Thin-layer mathematical modeling of apple slices drying, using open sun and cabinet solar drying methods

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Abstract

This paper aims to investigate the effect of climate conditions such as ambient temperature, humidity, pressure, sun radiation and pollution on sliced apples quality and drying time which are dried in an indirect forced cabinet solar drying (IFCSD) and open sun drying (OSD) systems. Both experiments were implemented at same place (Kabul, Afghanistan) and time. The IFCSD yield for saving time is 42.8% which is more effective than drying in the OSD system. Simultaneously with the decreasing of sliced apple weight from 512.9 g down to 73.9 g, the water activity decreased from 0.955 down to 0.355 in the IFCSD system. For OSD system, the sample weight decreased from 512.6 g down to 78.4 g and its water activity from 0.955 down to 0.411. On the experiment day the average sun radiation was 571 w/m². The pressure drop between inlet and outlet of the dryer was 0.1 kPa. Different thin-layer mathematical models were investigated to identify the best model fitting the experimental data. The mathematical models’ performances were investigated by comparing the coefficient of determination ($R^2$), reduced chi-square ($X^2$) and root mean square error (RMSE) coefficients. From all 11 applied thin-layer drying models the Page, Approximation diffusion, Verma et al and Midilli and Kacuk models are more fitted to our data.

Keywords: Apple, Cabinet solar drying, Open sun drying, Mathematical models, Climate conditions.

1. Introduction

Vegetable and fruits are seasonable agriculture products. Vitamins, minerals and fibers are the essential compounds of these products for human nutrition. Due to the presence of high moisture, vegetable and fruits are exposed to microbial spoilage sooner, and their shelf life is very short [1]. Apples (Malus domestica) are among the tree fruits that are grown and produced in most countries of the world. This fruit is rich in vitamins, minerals and fiber, and
also it is consumed in various forms such as fresh juice, dried and compote. Apples are also used in the manufacturing industries of jams, vinegar, etc. [2,3]. Afghanistan's climate is also very suitable for growing apple seedlings and apple production. Eleven different types of apples such as Red Chief, Blushing Gold, Royal Gala, Double Red Delicious, Michgla, Modal Gala, Fuji, Galaxy and Saturn have the highest yield in Afghanistan and most of them are produced in the central provinces [4,5].

The most well-known and easiest method for preservation of the fruit and vegetables is drying. Drying is an energy intensive process for water reducing from the sample. As the agricultural crops dries, not only the shelf-life become longer but also reducing the microbial activities compared to the fresh products. Additionally, the transportation, packaging, and storage costs are reduced as well [6]. In recent years, various drying methods for drying agricultural products have been studied, which include spray drying [7], freeze drying [8], vacuum drying [9], microwave drying [10] and solar drying methods such as open sun drying (OSD) [11], or cabinet solar drying (CSD) [12]. Supplying power required for drying is one of the fundamental problems in the drying process which constitutes the basic economics of the drying process. Solar drying of agricultural crops is the simplest and cheapest way for preserving such products [13]. Humans have been familiar with OSD for centuries. They used this method to dry meat, cereals, fruits, vegetables, etc.

Afghanistan is a landlocked and upland country, which is located in the central of the Asia with high temperature, low humidity and pressure. With more than 300 sunny days a year, Afghanistan is one of the best countries for solar drying. During the four seasons of the year, the average solar radiation intensity in Afghanistan is changed in an interval from 2.38 kWh/m$^2$/day up to 7.84 kWh/m$^2$/day [14]. Developing or underdevelopment countries such as Afghanistan still used OSD to dry meat and all kinds of agricultural products. Utilization of OSD is common as it is easy to use, inexpensive, and energy source is accessible anywhere. Main focus today is on drying development using renewable sources, especially solar energy. In the late 20th and early 21st centuries, OSD and CSD systems for drying of different products have been studied by many researchers.

