Mathematical modelling of lemon verbena leaves drying in a continuous flow dryer equipped with a solar pre-heating system

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RESEARCH ARTICLE

Abstract

The modelling of the drying process of lemon verbena leaves in a continuous flow dryer equipped with a solar pre-heating system was performed at three levels of drying temperature (50, 40, and 30 °C) and three levels of air velocity (2, 1.5 and 1 m/s). During the experiments, lemon verbena leaves were dried to the final moisture content of 10 from 76% wet basis in the continuous flow dryer. Drying kinetic showed to drying temperature and air velocity exerted significant influence on the drying time. Also, the dried lemon verbena leaves quality was obtained by determining the essential oil content of the product after drying in different conditions in the dryer. Finally, it was observed that the highest essential oil content was maintained at a temperature of 40 °C and air velocity of 1 m/s. Suitability of 10 different mathematical drying models was used to describe drying lemon verbena leaves in this dryer. The results have shown that Midilli and Kucuk's model can successfully predict the experimental data in all air temperatures and air velocities. In Midilli and Kucuk's model, the amounts of R^2 were above 999×10^{-3} and the amounts of root- mean-square error (RMSE) and chi-square (χ^2) were less than 174×10^{-4} and 19×10^{-4}.

Keywords: air velocity, air temperatures, drying kinetic, Midilli and Kucuk's model

1. Introduction

Lemon verbena (*Lippia citriodora* Kunth.) is one of the well-known medicinal plants that has many properties, including antispasmodic, carminative, diuretic, digestive and sedative agent (da Cunha *et al.*, 2012). The most important constituents of lemon verbena essential oil (EO) include neral, limonene and geranial (Ishkeh *et al.*, 2019). The most important process for keeping medicinal plants is drying. Drying is one of the methods of food storage (Javed *et al.*, 2019). The drying methods of medicinal plants have a great influence on their quality (Asekun *et al.*, 2007). Therefore, it is important to choose the suitable drying methods for sensitive products, such as medicinal plants (Motevali *et al.*, 2014).

Reducing moisture content (MC) reduces or stops the enzymatic or microbial activity and reduces the weight of products and facilitates the processing of products. Factors such as temperature and velocity of inlet air, initial and final humidity of the product, relative humidity and ambient air temperature affect the amount of moisture variation relative to time (Movagharnejad and Nikzad, 2007). In a research, the drying of lemon balm leaves in an indirect mode solar dryer with a double-pass air heater was investigated. According to the tests results, the temperature difference between the collector outlet and ambient declined significantly with increasing volumetric flow rate, whereas increasing the flow rate improved the collector thermal efficiency by ~20% (Shamekhi-Amiri *et al.*, 2018).

A common method for predicting moisture loss during drying time is the empirical modelling or regression modelling, which normally measures different variables by performing empirical experiments, and the best algebraic equation between variables is selected based on the fitting of the measured data with known algebraic equations related to the kinetics of drying. Modelling the actual process of drying in terms of mathematical relations is necessary to define optimum drying conditions (Panchariya *et al*., 2002). Akpinar (2010) fitted the thin-layer drying data in a solar dryer with forced convection and under the open sun with natural convection of mint leaves to 10 different mathematical models. Wang and Singh's model was found as the best model describing the thin layer drying behaviour of mint leaves (Akpinar, 2010).

In a study, 14 mathematical models of mint and thymus thin layer drying were tested to specify the suitable model in an indirect-mode forced convection solar dryer. The Midilli and Kucuk's model and Page and modified Page models were found for describing the drying curves of the mint and thymus, respectively (El-Sebaii and Shalaby, 2013).

Aral and Beşe (2016) investigated the thin-layer drying characteristics of hawthorn fruit in a convective dryer at different air temperatures and air velocities. The results of this study showed that drying time decreases with increasing air temperature and air velocity. Also, Midilli *et al*.'s model was obtained as the best model for drying behaviour in this study (Aral and Beşe, 2016).

Jayatunga and Amarasinghe (2018) examined the drying kinetics of black pepper in a conventional spouted bed dryer and a spouted bed dryer fitted with a non-porous draft tube. Their results showed that the highest drying rate was achieved when black pepper was dried without draft tube at the highest drying temperature. Also, a new thin layer drying model was proposed and compared with five commonly used models and the drying behaviour of black pepper in spouted bed dryer was best fitted to (Verma *et al*., 1985) model and the proposed model (Jayatunga and Amarasinghe, 2018). In a study, seven different mathematical drying models were compared for describing thin layer drying of cashew kernels in a batch dryer. The results showed that the Page model was found to be the best for describing the drying behaviour of cashew kernels (Asiru *et al*., 2013).

Knowing the drying behaviour is important in designing, simulating and optimising the drying process. Several studies have been conducted on the drying of agricultural products, including vegetables, such as drying savory leaves (Arslan and Özcan, 2012), drying turmeric rhizomes in a solar conduction dryer (Borah *et al*., 2015) and drying of thyme (*Thymus Vulgaris* L.) (Doymaz, 2011). Drying kinetic study is necessary to obtain information about the time required for drying and select the appropriate drying model (Baini and Langrish, 2008).

Due to the possibility of undesirable changes in the quality of food because of drying, its control is of particular importance; therefore, in order to maintain the safety of products, their moisture should be reduced to a certain amount. To achieve this goal, it is necessary to model the drying of various agricultural products so that the model of drying out the product can be predicted based on the pattern obtained from the model.

As conventional methods of drying leaves plants have many problems, such as lower product quality, in this article we used a continuous flow dryer. In this type of dryer, two sources of solar energy and natural gas were used to provide heat. Due to the importance and sensitivity of the lemon verbena medicinal plant to drying, the aim of this study was to develop a continuous dryer equipped with a solar pre-heating system, to find out the suitable model and to describe the drying characteristics of lemon verbena leaves in different air temperatures and air velocities.

