# Experimental studies on thin-layer drying of mint leaves in a solar dryer and under open sun

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**Thin layer drying behaviour of mint leaves was experimentally studied using a domestic, direct-type, natural convection solar drying unit and compared with traditional open sun drying. The experiments were conducted in Bengaluru (12.96°N, 77.56°E), Karnataka, India and the effect of various parameters on drying was studied. Drying time using the solar drying unit was compared with traditional open sun drying. Reduction in drying time was found using the solar drying unit compared to open sun drying. After 10 h, the moisture in the mint leaves was observed to reduce from 93% to 8.33% in the solar drying unit and to 26.6% under open sun drying conditions. The drying data were analysed and curve-fitting was done using five thin-layer drying models. Among these models, logarithmic model for solar drying unit and the Henderson and Pabis model for open sun drying were found to satisfactorily describe the drying kinetics of mint leaves.**

**Keywords:** Drying time, mint leaves, open sun drying, solar dryer, thin layer drying models.

THE process of removing moisture from a product is called drying[1]. It is an important post-harvest technique to enhance and maintain the quality of a product and helps in value addition[1]. It is also one of the oldest food preservation techniques to enhance the shelf life of a product[2]. Drying helps in reducing the weight and volume of a product, thus lowering the packaging size, storage and transportation costs[1]. Drying can be done in four major ways: open sun drying, biomass/fuel drying, electrical drying and solar drying[3]. The fuel and electrical drying systems consume a lot of energy and hence are costly processes compared to open sun or solar drying. Open sun drying is a time-consuming process compared to the drying done using a solar dryer. Solar drying systems use renewable energy and are optimized in terms of time and space consumption. Hence the process is considered to be effective and efficient[4]. It is evident that solar drying has a faster drying rate compared to open sun drying[5]. Solar drying may be done either in natural mode (passive type), wherein air is circulated naturally because of the density difference caused by the difference in temperatures or by forced convection (active-type) mode, where heated air is circulated using a fan or blower[6]. Passive solar dryers are less expensive and are generally suitable for batch drying of small quantities of products[7].

Green leaves like mint, tulsi, stevia and neem contain low fat, high protein and are typically used for medicinal purposes to treat or prevent diseases[8]. Green leaves possess high moisture content and must be dried in order to preserve them[9]. Mint leaves usually possess high water content of approximately 78–82% w/w, and need to be dried to inhibit the growth of microorganisms[10]. Various curve-fitting models to analyse the thin-layer solar drying systems have been developed by various researchers[11–24]. Hosseinzadeh *et al.*[25] compared the thin-layer behaviour of mint leaves under four different conditions: traditional, solar, hot air and microwave drying. The results showed that the evaporation rate in smaller slices was higher than that in bigger ones and the two-term drying model was found to satisfy all four conditions of thin-layer drying. An experimental study was carried out using a forced convection-type solar dryer consisting of a flat plate collector and a drying chamber to dry mint leaves[26]. A parametric study reported that the drying time is inversely proportional to the weight of the mint leaves and diffusevity. Kavak Akpinar[27] conducted an experimental study on thin-layer drying of mint leaves using a forced solar dryer and compared the results with open sun drying. Ten drying models were analysed, and it was found that the Wang and Singh model was best suited for both solar drying and open sun drying. It was also noted that there was no change in the quality of the dried leaves. The energy and exergy analysis for drying mint leaves using an indirect, natural, convection solar dryer was done by Boukadoum and Benzaoui[28]. The experiment lasted for 14 h, and the maximum value of exergy inflow and exergy loss was found to be 0.120 and 0.125 kJ/kg for the first day and 0.105 and 0.09 kJ/kg for the second day respectively. Sallam *et al.*[29] conducted a study on direct and indirect-type solar drying system operated under natural and forced convection modes for drying mint leaves. The results revealed that the drying of mint leaves was quicker in forced convection (4.2 m/s) and the Verma model was

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found to be a suitable thin-layer drying model for all the cases. Lebert *et al.*[30] studied various parameters involved in the drying of mint leaves. The results showed that temperature plays a major role in the drying process. Kadam *et al.*[31] developed a tunnel dryer to dry mint leaves. The drying curves were fitted to seven models and the two-term drying model was found to be the best fit. Doymaz[32] conducted experiments on thin-layer drying of mint leaves in a cabinet dryer. The increase in air temperature from 35°C to 60°C reduced the drying time significantly. Also, among the four drying models, the logarithmic model was found to be the best suited.