Various aspects of open sun drying have been evaluated in the work of these researchers [11,15,16,17]. A wide variety of solar dryers with different functions have been designed and developed by many researchers [13,18,19,20,21]. In the recent years many researchers are studied about apple drying [22,23,24]. During the apple drying process into the designed heat pump and solar dryers are experimentally compared and analyzed. The heat pump dryer system drying time is shorter than the solar drying system. Henderson and Pabis mathematical models are more suitable for both drying system [25]. Blanco-Cano et al. [26] have studied the use of many thin-layer Granny Smith apple drying models in indirect solar dryers. They found that Wang-Sing model is more fitted for conducted thermogravimetric analyzer (TGA) for different constant drying temperatures [26]. Sacilik and Elicin [27] evaluated dried apple slices with different thickness and temperature. They determined that the dried product with this device has good quality [27]. Using mean relative percent error, root mean square error and reduced chi-square coefficients determined the logarithmic model is the most suitable model among the 11 applied models. Drying of apple slices in a solar dryer with a thermal energy storage system was studied by [28]. By the installation of thermal energy
storage, they were able to recover 50 to 60% of the wasted energy. This unit had the ability to decrease 76.8% energy consumption among the studied literature devices. They also developed and evaluated some models for apple slices with 5 mm thickness under the constant temperatures. The fitted model for apple slice drying with this system is diffusion approximation between all applied models. Thin layer drying models are used for many others product drying like Marine products, Cereals, leafy vegetable, fruits etc. [29,30,31,32].

The objective of this study is the comparison of drying time, effect of climatic conditions (temperature, humidity, pressure and air pollution) typical for geographical locations with an altitude of 1800 to 2000 m above the sea level on dried product quality, reducing of water activity after each sampling, of the open sun drying and indirect forced cabinet solar drying for apple (Blushing Gold) slices. Another objective of this work was to select the most appropriate model (in terms of fitting ability) among the eleven models used in this study to describe the drying of thin layers slices under OSD, IFCSD and climate conditions used.

2. Materials and Methods

2.1 Sample preparation

The fresh apples (Blushing Gold) used for this study were purchased from the fresh fruits and vegetable market in Kabul, Afghanistan in the harvesting time. After selecting the uniform size of apples with diameters ranging from 6 to 8 cm, the apples were washed with tap water and cut it into 5 ± 0.1 mm thickness horizontally and semi circularly with a stainless steel manual cutter. For each experiment run (OSD and IFCSD) prepared 500 ± 2 g sliced apples and placed in the IFCSD trays and OSD plastic basket; the tray was placed into the IFCSD device and the plastic basket was exposed to the sunlight close to device for OSD experiment. The apple slices were weighted on digital scale.

2.2 Experimental procedure

IFCSD system

The current indirect forced cabinet solar drying (IFCSD) is a complementary system where all the energy used is supplied from renewable sources. This system is consisting of three essential parts: dryer chamber, solar collector and photovoltaic solar panel for centrifugal air blower and exhaust fan power supply. The wooden rectangular drying chamber is 1200 x 600 x 400 mm. The dryer chamber has four trays with a total capacity of 2000 g of sliced apple in one run. The flat solar collector dimensions are 1500 x 600 x 100 mm with a 0.9 m² surface area. Helix shape aluminum pipe with 10.5 m long and 55 x 35 mm rectangular cross-section are the main component of the collector. The surface of the pipes is covered with heat-absorbing and non-reflective materials layer. In order to strengthen the air velocity in the collector inlet and outlet of the drying chamber, DC blower and exhaust fan have been installed. For energy, supplying of the blower and exhaust, A 240 watt photovoltaic panel is used (Fig. 1a).

For measuring of the parameters, Testo 176T4 were used for temperature Testo 176P1 for pressure, temperature and humidity and Testo 405 for air velocity data loggers are used. All these instruments are produced by Testo SE & Co. KGaA.
Experiments of OSD were also performed like IFCSD at the middle of October, on sunny days from 9:00 am to 5:00 pm when ambient temperature varied between 18 and 29 °C and average air velocity was 1.8 m/s. In these experiments, 500 g sliced apple were placed in a plastic basket with the inner dimensions of 500 x 350 x 100 mm and exposed to direct sun radiation, same climate conditions and the same thickness of the sample as in the IFCSD device were considered (Fig. 1b).