2. Materials and methods

Material

Lemon verbena leaves were directly bought from local producers in Rasht, Iran. Leaves were packed in polyethylene packaging and stored in a refrigerator at a temperature of 6 °C. The initial MC of the samples was determined by placing three samples of leaves in a hot air oven at a temperature of 103 °C for 24 h (Zheng *et al*., 2005). The average initial MC of the lemon verbena leaves was equal to 76% wet basis (w.b.).

Experimental procedure

Drying experiments were performed in a continuous dryer equipped with a solar pre-heating system at the Renewable Energy Site of the University of Guilan, Rasht, Iran (49°35′19″E longitude and 37°16′33″N latitude). The dryer consists of air relative humidity/temperature sensors, solar water heater, gas water heater, continuous flow dryer, heat exchanger, water pump and centrifugal air blower (Figure 1). The air temperature and relative humidity in the drying chamber were measured by an air relative humidity/temperature sensor (Model AM2301, China).

The variation of the recorded temperatures from the set points during the experiments was ±1 °C. The air velocity of the input air was measured by a turbine-type anemometer (Lutron Model, 80 AM, Taiwan). The dryer was a continuous flow type with four sets of conveyor belts placed above each other. The speed of the conveyor belt was adjusted using a single-phase inverter (LG Model IC5, Korea). Based on some pretests, the speed of the conveyor was adjusted to 43.1×10^{-2} m/s.

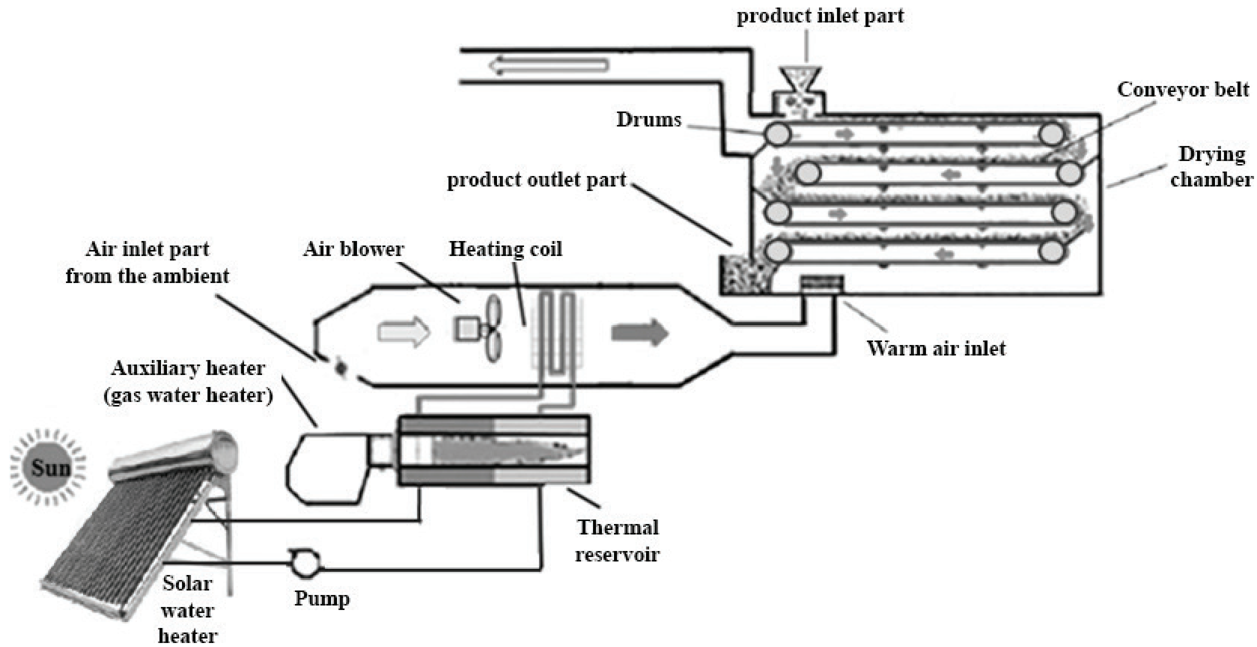

Figure 1. Schematic view of the continuous dryer equipped with solar pre-heating system.

The movement of the drive pulley of the conveyor belts was performed by an electric motor (0. 75 kW). For the production of hot air and drying, the product is used in conventional dryers from the thermal energy of a gas burner. A solar water heater combined with a gas water heater (Butane Model 3318IF, Iran) was used to heat the water. The heated water was then entered into a heat exchanger (Hepaco Model HP-1500, Iran) using pipelines. The airflow was blown into the water pipe by a blower to direct the heat of the pipes into the drying chamber. A portion of the required thermal energy was provided by a thermosiphon type of solar water heater having the capacity of 150 L. The four rows of conveyor belts moved in the opposite direction in the drying chamber (with dimensions of 150 × 150 × 80 cm^3). The centrifugal blower was able to change the amount of inlet air by a single-phase inverter (LG Model IC5, Korea).

After the dryer reached desired conditions, about 150 g of the samples was put into the dryer chamber for drying. Eventually, the MC of the lemon verbena reached 10% (w.b.) for each experiment. In this research, drying of the product was performed at 30, 40 and 50 °C temperatures and air velocities of 2, 1.5 and 1 m/s. The leaves were weighed (every 10 min) by a digital balance (A&D Model GF6000, Japan).