The objective of this study was to analyse the thin-layer drying characteristics of mint leaves by conducting experiments on a domestic, direct-type solar drying unit working in natural convection mode and compare the results with open sun drying. Parameters like solar insolation, moisture content, drying time and temperature were studied. Five different drying models were used for fitting the drying curve.

## Materials and methods

### *Experimental set-up*

The solar drying experimental set-up is a simple, direct-type, natural convection solar dryer (Figure 1). The ends of this passive dryer are open for the air to flow in and remove moisture by the thermosyphon effect. Hence hot exhaust air reduces humidity from the chamber. The whole set-up is made of aluminum material and consists of a frame, tray and a glass cover. A thin layer of mint leaves is placed on a black sliding tray of area 1 m$^2$. A transparent acrylic glass of thickness 5 mm is used as a cover above the tray. In open sun drying, the leaves are placed on a thick polythene sheet under the open sun.

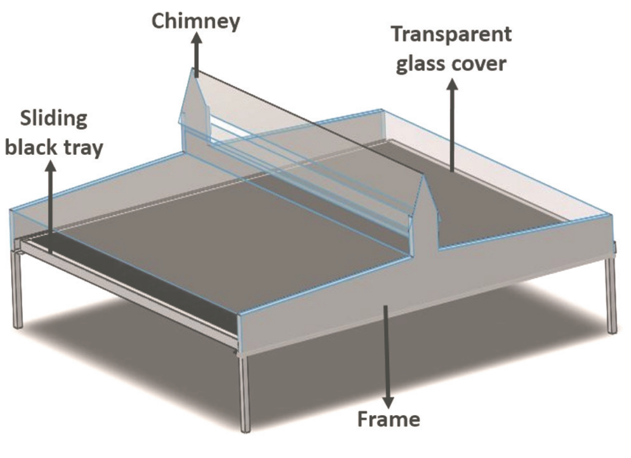


**Figure 1.** Schematic diagram of the solar dryer.

### *Experimental procedure*

Fresh mint leaves were purchased from a local market in Bengaluru, India. They were washed and excess water on the surface of leaves was removed using an absorbing paper sheet. The experiments were carried out in the BMS College of Engineering Campus at Bengaluru (12.96°N, 77.56°E) during month February 2019 from 08:00 to 18:00 h. The comparative study of thin-layer open sun drying and drying using a solar dryer was done by placing 300 g of mint leaves on 1 m$^2$ tray area of the solar dryer and on a sheet in open sun (Figure 2 *a–c*). The mint leaves kept for open sun drying were covered with a thin plastic sheet to avoid the settling of dust particles on them and also to avoid the removal of leaves by the wind.

The various parameters recorded hourly in the experiment were ambient temperature, tray temperature, glass-cover temperature, weight of the mint leaves, inlet wind velocity and relative humidity. The glass cover was cleaned daily to ensure that the parameters were not affected by dust. Table 1 shows the calibrated instruments used to record various parameters.

### *Mathematical modelling of drying curves*

Moisture content ($m$) in kilogram of water per kilogram of material on a wet basis is given by eq. (1)[33]

$$m = \frac{m_w}{m_w + m_d} = \frac{m_w}{m_T}, \tag{1}$$

where $m_w$ is the mass of water in the leaves, $m_d$ the mass of dry material in the leaves and $m_T$ is the total mass of the leaves.

