that maximum moisture diffusivity (1.85×10⁻⁹) was recorded at 65°C and 0.1 ms⁻¹ air velocity while minimum (0.85×10⁻⁹) was recorded at 45°C dry temperature and 1.0 ms⁻¹ air velocity in the dryer.

Table 3. Moisture diffusivity (m²·s⁻¹) as affected by different drying temperatures (°C) and air velocities (ms⁻¹) in the dryer.

Temperature (°C)	Air Velocity (ms ⁻¹)			Mean
	1.0	0.5	0.1	
65±1	1.78×10 ⁻⁹	1.77×10 ⁻⁹	1.85×10 ⁻⁹	1.76×10 ⁻⁹ a
55±1	1.35×10 ⁻⁹	1.20×10 ⁻⁹	1.32×10 ⁻⁹	1.24×10 ⁻⁹ b
45±1	0.85×10 ⁻⁹	0.86×10 ⁻⁹	1.11×10 ⁻⁹	0.91×10 ⁻⁹ c
Mean	1.39×10 ⁻⁹	1.24×10 ⁻⁹	1.29×10 ⁻⁹	

Cv =2.75,

LSD for Temperature (T) = 0.015x10⁻⁹

LSD for Air Velocity (V) = 0.018x10⁻⁹

Activation Energy (KJ mol⁻¹)

In the dryer, activation energy decreased with increasing air velocity. It was highest (45.07 kJ/mol) at 0.1 m/s and lowest (37.61 kJ/mol) at 1.0 m/s. The means of dryer temperature showed that maximum activation energy of 46.97 kJmol⁻¹ was recorded at

65°C while minimum of 38.19 kJmol⁻¹ was recorded at 45°C.

The interaction effect showed that maximum activation energy of 49.87 kJmol⁻¹ was recorded at 65°C and 0.1 ms⁻¹air velocity while minimum of 33.38 kJmol⁻¹ was recorded at 45°C dryer's temperature and 1.0 ms⁻¹ air velocity inside the dryer.

Table 4. Activation energy (KJ·mol⁻¹) as affected by different drying temperatures (°C) and air velocities (ms⁻¹) in the dryer.

Temperature (°C)	Air Velocity (ms ⁻¹)			Mean
	1.0	0.5	0.1	
65±1	42.71	48.32	49.87	46.97a
55±1	36.73	41.73	45.96	41.47b

45±1	33.38	41.80	39.40	38.19c
Mean	37.61	43.95	45.07	

CV 5.78

LSD for Temperature (T) = 1.334,

LSD for Air Velocity (V) = 0.981

Applicability of Thin Layer Models on Moisture Loss Ratio

Based on the results of moisture loss from plums at different levels of temperature and air velocity, the model has been tested using the moisture ratio obtained at 65°C temperature and 0.5 ms⁻¹ air velocity in the dryer. we developed a physical model and applied on the moisture ratio, we also tested five other published models in terms of R², RMSE and χ². The

results showed that among all the six models Modified Page gave us a better result with R² 0.99, RMSE 0.01 and χ² 2.12 while the physical scale model developed for the research showed poor results in terms of R² 0.91, RMSE 0.10 and χ² 2.12.

Table 5. Applicability of Thin Layer Models on Moisture Loss Ratio

Model Name	Model Equation	R ²	RMSE	χ ²
Logarithmic	MR = α exp (-kt) + c	0.95	0.08	1.80
Lewis	MR = exp (-kt)	0.96	0.06	1.73
Henderson and Pabis	MR = α exp (-kt)	0.95	0.06	1.55
Page	MR = exp (-ktn)	0.97	0.04	1.28
Modified Page	MR = exp [-(kt)n]	0.99	0.01	0.62
Physical applied model of the research data	[MR = a+bx]	0.91	0.10	2.12