Drying calculation

The MC and moisture ratio of lemon verbena leaves samples during drying experiments was calculated using the following equations (Omolola *et al.*, 2018; Erenturk *et al.*, 2004):

$$MC_{w.b} = \frac{W_a - W_b}{W_a} \tag{1}$$

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{2}$$

where MC, W_o and W_d are the MC (%), weight (g) of the sample and dried sample, respectively, and M_t and M_o are the MC at any drying time and the initial MC, respectively. This equation can be simplified to M_t/M_o because the equilibrium MC value (M_e) is small compared with that of M_t and M_o (Essalhi *et al.*, 2018; Rabha *et al.*, 2017). Also, Equation (3) was used to calculate the drying rate during leaves drying experiments (Labed *et al.*, 2016).

$$DR = \frac{\left(M_{t+dt} - M_t\right)}{d_t} \tag{3}$$

Extraction of the EO

Medicinal plants have unique and valuable properties. EO derived from medicinal plants had long been used in the food, pharmaceutical, perfume and cosmetics industries (Sari, 2018). One of the most important methods of preserving medicinal plants is drying (Bhardwaj *et al.*, 2019). The method and temperature of drying of these plants have a great influence on their EO content and quality. For this reason, in the present study, the amount of EO of lemon verbena leaves after drying was obtained for each sample at different drying temperatures and speeds.

For EO extraction by the hydro-distillation method, 30 g of each sample was placed into a Clevenger with 450 ml of water for 3 h (Abd El-Gaber *et al.*, 2018). Isolation of EO from water due to density difference was easy (Saleh *et al.*, 2019). The EO content of each sample after weighing by a digital balance was calculated using Equation (4).

$$Essential\ oil\ content\ (\%) = \frac{EO(g)}{Dry.matter(g)} \times 100 \quad (4)$$

Mathematical modelling

Ten drying equations given in Table 1 were evaluated to select the most suitable model for describing the drying curves of lemon verbena leaves. Regression analysis was performed using MATLAB and SPSS 11.5.1 software package. In order for the superior model to be chosen, the value of the coefficient of determination must be high and the value of RMSE and χ^2 must be low (Torki-Harchegani *et al.*, 2016). The calculations were performed using Equations (5), (6) and (7) (Akpinar, 2010):

$$R^2 = \frac{\sum_{i=1}^{N}(MR_i - MR_{pre,i})\sum_{i=1}^{N}(MR_i - MR_{\exp,i})}{\sqrt{\left[\sum_{i=1}^{N}(MR_i - MR_{pre,i})^2\right].\left[\sum_{i=1}^{N}(MR_i - MR_{\exp,i})^2\right]}} \quad (5)$$

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

$$x^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-n} \quad (7)$$

where $MR_{pre,i}$ and $MR_{exp,i}$ are the predicted and experimental moisture ratio, respectively, and n and N are the number of the drying constants and observations, respectively.

Table 1. Mathematical models applied to the moisture ratio curves.

Models	Equations	References
Two-term exponential	$MR = a \cdot e^{(-kt)} + (1-a) \cdot e^{(-kat)}$	Badaoui *et al.* (2019)
Henderson and Pabis	$MR = a \cdot e^{(-kt)}$	Mghazli *et al.* (2017)
Logarithmic	$MR = a \cdot e^{(-kt)} + c$	Motevali *et al.* (2016)
Diffusion approach	$MR = a \cdot e^{(-kt)} + (1-a) \cdot e^{(-kbt)}$	Vijayan *et al.* (2016)
Midilli and Kucuk	$MR = a \cdot e^{(-kt)^n} + bt$	El-Sebaii and Shalaby (2013)
Newton	$MR = e^{(-kt)}$	Yogendrasasidhar and Setty (2018)
Modified Page	$MR = e^{(-(kt)^n)}$	Duffie and Beckman (2013)
Two-term	$MR = a \cdot e^{(-kt)} + b \cdot (-kt)$	(Torki-Harchegani *et al.* (2016)
Page	$MR = e^{(-kt^n)}$	Vijayan *et al.* (2016)
Wang and Singh	$MR = 1 + at + bt^2$	Aregbesola *et al.* (2015)

3. Results and discussion

Drying kinetics

Lemon verbena leaves were dried to in a continuous dryer equipped with a solar pre-heating system at different temperatures (30, 40 and 50 °C) and different air velocities (2, 1.5 and 1 m/s). Experimental data obtained from the drying process of lemon verbena leaves were converted into MC. The MC diagram of the lemon verbena leaves during the drying period is shown in Figure 2. From the figure, it is clear that with an increase in the air temperature from 30 to 50 °C, the slope of the MC curve increases.

Air temperature is an important parameter in drying the products. Therefore, with increasing air temperature, the moisture removal increased and, as shown in Figure 3, the drying time also significantly decreased (Akhondi *et al.*, 2011; Mujaffar and John, 2018). It was also observed that with an increase in the air velocity from 1 to 2 m/s, the drying time decreased. As shown in Figure 3, the minimum drying time of leaves (110 min) was obtained at 50 °C and an air velocity of 2 m/s. The temperature and air velocity of the drying have a great influence on the drying time of the product (Ertekin and Yaldiz, 2004). With increasing air velocity, the moisture transfer rate increases (Motevali *et al.*, 2010). At air velocity of 2 m/s and with an increase in the air temperature from 30 to 50 °C, the drying time reduced by 26.66%, while at air velocities of 1.5 and 1 m/s, the drying time was reduced by 25 and 23.52%, respectively. With an increase in air velocity from 1 to 1.5 and 2 m/s, the drying time was reduced by 5.888 and 11.76%, respectively. Drying time is one of the important factors in preserving the quality of medicinal plants.