The moisture ratio (MR) and drying rate of mint leaves are calculated using the following two equations[32]

$$\mathrm{MR} = \frac{M - M_e}{M_0 + M_e} = \frac{M}{M_0}, \tag{2}$$

$$\text{Drying rate} = \frac{M_{t+\mathrm{d}t} - M_t}{\mathrm{d}t}, \tag{3}$$

where $M$ is the instantaneous moisture content, $M_0$ the initial moisture content, $M_e$ the equilibrium moisture content, $M_t$ the moisture content at $t$ and $M_{t+\mathrm{d}t}$ the moisture content at $t$ + d$t$ (kg water/kg dry matter) and $t$ is the drying time (min).

The regression analysis was performed and the correlation coefficient ($R$) obtained is an important criterion for selecting the best drying model to describe drying behaviour. In addition to $R$, root mean square error analysis (RMSE) is used to determine the goodness of fit. Highest values of $R$ and lowest values of RMSE determine the


**Figure 2.** ***a***, Mint leaves placed on the black tray. ***b***, Solar dryer. ***c***, Open sun drying.

**Table 1.** Instruments used in the experiments

| Parameters | Instruments | Model | Specifications |
|---|---|---|---|
| Humidity | Hygrometer | STC 2 | Accuracy ± 5% |
| Wind velocity | Anemometer | Lutron AM 4201 | Least count 0.1 m/s |
| Temperature | IR thermometer | AP-IS11A001 | Accuracy ± 1°C |
| Weight | Weighing balance | SF 400 | Least count 1 g maximum weight 10 kg |
| Solar radiation | From the weather station set up in the B.M.S. College campus where the experiments are carried out | | |

**Table 2.** Thin-layer drying models

| Model | Model equation | Reference |
|---|---|---|
| Lewis/Newton | $MR = \exp(-kt)$ | 11–14, 27, 32 |
| Henderson and Pabis | $MR = a \exp(-kt)$ | 15–17, 27, 32 |
| Logarithmic | $MR = a \exp(-kt) + c$ | 18–20, 27, 32 |
| Page | $MR = \exp[-(kt)^n]$ | 21–23, 27, 32 |
| Wang and Singh | $MR = 1 + at + bt^2$ | 24, 27, 32 |

goodness of fit[27,32]. These can be calculated using eqs (4) and (5) below.

$$R^2 = \frac{\sum_{i=1}^{n}(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i}) \cdot \sum_{i=1}^{n}(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{exp},i})}{\sqrt{\left[\sum_{i=1}^{n}(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i})^2\right] \cdot \left[\sum_{i=1}^{n}(\mathrm{MR}_i - \mathrm{MR}_{\mathrm{pre},i})^2\right]}}, \quad (4)$$

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i})^2\right]^{1/2}, \quad (5)$$

where $\mathrm{MR}_{\mathrm{exp},i}$ is the $i$th experimentally observed moisture ratio, $\mathrm{MR}_{\mathrm{pre},i}$ the $i$th predicted moisture ratio, $N$ the number of observations and $n$ is the number of constants.

The drying curves obtained using the solar dryer and open sun drying were then fitted to five thin-layer drying models (Table 2).

## Results and discussion

Experiments were carried out in February 2019 and the results for various parameters recorded were plotted for a typical day in the mentioned period, i.e. 26 February 2019, which gave an average value of the repeated experiments conducted for the whole month.