2.3 Experimental procedure

The IFCSD device trays and OSD plastic basket washing with tap water and cleaning of the chamber inside, collector and PV solar penal surface was the first step of our experiment startup. The second step was the measuring and determination of initial water activity and moisture content of fresh apple slices. Water activity analyzer (LABTOUCH - aw SET ADVANCED, Novasina AG, Switzerland) and analytical moisture analyzer (VWR MBT160 moisture analyzer, VWR International, Italy capacity: 0.001–160 g) devices were respectively used for measuring and determination of fresh apple initial water activity and moisture content.

After the samples were moved in the trays of solar dryer device and the plastic basket for OPS drying, by turning on the blower and exhaust switch, the measurement starts. During every two hours sampling, simultaneously with sampling, ambient parameters (temperature, pressure, solar radiation intensity and humidity), parameters in the device (temperature at the outlet of the collector, air velocity at the inlet of the chamber (50.8 mm Ø-pipe), humidity at the outlet of the chamber, pressure at the outlet of the chamber) and parameters in the laboratory (sample weight, sample moisture and water activity) were also measured and recorded.

2.4 Mathematical modeling

Various thin layer mathematical models were proposed in the literature [33,34,35,36,37]. In this work the models shown in Table 1 were tested for drying of apple slice in both OSD and IFCSD systems.
Table 1: Selected thin layer mathematical models

| No | Model name          | Model                                      | Reference |
|----|---------------------|--------------------------------------------|-----------|
| 1  | Newton              | \( MR = \exp(-kt) \)                        | [35]      |
| 2  | Page                | \( MR = \exp(-kt^n) \)                      | [38]      |
| 3  | Modified Page       | \( MR = \exp[-(kt)^n] \)                    | [33]      |
| 4  | Logarithmic         | \( MR = a \exp(-kt) + c \)                  | [39]      |
| 5  | Henderson and Pabis | \( MR = a \exp(-kt) \)                      | [36]      |
| 6  | Two-term            | \( MR = a \exp(-k_0 t) + b \exp(-k_1 t) \) | [40]      |
| 7  | Two term exponentials | \( MR = a \exp(-kt) + (1 - a) \exp(-kt) \) | [34]      |
| 8  | Midilli et al       | \( MR = a \exp(-kt)^n + bt \)               | [37]      |
| 9  | Approximation of diffusion | \( MR = a \exp(-kt) + (1 - a) \exp(-kbt) \) | [41]      |
| 10 | Verma et al         | \( MR = a \exp(-kt) + (1 - a) \exp(-gt) \) | [32]      |
| 11 | Midilli and Kucuk   | \( MR = a \exp(-kt^n) + bt \)               | [42]      |

In all models, \( MR \) is moisture ratio, \( t \) is time, \( k \) is drying rate constant, \( a, b, c, g \) and \( n \) are model coefficients. Eq.1 is used for calculation of \( MR \) for apple drying [31].

\[
MR = \frac{M_f - M_e}{M_0 - M_e}
\] (1)

The initial and final moisture content of sliced apple has been funded with Eqs. 2,3 [40].

\[
M_0 = \frac{m_i - m_d}{m_d}
\] (2)

\[
M_f = \frac{m_w - m_d}{m_d}
\] (3)

In these equations, \( M_0, M_i, M_e, \) and \( M_f \), represent initial moisture content (kg H\(_2\)O/kg dry matter), final moisture content (kg H\(_2\)O/kg dry matter), transient moisture content (kg H\(_2\)O/kg dry matter) and equilibrium moisture content (kg H\(_2\)O/kg dry matter); \( m_o, m_w \) and \( m_e \) represent initial mass (kg), dry material mass (kg) and mass of wet mater after drying process.