The resulted MC curves showed that the drying time and the slope of the curved surface are inversely related. At the beginning of the drying process, the speed of moisture loss is higher due to increased moisture release from the inside to the product surface. At the end of the drying period, the leaves are dampened with a milder gradient and ultimately the sample is weighed down the constant (Doymaz *et al.*, 2006).

Figure 4 shows the changes in the drying rate versus MC at temperatures of 30, 40 and 50 °C and air velocities of 1, 1.5 and 2 m/s. The process of leaves drying occurred in the falling rate period.

As shown in the figure, the drying rate increased when the drying air temperature increased, and at air temperature of 50 ° C at all air velocities, the highest drying rate was obtained. The reason for this increase could be the increased heat transfer potential between the drying air and product leaves.

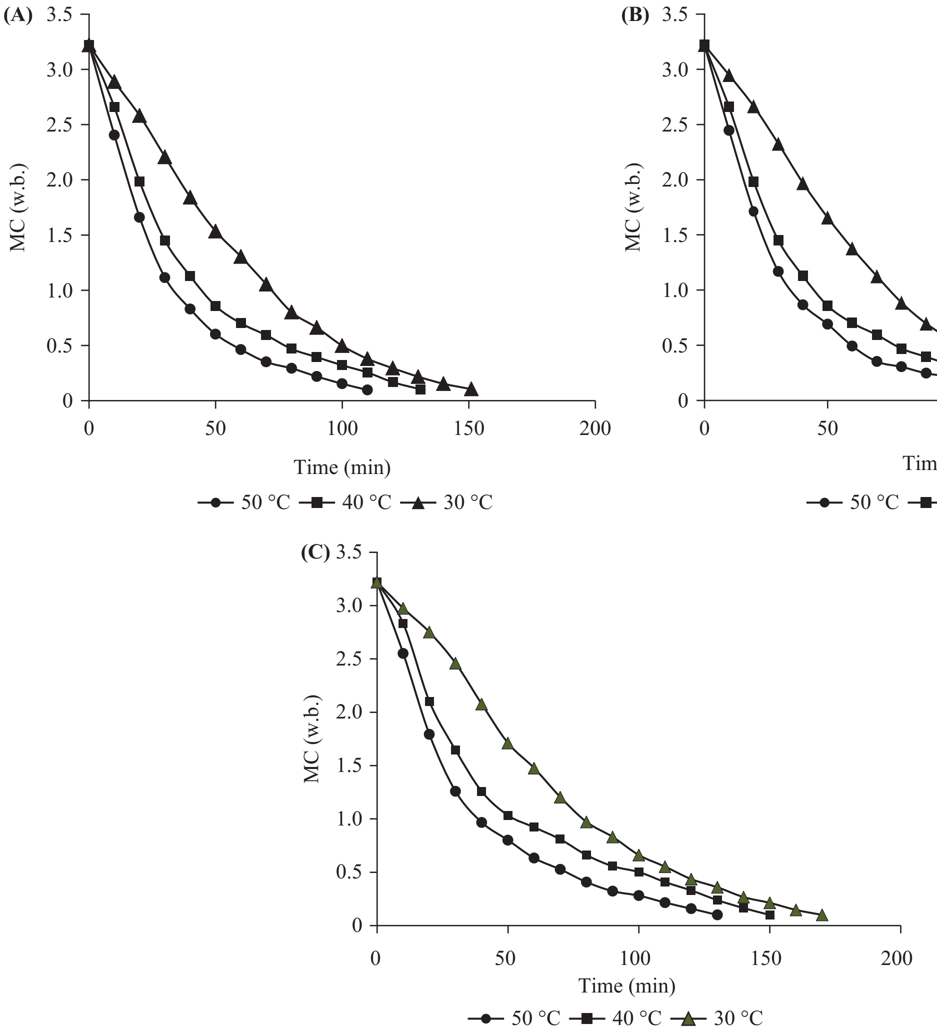

Figure 2. Variation of moisture content as a function of time for different temperatures and air velocities of (A) 2, (B) 1.5 and (C) 1 m/s.

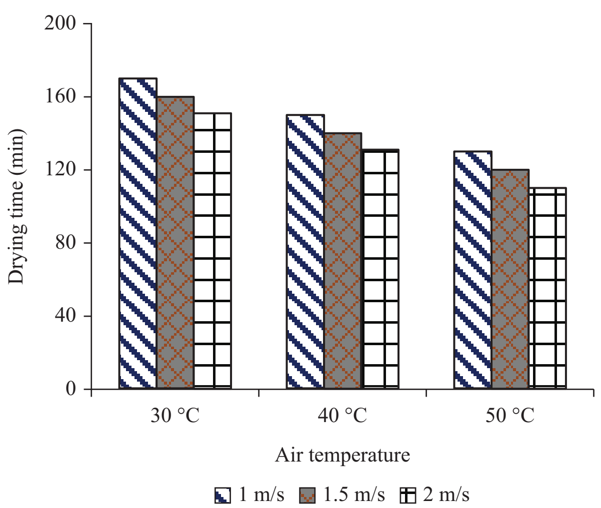

Figure 3. A comparison of the drying time of lemon verbena leaves at different air velocities.

Quality evaluation

Table 2 shows the effect of three air velocities of 1, 1.5 and 2 m/s and temperatures of 30, 40 and 50 °C on the EO content of lemon verbena leaves. As can be seen from the data in the table, due to the sensitivity of the EO to high temperature, the EO content decreases with increasing temperature.

According to the results, the EO content at a temperature of 30 °C was less than that of 40 °C. This may be due to the sudden accumulation of EO in its storage cells. The lowest EO content was obtained at drying temperature of 50 °C and air velocity of 1 m/s (0.33%) and the highest EO content was obtained at drying temperature of 40 °C and air velocity of 2 m/s (0.60%). According to the results, drying air temperature and air velocity affected EO content (Pirbalouti *et al*., 2013; Torki-Harchegani *et al*., 2016).