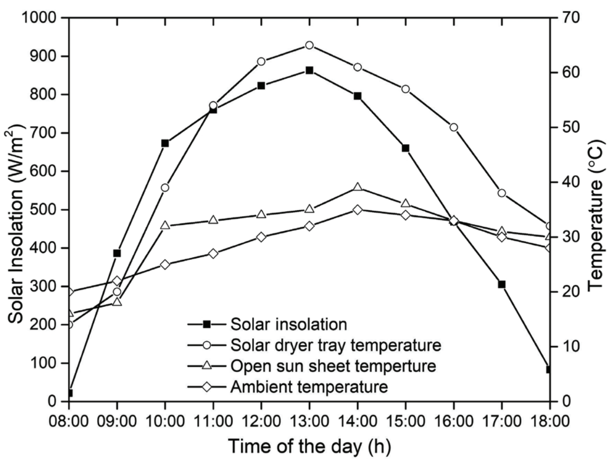


**Figure 3.** Variation of solar insolation and temperature with time.

### *Temperature and solar insolation*

The hourly variation of solar insolation and various temperatures like ambient, black tray and open sun drying considering the top sheet cover with time was plotted (Figure 3). Solar insolation increases in the morning, reaches a peak in the afternoon at 13:00 h and starts to reduce thereafter. The highest insolation recorded for 26 February 2019 was 863 W/m$^2$ and the average insolation was found to be 530 W/m$^2$ for the same day. The average ambient temperature was observed to be 29°C; the lowest was in the morning at 08:00 h and the highest was in the afternoon as solar insolation was high. The highest temperature of the black tray and open sun drying sheet was observed to be 65°C at 13:00 h and 39°C at 14:00 h respectively. The tray of the solar dryer achieved and sustained higher temperatures compared to open sun drying

**Table 3.** Results of various thin-layer drying models for the solar dryer

| Model | Model constants | *R* | RMSE |
|---|---|---|---|
| Lewis/Newton | $k = 0.000148$ | 0.9871 | 0.0496 |
| Henderson and Pabis | $a = 1.025$; $k = 0.3938$ | 0.9880 | 0.0514 |
| Logarithmic | $a = 0.9925$; $k = 0.4952$; $c = 0.05016$ | 0.9914 | 0.0463 |
| Page | $k = 0.3675$; $n = 1.01$ | 0.9878 | 0.0519 |
| Wang and Singh | $a = –0.2708$; $b = 0.0187$ | 0.9795 | 0.0672 |

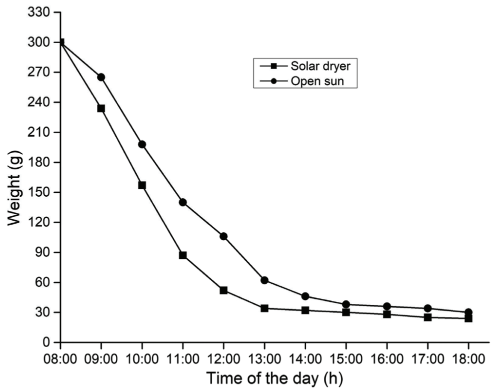


**Figure 4.** Hourly variation in the weight of mint leaves in the solar dryer and open sun drying.

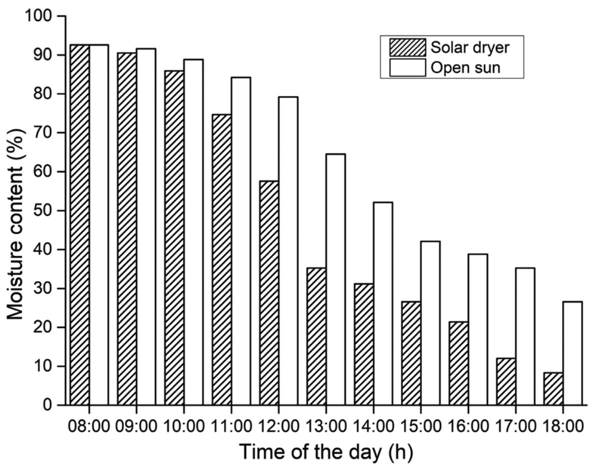


**Figure 5.** Reduction in moisture content (%) of mint leaves in the solar dryer and open sun drying with time.

because of the black coating on the tray and the greenhouse effect. Wind velocity was noted to be in the range 0.3–2.2 m/s, with relative humidity between 10% and 47%.

## *Drying curves*

Fresh mint leaves with initial weight of 300 g were dried using both solar dryer and open sun drying under the same conditions. The final dried product weighed 24 and 30 g respectively, in the solar dryer and open sun drying. The hourly variation in the weight of the mint leaves was plotted (Figure 4).