PCA-Biplot and Scree plot

Through the scree plot and eigenvalue analysis, it is observed that PC1 (54.67 %) PC2 (28.29 %), and PC3 (13.94 %) had the highest contribution by the variance and the three combined with each other represent approximately 96.90 % of variance. The loading of Drying Time (hr.) and Dryer Humidity (%) was found to be positive and strong in relation to PC1, but on the same component, the loading of Solar Irradiance (W/m²) and Diffusivity (x10⁻⁹ m/s²) was found to be

negative and strong. Moisture Loss WB (%) and Moisture Loss DB (g /g/h) were highly loaded under the apparent PC2 defining a specific moisture-kinetics axis regardless of the drying-efficiency gradient that PC1 represents. The contribution of Activation Energy (kJ/mol) to either of the two principal components was low, which means that it is relatively independent of the major patterns of variation of drying data point (Figure 6).

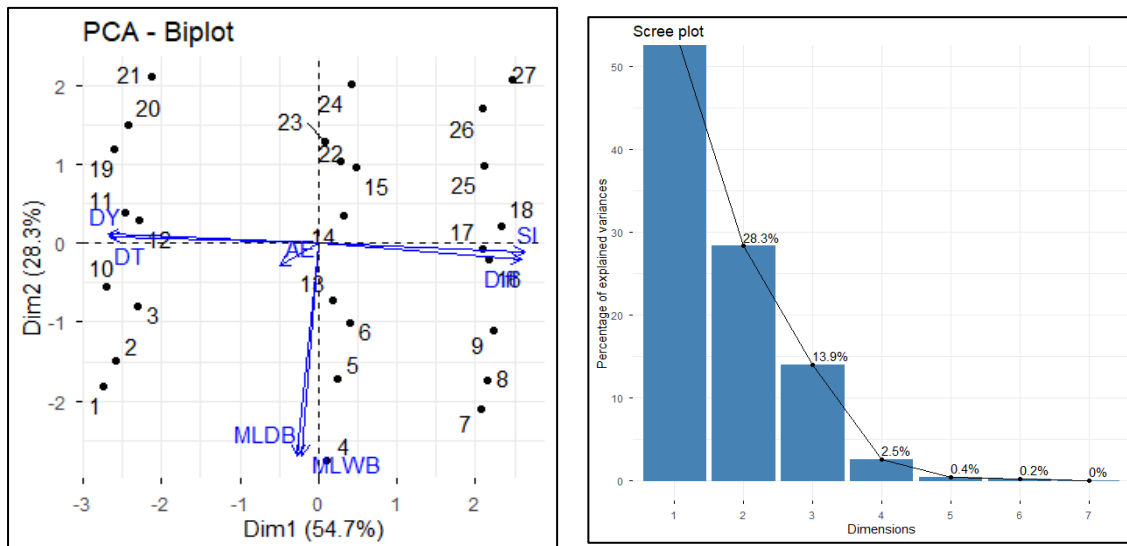


Figure 6. PCA-Biplot and Scree plot

DISCUSSION

Solar irradiance increased from 6 am to 12:00 pm and then decreased and became zero after 7 pm. This is due to the reason that sun light makes an angle (Azimuth) with the sun power meter and according to Hanif *et al.*, (2018), the solar irradiance is directly related with solar Azimuth. As the Azimuth increased so was the flux of solar irradiance. The same fact was reported by Khattak *et al.*, (2019). They reported their results in line with findings of this research that solar flux increased with day timing and was recorded maximum at noon. The results are also in accordance with findings of Fahimullah *et al.*, (2019) who reported the same relation of solar irradiance with day timing. Ambient temperature is relative to solar irradiance and daytime the fact that temperature raised is that solar flux gave heat to the soil and environment causes increase in Enthalpy of air. Due to this reason the ambient air temperature increased. These results are in accordance with the finding of Muhammad *et al.*, (2020). Who reported an increase in ambient temperature during daytime. Similarly, dryer temperature also increased with daytime. The higher temperature values of the dryer than ambient air is due to the reason that heat was supplied from the Flat Plat Solar Collector to drying chamber. This caused more heat transfer to the dryer causing higher temperatures. The results are in line with the findings of Hanif *et al.*, (2019) and Fahimullah *et al.*, (2018). Who reported an increase in dryer temperatures during the daytime. The results are also in accordance with the finding of Marin *et al.*, (2017), who reported dryers temperature increase in relation with solar irradiance and day timing. Also, relative humidity is relative to enthalpy of the air present inside the dryer. Relative humidity decreased with increased dryer temperatures. In due to this fact the result is in accordance with the findings

of Hanif *et al.*, (2018, 2015). These results are also in line with the relative humidity results reported by Chabane *et al.*, (2019)