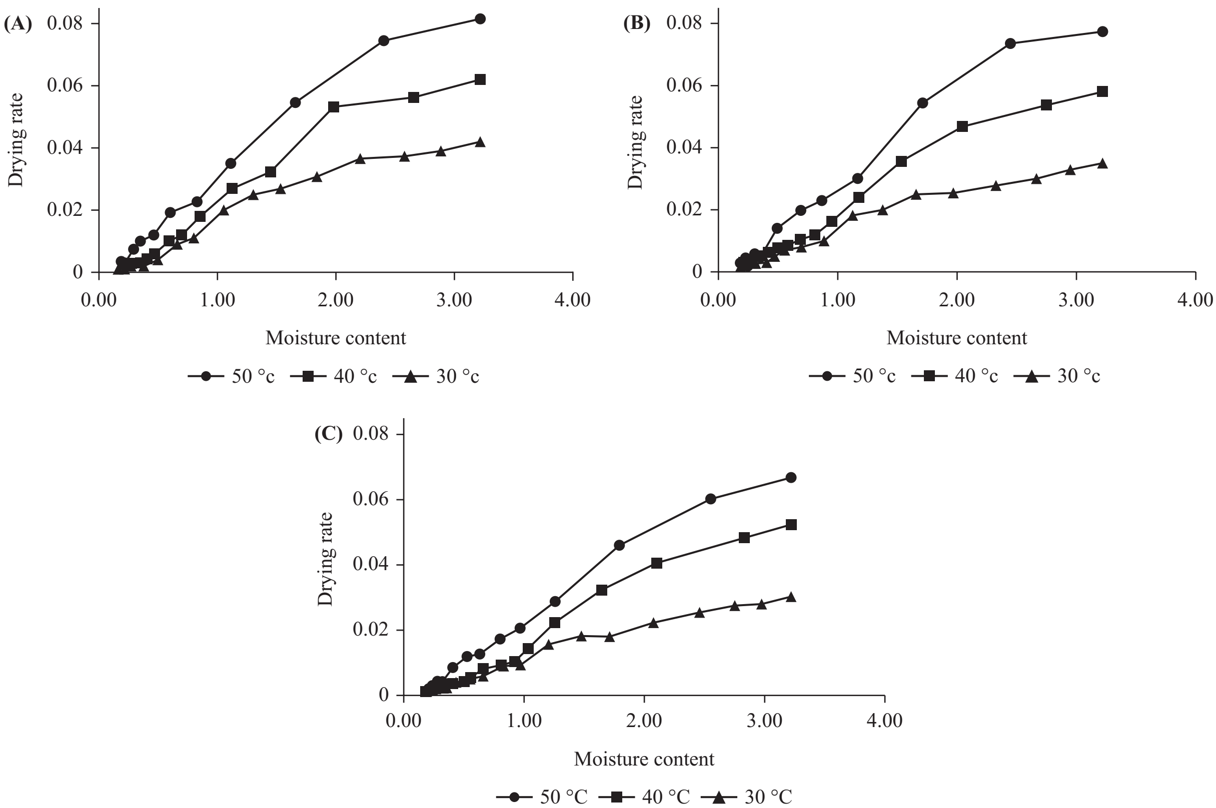

Figure 4. Variation in the drying rate versus moisture content of lemon verbena leaves at air velocities of (A) 2, (B) 1.5 and (C) 1 m/s.

Table 2.The essential oil content (%) of lemon verbena leaves at different drying temperatures and air velocities.

Air velocity (m/s)	Air temperature (°C)		
	30	40	50
1	0.47	0.43	0.33
1.5	0.53	0.50	0.37
2	0.57	0.60	0.40

Mathematical modelling of drying curves

In this study, different regression models were evaluated with respect to R^2, RMSE and χ^2 values. The criterion for choosing the superior model was a greater amount of R^2 and lower values of χ^2 and RMSE. Table 3 presents the results of statistical indices obtained from different models for lemon verbena drying at different levels of temperature and air velocity. As can be seen from the data, the highest matching with experimental data was obtained in Midilli and Kucuk's model for drying of lemon verbena leaves. The arbitrary constant of this model for all drying conditions (temperature and velocity) is given in Table 4.

The variation of moisture ratio of lemon verbena leaves with time for 2, 1.5 and 1 m/s air velocities is shown in Figure 5. The results have shown that Midilli and Kucuk's model can successfully predict the experimental data. From the plots in the figure, it is observed that Midilli and Kucuk's model exhibits a good fit to the experimental data. Also other researchers have confirmed Midilli and Kucuk's model as the suitable model to describe the drying behaviour of different products, such as drying kinetics of pumpkin slice (Benseddik *et al.*, 2018), yacon slices (Shi *et al.*, 2013), sage leaves in a cabinet dryer (Doymaz and Karasu, 2018) and apple slices (Meisami-Asl *et al.*, 2010).

4. Conclusions

In this study, a continuous flow dryer equipped with a solar pre-heating system was used for drying the lemon verbena leaves. The developed system has the proper ability to provide the primary thermal energy for drying lemon verbena leaves. The benefits of using solar energy for drying include reducing pollution emission and fossil fuel consumption. The temperature of the air for drying the lemon verbena was 30, 40 and 50 °C during the experiments, which was sufficient for leaves drying. The increase in drying temperature and air velocity reduced the drying time of lemon verbena leaves. As the air velocity in the dryer increased, the drying rate increased at all three drying temperatures. Also the MC of lemon verbena

Table 3. Accuracy of fitting models based on different statistical indices.

