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MATHEMATICAL MODELING OF THIN LAYER DRYING KINETICS OF WHITE MULBERRY (*Morus alba* L.) IN SOLAR TUNNEL DRIER

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Abstract

Drying of thin layer white mulberry fruits was studied using a solar tunnel dryer under the ecological conditions of Isparta, Turkey. An experimental solar dryer with a flat plate solar collector has been constructed at the Department of Agricultural Machinery and Technologies Engineering at Suleyman Demirel University. In this work, the effects of solar tunnel drying on drying time, drying ratio of white mulberry were investigated. During the drying process, solar irradiation, drying air temperature, relative humidity, and air velocity were measured constantly in different parts of the dryer. The change of white mulberry fruits mass was measured daily. In this study, the fresh white mulberry fruit samples were selected, sorted, washed in water. The drying characteristic curves were evaluated against ten mathematical models and the Midlli-Kucuk was found to be the best descriptive model for solar tunnel drying of thin layer white mulberry fruit samples.

Key words*: Drying characteristics, white mulberry fruits, tunnel dryer, mathematical modeling.*

INTRODUCTION

The production of white mulberry in 2005 was 78,000 tons in Turkey. Mulberry trees are extensively grown for their leaves as foods for silkworms. There are three varieties of mulberry: white mulberry (*Morus alba* L.), black mulberry (*Morus nigra* L.), and red mulberry (*Morus rubra* L.).

White mulberry originated in Western Asia, red mulberry in North and South America, and black mulberry is from Southern Russia.

White mulberry fruit has a high level of moisture content at harvest. Because of the short harvesting season and their sensitivity to storage, fresh mulberry fruits should be preserved in some form. Unwashed berries can be kept only several days in a refrigerator in a container.

A commonly used preservation method for mulberry is drying. Their fruits can be eaten raw or dried or used in mulberry pekmez, juices, paste, marmalade and wine production (Maskan and Gögüs,1998).

Drying using the sun under the open sky for preserving food and agricultural crops has been practiced since ancient times. However, this process has many disadvantages, spoilt products due to rain, wind, moisture and dust; loss of produce due to birds and animals; deterioration in the harvested crops due to decomposition, insect attacks and fungi etc.

Further, the process is labor intensive, time consuming and requires a large area for spreading the produce out to dry. Artificial mechanical drying, a relatively recent development, is energy intensive and expensive, and ultimately increases the product cost.

Solar-drying technology proposes an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions to national and international standards with zero energy costs.

It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment (Sharma et al., 2009).

Solar tunnel drier can be operated by a fan driven by photovoltaic module and this system removes moisture inside dryer.

Additionally, it was reported that fan power requirement from photovoltaic module is low. Solar tunnel drier was utilized for drying of many agricultural products such as fruits, vegetables, cereals, grain, legumes, oil seeds, spices and even fish and meat (Bala et al., 2003).

The main objective of this study to use the solar tunnel dryer for thin layer drying of white mulberry fruits.
This study specifically focused on evaluation of the effects of white mulberry fruits on the drying process using a solar tunnel dryer in Isparta conditions and to determine the best describing mathematical model to experimental data.

MATERIALS AND METHODS

Homogeneously sized mulberry samples were used in this study as experimental material. Fresh mulberry samples (*Morus alba* L) were purchased from the supermarket to use in the experiment.
A solar tunnel dryer constructed at Department of Agricultural Machinery and Technologies Engineering at Suleyman Demirel University was used in this study (Figure 1).