For selecting of the best fitted mathematical models for apple slices drying, is necessary to calculate these three important statistical parameters: correlation coefficient \( (R^2) \) Eq. 4, chi-square \( (X^2) \) Eq. 5, and root mean square error \( (\text{RMSE}) \) Eq. 6. The model with the highest value of \( R^2 \) and lowest \( X^2 \) and \( \text{RMSE} \) indicate the best fit of the model. The empirical constants for the models were obtained using Microsoft office Excel Solver, [39,31,35,33,41].

\[
R^2 = 1 - \frac{\sum_{i=1}^{n}(MR_{\text{pre},i} - MR_{\text{exp},i})^2}{\sum_{i=1}^{n}(MR_{\text{exp},i} - MR_{\text{exp,av}})^2}
\] (4)

\[
X^2 = \frac{\sum_{i=1}^{n}(MR_{\text{pre},i} - MR_{\text{exp},i})^2}{N - z}
\] (5)

\[
\text{RMSE} = \left[ \frac{1}{N} \sum_{i=1}^{n}(MR_{\text{pre},i} - MR_{\text{exp},i}) \right]^{1/2}
\] (6)

In these equations, \( MR_{\text{exp},i} \) represents the \( \text{ith} \) experimentally observed normalized moisture ratio, \( MR_{\text{pre},i} \) represents the \( \text{ith} \) predicted value, \( MR_{\text{exp}, \text{av}} \) is average of normalized \( MR \) of experimental points, \( N \) is the number of observations and \( z \) is the number of constants in the model.
3. Results and discussion

3.1 Effect of ambient conditions on drying

Figure 2 shows the ambient and collector outlet temperature changes simultaneously with the change in the intensity of sun radiation. Usually, existence pieces of the clouds in the sky have caused inconsistencies in the curves of the first day (first 6 h). The second day (from 8 to 16 h) data show the same changes for all three curves. By increasing of the sunlight intensity from 182 up to 972 w/m² the ambient temperature increased from 22.4 up to 29.1 °C and collector outlet temperature increased from 33 °C to 55.4 °C. The collector heating efficiency was 90.4% at maximum against ambient air temperature. Sun radiation intensity of Kabul, Afghanistan during the experiment time was 571 w/m² in the average case.

Figure 3. Ambient air relative humidity (%) and temperature (°C) versus drying time (h).

Fig. 2. Ambient temperature (°C), collector outlet temperature (°C) and sun radiation (w/m²) versus drying time (h).

Ambient humidity changes are inversely related to ambient temperature changes. Fig. 3 proves and illustrates this point; when the ambient temperature increased the ambient humidity decreased. During experiment the ambient temperature changed from 22.4°C to 29.1°C while the air relative humidity was changed from 18.9% to 34.1%.

Fig. 3. Ambient air relative humidity (%) and temperature (°C) versus drying time (h).

Fig. 4. Apple slices moisture reducing (%) against drying time (h).

By using the data obtained experimentally on the mass loss of the sample and the Eqs. 1, 2 and 3, the transient moisture content of the sample (d.b) and the moisture ratio (MR) were calculated. The change of the product moisture content measured by a moisture analyzer (capacity: 0.001–160 g, VWR, Italy) is presented in the Fig. 4. The initial moisture content of apple slices was 87.53% which decreased down to 15.26% with IFCSD and to 20.34% with OSD. During the last measurement hours, a slight increase of the product moisture content was recorded. Fig. 5 illustrates that the IFCSD has a 42.8% time efficiency against OSD. This figure also represents the samples mass drop (H) for both systems during the night (25% for OSD and 6% for IFCSD). OSD higher mass drop is related to the effect of airflow in the open space, which the airflow is not so affected for IFCSD system.
The change of the product water activity was measured by a water activity analyzer. The initial water activity of apple slices was 0.955 which decreased down to 0.355 with IFCSD and to 0.495 with OSD in end of second experimental day (Fig. 6).

Figure 8 illustrates the whole Blushing Gold fresh apple (Fig. 8a), fresh slices, OSD and IFCSD dry apple slices (Figs. 8b - 8e). The Figs. 8b and 8e samples are dried with IFCSD system and Figs. 8c and 8d are dried with OSD. All last four pictures are representing the effect of sunlight and air pollutions on OSD dried product, Figs. 8c and 8d. The IFCSD dried product better color quality of product is clearly visible in Figs. 8b and 8e.