Temperature	30 °C			40 °C			50 °C		
Model name	**RMSE**	χ^2	R^2	**RMSE**	χ^2	R^2	**RMSE**	χ^2	R^2
1 m/s									
Two-term exponential	78×10^{-4}	132×10^{-4}	$9{,}950 \times 10^{-4}$	$3{,}078 \times 10^{-4}$	120×10^{-4}	$9{,}959 \times 10^{-4}$	$3{,}003 \times 10^{-4}$	90×10^{-4}	$9{,}920 \times 10^{-4}$
Henderson and Pabis	$3{,}001 \times 10^{-4}$	$4{,}679 \times 10^{-4}$	$5{,}890 \times 10^{-4}$	$3{,}012 \times 10^{-4}$	$2{,}004 \times 10^{-4}$	$8{,}907 \times 10^{-4}$	$3{,}129 \times 10^{-4}$	$2{,}348 \times 10^{-4}$	$7{,}987 \times 10^{-4}$
Logarithmic	$2{,}104 \times 10^{-4}$	450×10^{-4}	$9{,}567 \times 10^{-4}$	$2{,}978 \times 10^{-4}$	658×10^{-4}	$9{,}485 \times 10^{-4}$	$3{,}036 \times 10^{-4}$	246×10^{-4}	$9{,}568 \times 10^{-4}$
Diffusion approach	0	126×10^{-4}	0	$2{,}584 \times 10^{-4}$	15×10^{-4}	$6{,}539 \times 10^{-4}$	$3{,}002 \times 10^{-4}$	17×10^{-4}	$5{,}377 \times 10^{-4}$
Midilli and Kucuk	$\mathbf{87 \times 10^{-4}}$	$\mathbf{19 \times 10^{-4}}$	$\mathbf{9{,}994 \times 10^{-4}}$	$\mathbf{71 \times 10^{-4}}$	$\mathbf{18 \times 10^{-4}}$	$\mathbf{9{,}990 \times 10^{-4}}$	$\mathbf{173 \times 10^{-4}}$	$\mathbf{10 \times 10^{-4}}$	$\mathbf{9{,}995 \times 10^{-4}}$
Newton	$2{,}348 \times 10^{-4}$	2.8976	$5{,}468 \times 10^{-4}$	$2{,}786 \times 10^{-4}$	$7{,}655 \times 10^{-4}$	$8{,}134 \times 10^{-4}$	$3{,}100 \times 10^{-4}$	$6{,}754 \times 10^{-4}$	$8{,}076 \times 10^{-4}$
Modified Page	165×10^{-4}	18×10^{-4}	$9{,}896 \times 10^{-4}$	$3{,}187 \times 10^{-4}$	16×10^{-4}	$9{,}980 \times 10^{-4}$	$3{,}658 \times 10^{-4}$	38×10^{-4}	$9{,}879 \times 10^{-4}$
Two-term	$3{,}015 \times 10^{-4}$	126×10^{-4}	$9{,}979 \times 10^{-4}$	$3{,}006 \times 10^{-4}$	66×10^{-4}	$9{,}965 \times 10^{-4}$	$3{,}457 \times 10^{-4}$	21×10^{-4}	$9{,}891 \times 10^{-4}$
Page	$1{,}116 \times 10^{-4}$	392×10^{-4}	$8{,}746 \times 10^{-4}$	$1{,}053 \times 10^{-4}$	164×10^{-4}	$9{,}757 \times 10^{-4}$	$2{,}256 \times 10^{-4}$	244×10^{-4}	$9{,}431 \times 10^{-4}$
Wang and Singh	0	2.998	0	$3{,}012 \times 10^{-4}$	$4{,}358 \times 10^{-4}$	$5{,}678 \times 10^{-4}$	$3{,}014 \times 10^{-4}$	$3{,}178 \times 10^{-4}$	$7{,}034 \times 10^{-4}$
1.5 m/s									
Two-term exponential	158×10^{-4}	37×10^{-4}	$9{,}974 \times 10^{-4}$	$3{,}175 \times 10^{-4}$	66×10^{-4}	$9{,}965 \times 10^{-4}$	$3{,}149 \times 10^{-4}$	96×10^{-4}	$9{,}915 \times 10^{-4}$
Henderson and Pabis	$2{,}627 \times 10^{-4}$	$3{,}737 \times 10^{-4}$	$6{,}912 \times 10^{-4}$	$2{,}981 \times 10^{-4}$	$1{,}381 \times 10^{-4}$	$8{,}896 \times 10^{-4}$	$2{,}849 \times 10^{-4}$	$1{,}986 \times 10^{-4}$	$8{,}147 \times 10^{-4}$
Logarithmic	$3{,}103 \times 10^{-4}$	490×10^{-4}	$9{,}649 \times 10^{-4}$	$3{,}064 \times 10^{-4}$	689×10^{-4}	$9{,}385 \times 10^{-4}$	$3{,}127 \times 10^{-4}$	303×10^{-4}	$9{,}756 \times 10^{-4}$
Diffusion approach	0	26×10^{-4}	0	$2{,}634 \times 10^{-4}$	4×10^{-4}	$6{,}939 \times 10^{-4}$	$2{,}383 \times 10^{-4}$	9×10^{-4}	$5{,}678 \times 10^{-4}$
Midilli and Kucuk	$\mathbf{59 \times 10^{-4}}$	$\mathbf{18 \times 10^{-4}}$	$\mathbf{9{,}996 \times 10^{-4}}$	$\mathbf{61 \times 10^{-4}}$	$\mathbf{16 \times 10^{-4}}$	$\mathbf{9{,}993 \times 10^{-4}}$	$\mathbf{162 \times 10^{-4}}$	$\mathbf{4 \times 10^{-4}}$	$\mathbf{9{,}996 \times 10^{-4}}$