Figure 1. The experimental solar tunnel dryer

It comprised of a flat plate solar collector, a drying tunnel, a solar cell module, and a small axial fan. All units are mounted on metal frame. The bottom of solar collector has hexagonal channels and are directly connected to drying tunnel. The bottom of solar tunnel dryer is painted black to absorb radiation.
The collector is coated with a transparent polycarbonate material. The dryer is equipped with a 150 W solar cell module. A fan delivers air to the drying tunnel. Solar energy absorption area of the collector is 2 m length and 1.9 m width. The drying tunnel area is twice the area of collector. The dryer is oriented in east-west direction and its drying tunnel is not shaded by trees or buildings between 9:00 am and 5:00 pm.
Mulberry samples weighted on a balance reading to 0.01 g (Sartorius GP3202, Germany). Approximately 1000 g of mulberry samples were placed into trays and processed for drying experiments. Drying experiment started after completion of the loading at 9:00 am and was paused at 5:00 pm.
Weight loss of the mulberry samples in the solar tunnel drier was measured during the drying period at one hour interval with a digital balance. In the afternoon after 5:00 pm, the samples of mulberry in the solar tunnel drier were kept in the drier in the environmental conditions. Then, mulberry samples were exposed to the same weather conditions. The drying process was terminated until no mass change was detected.
Experiments were carried out on July 22-24, 2016. Solar irradiance was measured hourly (09:00 am - 17:00 pm) on a horizontal surface by pyranometer. Relative humidity and temperature of drying air were measured using K type thermocouples and DT-3 hygrometer at the drying tunnel of dryer. Air velocity at the outlet of drying tunnel was measured by a hotwire anemometer.
Mulberry samples were subjected to the moisture analysis at the oven at the temperature of 105 °C for 24 hours.
The moisture ratio (MR) was calculated based on moisture content as a function of time (t) (M(t)), initial moisture content of samples (M_0), and equilibrium moisture content of samples (M_e).

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

All moisture contents were reported as wet basis (%, w.b). Simplification of MR in Eq. (1) as M/Mo was suggested by Diamente and Munro, 1993, Elicin and Sacılık, 2005, due to the continuous fluctuation of relative humidity of drying air under solar tunnel dryer conditions. Therefore, the drying rate as g_{water}/h (DR) of the white mulberry samples was determined by Eq. (2)

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

Where M_{t+dt} is the moisture content at t+dt (g water/g dry matter). A non-linear regression analysis (Sigma Plot 12.00) was applied to

experimentally obtained MR as a function of time using drying models given in Table 1.
The constants (a, n, b, c, m, k, and g) of models tested in Table 1 were determined based on the non-linear regression analysis.

The performance of models was evaluated by coefficient of determination (R^2), the standard error of estimate (SEE), and residual sum of square (RSS).

Table 1. Mathematical models tested for the moisture ratio values of the white mulberry samples

No	Model name	Model Equation	References
1	Diffusion approach	MR=a exp(-k t)+(1-a) exp(-k b t)	Artnaseaw et al. 2010
2	Henderson and pabis	MR=a exp(-k t)	Doymaz, 2014
3	Logarithmic	MR=a exp(-k t)+c	Akpinar 2008
4	Midilli et al.	MR=a exp(-kt^m)+b t	Midilli et al. 2002
5	Newton	MR=exp(-kt)	Toğrul and Pehlivan 2002
6	Page	MR=exp(-kt^n)	Akpinar 2008
7	Two term	MR=a exp(-k_0t)+b exp(-k_1t)	Yaldiz et al.2001
8	Two term exponential	MR=a exp(-kt)+(1-a)*exp(-m*k*x)	Sharaf-Elden et al. 1980
9	Verma et al.	MR=a exp(-kt)+(1-a) exp(-gt)	Verma et al. 1985
10	Wang and Singh	MR=1+at+bt^2	Babalis et al. 2006

RESULTS AND DISCUSSIONS

Solar drying of white mulberry samples was conducted on July in 2016. Throughout the drying experiment, the weather was sunny and no rain was recorded. The drying experiment lasted for 3 days.
The influence of thin layer white mulberry samples on moisture ratio and drying rate were also investigated.

The drying time necessary for reduction of initial moisture content from (80 % w.b.) to the desired final moisture content up to (12,4% w.b.) for solar tunnel drying was found to be 32 hours.
As shown in Figure 1, moisture ratio decreased continuously with decreasing moisture content. The absence of lines in drying cycle in each day in Figure 2 indicates the night periods (Saçılık and Eliçin, 2005).