The data of moisture loss per hour from plum slices showed that moisture loss is significantly affected by temperature but there was no-significant affect showed by plum slices for moisture loss at different air velocity. The reason behind this is that increasing temperature causes an increase in enthalpy of the air causes more energy to be carried out by the air as medium to the dryer. There it easily gains moisture from the plum slices due to low relative humidity in the air. The results are in accordance with the findings of Hanif *et al.*, (2016), who reported that increase in temperature increase moisture loss from plums and reduce drying time. The results are also in accordance with the findings of Hadi *et al.*, (2016), who reported moisture loss results in line with the findings of this research and stated that temperature significantly affected the drying process and increased moisture loss per hour if increased.

The activation energy of plums increased with increased in temperature and decreased with increased air velocity. This was due to the fact that at lowest air velocity (0.1 ms^{-1}) among the treatments, the air has better contact with the sample surface which results in a greater absorption of moisture. These results are in accordance with the findings of Garau *et al.*, (2006) who reported that increasing air velocity decreased activation energy in orange skin also at high air velocity, the air passing through sample is turbulent, therefore the moisture gradient tends to decrease as well as activation energy accordingly reduces. The results of activation energy for the plum fruit in the drying experiments are in line with the findings of Mirzaee *et al.*, (2009), who reported that temperature

increases activation energy and increase in air velocity decreases activation energy in apricots.

The moisture diffusivity was affected by both air velocity and drying temperature. The reason for high moisture diffusivity is due to the fact that at high temperature the air enthalpy increases. This causes an increase in capacity of the air to retain moisture in it. The air velocity played a vital role by speeding up the process of moving the hot air through the samples causing increased moisture diffusivity. The results are in accordance with the findings of Zivkovic *et al.*, (2011) and Lopez *et al.*, (2017). It is also reported that increase in temperature and air velocity increased diffusivity effectively. The reason was that they dried plums at 75°C at 10-time higher air velocity. Zivkovic *et al.*, (2011) and Velic *et al.*, (2004) reported that the average moisture diffusivity increased with airflow and temperature. The reason was that heat transfer increased with the increased air flow velocity.

CONCLUSIONS

Increase in dryer temperature showed significant effect on increase moisture loss per hour, Activation Energy, and Moisture Diffusivity. Increasing air velocity showed significant effect on moisture diffusivity and decreasing activation energy. In thin layer drying kinetics models, Modified Page Models showed good results of drying kinetics. The developed and applied thin layer drying kinetic model for air flow and heat transfer through forced air showed poor results of R², RMSE, and χ^2 as compared to already published thin layer drying kinetics models.

RECOMMENDATIONS

It is recommended to dry plums at 65 °C dryer temperature and 0.5 ms⁻¹ dryer air velocity to get reliable results of drying of plums. It is also recommended to apply modified page models for getting reliable results of drying of plums.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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Authors' Contributions

Hussain Yousaf and Inayat Ullah designed the study. Ayesha Khan assisted with experimental planning and interpretation. Adnan Khan and Sanaullah Khan conducted experiments and collected data. Aizaz Ali, Abdullah, Baheeya Zaman, and Fazal E Wahid supported data analysis and technical work. Inayat Ullah and Muhammad Suleman Khan wrote the manuscript, with Muhammad Suleman Khan as corresponding author.

All authors contributed to the study as per CRediT roles and approved the final manuscript.

Ethical STATEMENT

This research did not involve human or animal subjects.

SDG Addresses

This work supports SDGs 2, 7, 9, and 12.

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