Newton	$1{,}902 \times 10^{-4}$	2.7311	$3{,}617 \times 10^{-4}$	$2{,}652 \times 10^{-4}$	$7{,}785 \times 10^{-4}$	$7{,}034 \times 10^{-4}$	$2{,}652 \times 10^{-4}$	$7{,}785 \times 10^{-4}$	$7{,}034 \times 10^{-4}$
Modified Page	145×10^{-4}	12×10^{-4}	$9{,}931 \times 10^{-4}$	$3{,}162 \times 10^{-4}$	14×10^{-4}	$9{,}976 \times 10^{-4}$	$3{,}159 \times 10^{-4}$	26×10^{-4}	$9{,}979 \times 10^{-4}$
Two-term	$3{,}158 \times 10^{-4}$	27×10^{-4}	$9{,}964 \times 10^{-4}$	$3{,}156 \times 10^{-4}$	76×10^{-4}	$9{,}958 \times 10^{-4}$	$3{,}161 \times 10^{-4}$	17×10^{-4}	$9{,}906 \times 10^{-4}$
Page	$2{,}108 \times 10^{-4}$	291×10^{-4}	$9{,}632 \times 10^{-4}$	$2{,}153 \times 10^{-4}$	65×10^{-4}	$9{,}963 \times 10^{-4}$	$2{,}136 \times 10^{-4}$	146×10^{-4}	$9{,}830 \times 10^{-4}$
Wang and Singh	0	2.9576	0	$2{,}734 \times 10^{-4}$	$3{,}594 \times 10^{-4}$	$6{,}999 \times 10^{-4}$	$2{,}686 \times 10^{-4}$	$2{,}735 \times 10^{-4}$	$7{,}206 \times 10^{-4}$
2 m/s									
Two term exponential	169×10^{-4}	40×10^{-4}	$9{,}886 \times 10^{-4}$	$3{,}195 \times 10^{-4}$	70×10^{-4}	$9{,}884 \times 10^{-4}$	$3{,}019 \times 10^{-4}$	86×10^{-4}	$9{,}930 \times 10^{-4}$
Henderson and Pabis	$3{,}101 \times 10^{-4}$	$3{,}897 \times 10^{-4}$	$6{,}012 \times 10^{-4}$	$3{,}283 \times 10^{-4}$	$2{,}581 \times 10^{-4}$	$7{,}895 \times 10^{-4}$	$3{,}485 \times 10^{-4}$	$2{,}316 \times 10^{-4}$	$7{,}645 \times 10^{-4}$
Logarithmic	$3{,}870 \times 10^{-4}$	679×10^{-4}	$9{,}438 \times 10^{-4}$	$3{,}184 \times 10^{-4}$	729×10^{-4}	$9{,}168 \times 10^{-4}$	$3{,}547 \times 10^{-4}$	403×10^{-4}	$9{,}470 \times 10^{-4}$
Diffusion approach	0	126×10^{-4}	0	$2{,}587 \times 10^{-4}$	12×10^{-4}	$7{,}839 \times 10^{-4}$	$2{,}012 \times 10^{-4}$	11×10^{-4}	$6{,}675 \times 10^{-4}$
Midilli and Kucuk	$\mathbf{51 \times 10^{-4}}$	$\mathbf{15 \times 10^{-4}}$	$\mathbf{9{,}998 \times 10^{-4}}$	$\mathbf{60 \times 10^{-4}}$	$\mathbf{16 \times 10^{-4}}$	$\mathbf{9{,}995 \times 10^{-4}}$	$\mathbf{174 \times 10^{-4}}$	$\mathbf{9 \times 10^{-4}}$	$\mathbf{9{,}994 \times 10^{-4}}$
Newton	987×10^{-4}	1.8759	$5{,}648 \times 10^{-4}$	$2{,}027 \times 10^{-4}$	$6{,}548 \times 10^{-4}$	$8{,}237 \times 10^{-4}$	$1{,}627 \times 10^{-4}$	$6{,}775 \times 10^{-4}$	$8{,}036 \times 10^{-4}$
Modified Page	120×10^{-4}	10×10^{-4}	$9{,}945 \times 10^{-4}$	$2{,}154 \times 10^{-4}$	12×10^{-4}	$9{,}980 \times 10^{-4}$	$2{,}127 \times 10^{-4}$	16×10^{-4}	$9{,}989 \times 10^{-4}$
Two-term	$2{,}984 \times 10^{-4}$	23×10^{-4}	$9{,}970 \times 10^{-4}$	$3{,}026 \times 10^{-4}$	56×10^{-4}	$9{,}968 \times 10^{-4}$	$2{,}261 \times 10^{-4}$	15×10^{-4}	$9{,}936 \times 10^{-4}$
Page	$3{,}024 \times 10^{-4}$	$1{,}247 \times 10^{-4}$	$9{,}012 \times 10^{-4}$	$2{,}587 \times 10^{-4}$	146×10^{-4}	$9{,}087 \times 10^{-4}$	$2{,}547 \times 10^{-4}$	268×10^{-4}	$9{,}580 \times 10^{-4}$
Wang and Singh	0	2.7547	0	$3{,}346 \times 10^{-4}$	$4{,}337 \times 10^{-4}$	$5{,}698 \times 10^{-4}$	$3{,}623 \times 10^{-4}$	$3{,}765 \times 10^{-4}$	$6{,}206 \times 10^{-4}$