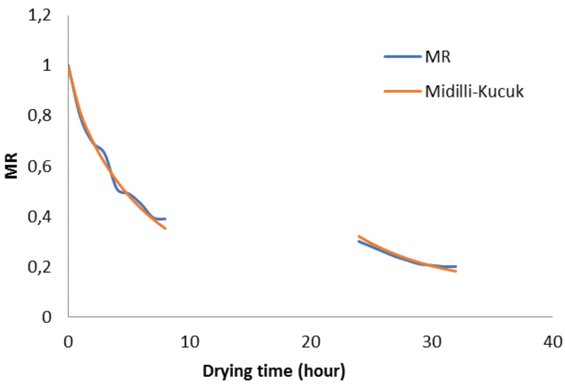

Figure 2. Variation of moisture ratio with drying time for solar tunnel drying of white mulberry

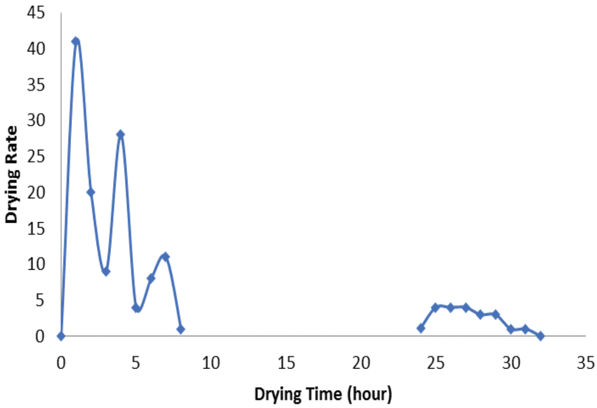

Figure 3. Variation of drying rate as a function of drying time for solar tunnel drying of white mulberry

The change of drying rate as a function of time is depicted in Figure 3 in solar tunnel drier. The results showed that the drying rate was 41.2 g/h within one hour and at the final stage of drying rate decreased to 1.5 g/h for white mulberry samples. The drying rate sharply increased within one hour and then decreased. This behavior was periodic and gradually diminishing in magnitude on each day of drying.

Table 2 shows the outcomes of nonlinear regression analysis applied to the ten drying models to the experimental data for white mulberry samples with R^2, SEE, and RSS. The best model describing drying of white mulberry samples in given conditions was determined based on R^2 with the lower value of SEE and RSS, which are evaluation criteria used to compare the statistical validity of the fit. The results showed that the R^2, SEE, and RSS values of nonlinear regression analysis ranged from 0.9515 to 0.9937, from 0.0206 to 0.0548, and from 0.0060 to 0.0451, respectively (Table 2). Furthermore, Midilli et al. model yielded the highest R^2 (0.9937) for white mulberry samples, with the lowest SEE and RSS values (Table 2).

Table 2. Results of nonlinear regression analysis of fitting the ten drying models to the experimental data for solar tunnel drying of mulberry samples

	Model No									
	1	2	3	4	5	6	7	8	9	10
R^2	0.9519	0.9722	0.9912	0.9937	0.9519	0.9928	0.9918	0.9915	0.9915	0.9625
SEE (±)	0.0548	0.0404	0.0235	0.0206	0.0515	0.0206	0.0235	0.0231	0.0231	0.0469
RSS (±)	0.0451	0.0261	0.0083	0.0060	0.0451	0.0068	0.0077	0.0080	0.0080	0.0352

CONCLUSIONS

In this work, experiment of solar tunnel drying of white mulberry samples are presented. Based on the experimental results reported, following conclusions can be made:

Drying time decreased considerably with increased temperature.

Different mathematical models, namely, Diffusion Approach, Henderson and Pabis, Logarithmic, Midilli-Kucuk, Newton, Page, Two Term, Two Term Exponential, Verma Wang and Singh used to describe the drying kinetics of white mulberry samples. The Midilli-Kucuk model gave excellent fit for all data points with higher R^2 values and lower SEE and RSS values.

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