Ambient air pollution is a major quality problem for OSD dry products in Afghanistan; the air pollutants reduce the quality of dried products in the OSD system. The dried apple slices placed under a microscope (VWR - Digital-Microscope VisiScope series 200, Model: BL254T1) which is equipped with an imaging system and the surface of the dried samples were photographed Fig. 9 stains on the surface of dried apple slices in the OSD indicate the presence of air pollutants that accumulate on the dried apple slices and cause a change in color and even the taste of the product. Therefore, based on the photos taken of both products (Fig. 9), it can be said that; the dried products in the IFCSD have good quality and taste than the dried products in the OSD.
Fig. 8. OSD and IFCSD Sample preparation and color comparison of apple slices: (a) fresh apples (Blushing Gold), (b), and (e) IFCSD products, (c), and (d) OSD products.

Fig. 9. Air pollution effect on dry apple sliced OSD and IFCSD product

3.2 Mathematical model selection

In order to select a convenient thin-layer model for drying apple slices in the IFCSD and OSD, empirical models given in Table 1, have been used to compare the experimental and theoretical moisture ratio data versus time. In Figs. 10 and 11 the comparison of experimental data with predicted data by Page, Approximation diffusion, Verma et al. [47], and Midilli Kacuk [48] models are shown.

From the comparison of Figs. 10 and 11, it can be concluded that the drying in the IFCSD take place under stabilized conditions and thin layer models better describe the behavior of experimental data; the experimental data ($MR_{exp}$, curve) are very close to the calculated theoretical data ($MR_{pre}$, curve). In the case of open sun drying the drying conditions are not stable; experimental data are more scattered, for this reason the thin layer model do not provide perfect fitting of experimental data.
Fig. 10. IFCSD thin layer models comparison of experimental and calculated MR versus drying time, (a) Page model, (b) Approximation diffusion model, (c) Verma et al. model and (d) Midilli Kacuk model.

Fig. 11. OSD thin layer models comparison of experimental and calculated MR versus drying time, (a) Page model, (b) Approximation diffusion model, (c) Verma et al. model and (d) Midilli Kacuk model.

Statistical analysis was done to select the most appropriate thin-layer empirical model for drying apple slices for both IFCSD and OSD systems. The analysis was conducted to decide the most suitable model with the highest value of statistical parameter, $R^2$ (Eq. 4) and the lowest values of $X^2$ (Eq. 5) and $RMSE$ (Eq. 6).

Table 2 shows all constants values ($k$, $n$, $a$, $b$, $c$, $g$) of the eleven models received by fitting the experimental data to the thin layer drying models and the results of statistical parameters calculated by Eqs. 4, 5 and 6 for IFCSD apple slices drying. The same results for OSD apple slices drying thin layer models are listed in Table 3.
Table 2: Thin layer models and statistical parameters for IFCSD system

| Model No | Model Constants | $R^2$     | $X^2$     | RMSE    |
|----------|-----------------|-----------|-----------|---------|
| 1        | $k = 0.329555933$ | 0.991268274 | 0.001147879 | 0.031692172 |
| 2        | $k = 0.226979419; n = 1.271372879$ | 0.998454327 | 0.001147879 | 0.013334008 |
| 3        | $k = 0.299548934; n = 1.100173944$ | 0.991268274 | 0.001147879 | 0.031692172 |
| 4        | $k = 0.334477339; a = 1.018914216; c = 0$ | 0.991696734 | 0.001091553 | 0.030904836 |
| 5        | $k = 0.334477655; a = 1.018913915$ | 0.991696734 | 0.001091553 | 0.030904836 |
| 6        | $k = 0.334477516; k = 0.33448328; a = 0.971085939; b = 0.047828017$ | 0.991696734 | 0.001091553 | 0.030904836 |
| 7        | $k = 0.395555998; a = 1.000455506$ | 0.991268274 | 0.001147879 | 0.031692172 |
| 8        | $k = 0.395555998; a = 1.000455506$ | 0.991268274 | 0.001147879 | 0.031692172 |
| 9        | $k = 0.395555998; a = 1.000455506$ | 0.991268274 | 0.001147879 | 0.031692172 |
| 10       | $k = 0.395555998; a = 1.000455506$ | 0.991268274 | 0.001147879 | 0.031692172 |