Table 4. Arbitrary constant of the Midilli and Kucuk's model for different temperatures and air velocities.

V (m/s)	T (°C)	*n*	*b*	*k*	*a*
	30	1.126	−0.00021	0.00576	0.9913
1	40	1.129	−0.00001	0.00904	0.9954
	50	1.193	−0.00076	0.01845	0.9864
	30	1.034	−0.00011	0.00875	0.9924
1.5	40	1.127	−0.00000	0.00975	0.9962
	50	1.184	−0.00043	0.01743	0.9878
	30	1.128	−0.00012	0.00764	0.9986
2	40	1.124	−0.00001	0.00986	0.9972
	50	1.192	−0.00102	0.02573	0.9789

leaves was reduced to 10% w.b. in this dryer. The resulted MC curves showed that the time of drying and the slope of the curved surface were inversely related.

The dried lemon verbena leaves quality was obtained by determining the EO content of the product after drying in different dryer conditions. Finally, it was observed that the highest EO content was maintained at a temperature of 40 °C and air velocity of 1 m/s. A number of mathematical models were tested for the prediction of drying lemon verbena leaves in this dryer. According to statistical analysis, Midilli and Kucuk's model was selected due to the high coefficient of determination, low RMSE

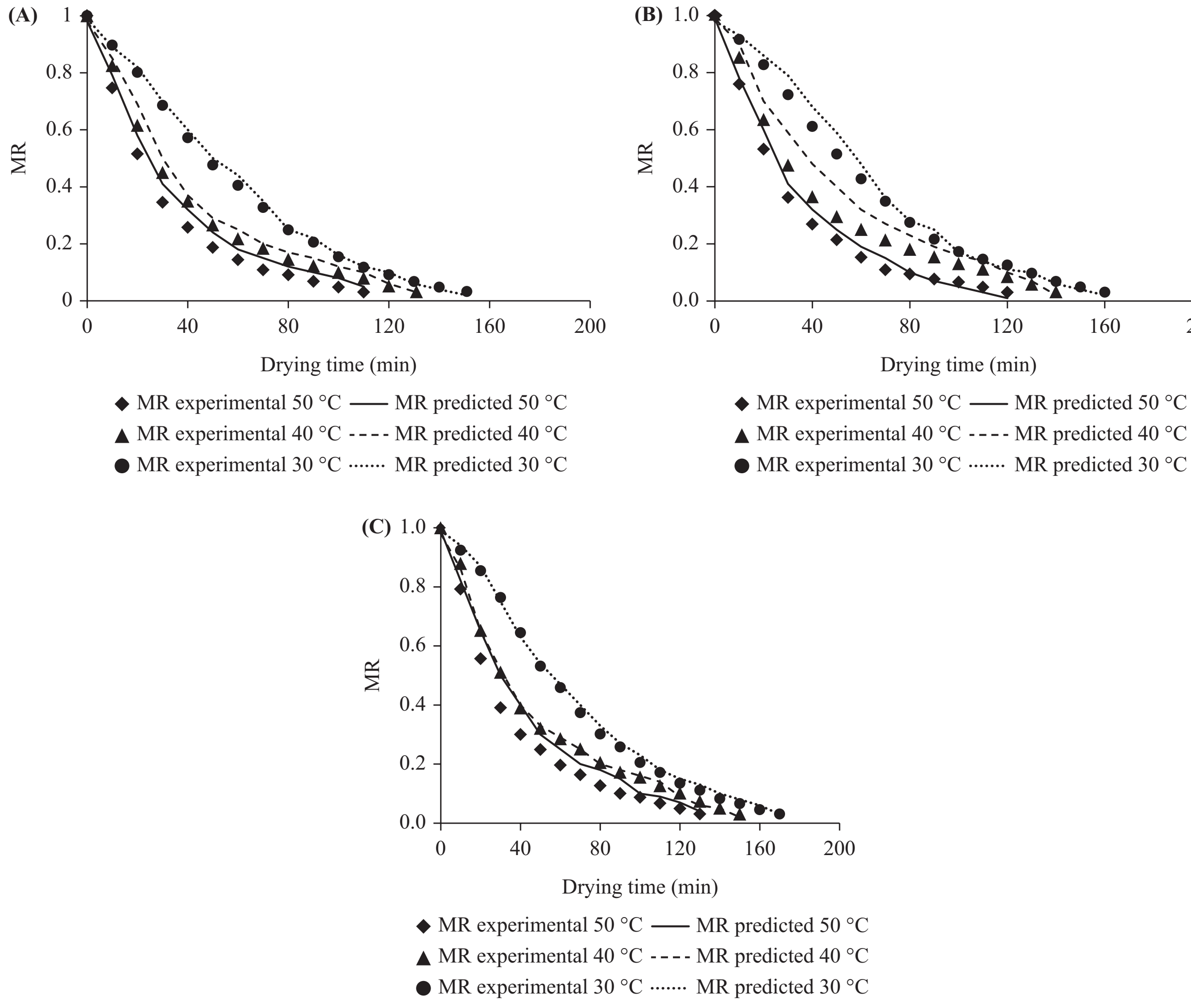

Figure 5. Variation of moisture ratio (MR) experimental and MR predicted with drying time at air velocities of (A) 2, (B) 1.5 and (C) 1 m/s and different air temperatures.

and low $\chi^2$and also due to the simplicity of the relationship between kinetics and prediction of drying process for lemon verbena in different air velocities and temperatures. In these models, the amount of R^2 was above 999×10^{-3} and the amounts of *RMSE* and χ^2 were less than 174×10^{-4} and 19×10^{-4}, respectively. Therefore, among the models examined in this article, Midilli and Kucuk's model was selected as the appropriate model for the process of lemon verbena drying in a dryer equipped with a solar pre-heating system for all drying conditions.

Conflict of interest

The authors declare no conflicts of interest with respect to research, authorship and/or publication of this article.

Compliance with ethical standards

This article followed all ethical standards for a research without direct contact with human or animal subjects.

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