Table 3: Thin layer models and statistical parameters for OSD system

| Model No | Model Constants | $R^2$     | $X^2$     | RMSE    |
|----------|-----------------|-----------|-----------|---------|
| 1        | $k = 0.185372091$ | 0.944946791 | 0.00701093 | 0.080166616 |
| 2        | $k = 0.05374541; n = 1.648155152$ | 0.980767691 | 0.002449201 | 0.047382497 |
| 3        | $k = 0.224659809; a = 0.825123511$ | 0.944946791 | 0.00701093 | 0.080166616 |
| 4        | $k = 0.19515452; a = 1.068250151; c = 0$ | 0.949490233 | 0.006432331 | 0.076787391 |
| 5        | $k = 0.195511622; a = 1.06829507$ | 0.949490237 | 0.006432331 | 0.076787388 |
| 6        | $k = 0.195511394; k = 0.195509285; a = 0.949490237; b = 0.025784432$ | 0.949490237 | 0.006432331 | 0.076787388 |
| 7        | $k = 0.185372151; a = 1.06829507$ | 0.949490237 | 0.006432331 | 0.076787388 |
| 8        | $k = 1.042510353; b = 0.025784432$ | 0.944946791 | 0.00701093 | 0.080166616 |
| 9        | $k = 0.563936824; a = 36.69902136; b = 1.019499207$ | 0.998267062 | 0.000227813 | 0.014118658 |
| 10       | $k = 0.583274938; a = 15.38929328; g = 0.225359199; n = 1.274744729; a = 0.997288362; b = 0$ | 0.998265311 | 0.000228043 | 0.01412579 |
| 11       | $k = 0.563936824; a = 36.69902136; b = 1.019499207$ | 0.998267062 | 0.000227813 | 0.014118658 |
According to the achieved statistical parameters from empirical and calculated data IFCSD apple slices drying $R^2$ fluctuated form 0.991268 up to 0.998462, $X^2$ from 0.000228 up to 0.001148 and RMSE from 0.001091 up to 0.031692. For OSD apples drying $R^2$ fluctuated form 0.980768 up to 0.944947, $X^2$ from 0.002449 up to 0.007011 and RMSE from 0.047382 up to 0.080167. All data which obtained from the statistical analysis coefficients are dimensionless. In the case of IFCSD system all models provide comparable god description of experimental data; the differences are negligible. However, in the case of OSD system more parametric models such as Midilli and Kucuk, Verma et al and approximation of diffusion provide better results than others.

4. Conclusions

In this study, the drying behavior of apple slices was experimentally and mathematically investigated under open sun drying and indirect forced cabinet solar drying. Changes in ambient conditions such as temperature, air relative humidity, and the presence of the pollutant in the air during the day can significantly affect the performance of IFCSD and OSD drying time and dry product quality. The Color and taste, which are among the quality indicators of dried products (dried apples) which are reduced by the sediment of air pollutants and radiation of sunlight on pieces of dried apples in the OSD drying system, which is clearly visible as a result of this research. In locations with dry climate such as Afghanistan, dried product rehydration during the processing do not represent a significant issue. However, in locations with higher air humidity, this hazard can be quite significant since water activity of the dried product can reach values suitable for microorganisms’ reproduction.

Drying in an IFCSD system has a 44% efficiency of drying time compared to drying in OSD system. In the first 8 hours of the experimental day, the weight of the sample was reduced to about 80% in IFCSD and up to 45% in OSD, which shows the effectiveness of IFCSD against the OSD.

In the case of IFCSD system all 11 studied models provided comparable god description of experimental data because of stable experimental conditions in the IFCSD system. However, in the case of OSD system more parametric models such as Midilli and Kucuk provide better results than others, because of experimental data scattering.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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