Figure 5 shows that the moisture content in the mint leaves had reduced to 26.6% in 7 h in solar dryer, while it took 10 h in open sun drying. It also took 10 h in the solar dryer to reach the final moisture content of 8.33%. A decreasing trend in weight and moisture ratio was observed with time. The reduction in drying time in the solar dryer can be related to higher drying temperature above the tray because of the greenhouse effect. In greenhouse dryers, the solar energy is converted to heat energy. Visible light of shorter wavelength passes through the transparent glass cover and is absorbed by the leaves and the surfaces of the dryer. The heated surfaces in turn emit longer wavelength infrared radiations which heat up the air inside the chamber. The hot air is retained within the chamber by the walls and roof, acting as an envelope, which minimizes the heat loss by convection[7,34]. The drying rate showed a falling trend and no constant drying rate was observed. A similar trend was observed by other researchers[27,29,30,32]. Figure 6 *a–c* shows photographs of mint leaves before and after complete drying in the solar dryer and under open sun conditions.

## *Evaluation of the modelling curves*

In order to perform curve fitting for the drying curves, the moisture ratio versus drying time was plotted (Figure 7).

The obtained moisture data at different experimental modes were converted to moisture ratio expressions and then curve fitting was done on the five thin-layer drying models. Tables 3 and 4 show the results of statistical analysis on these models for the drying of mint leaves under the open sun and in the solar dryer respectively.

Correlation coefficient values (*R*) obtained were in the range 0.9795–0.9914 for the drying of mint leaves in the solar dryer and 0.9529–0.9938 for open sun drying, which indicates that every model satisfactorily describes the drying kinetics of mint leaves. Based on the values of RMSE and *R*, it is clear that the logarithmic model for the solar drying unit, and the Henderson and Pabis model for open sun drying are the best fit.

## Conclusion

The maximum temperature obtained in the solar dryer tray reached up to 65°C compared to 39°C obtained in

**Table 4.** Results of various thin-layer drying models for open sun drying

| Model | Model constants | *R* | RMSE |
|---|---|---|---|
| Lewis/Newton | $k = 0.2627$ | 0.9870 | 0.0525 |
| Henderson and Pabis | $a = 0.99$; $k = 0.2793$ | 0.9938 | 0.0490 |
| Logarithmic | $a = 1.073$; $k = 0.2712$; $c = -0.01247$ | 0.9529 | 0.0518 |
| Page | $k = 0.1885$; $n = 1.246$ | 0.9860 | 0.0566 |
| Wang and Singh | $a = -0.2127$; $b = 0.01242$ | 0.9652 | 0.0910 |


**Figure 6.** ***a***, Fresh mint leaves before drying. ***b***, Mint leaves after drying in solar dryer. ***c***, Mint leaves after drying under open sun.

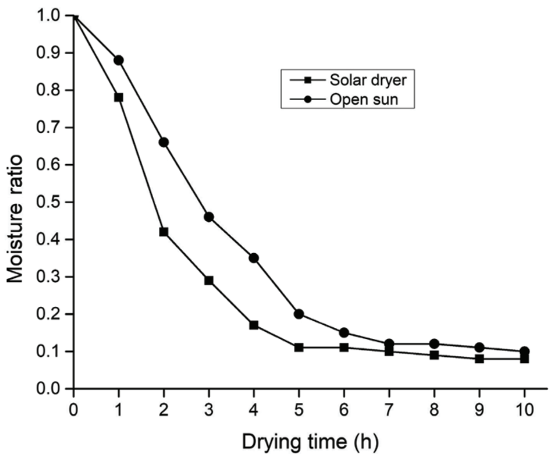


**Figure 7.** Variation of moisture ratio with drying time.

open sun drying. Temperature of the solar dryer plays a major role in drying. The drying curve data display a declining rate and not a constant rate of drying period. High drying rate and low drying time were observed in the solar dryer. The experimental data suggest that the thin-layer drying of mint leaves is more effective in the solar drying unit compared to the traditional open sun drying. The curve fitting of experimental data was done using the five thin-layer drying models. Based on the values of RMSE and *R*, the logarithmic model was found to be the satisfactory for drying in the solar dryer, while the Henderson and Pabis model was best suited for open sun drying. This simple, domestic drying unit uses solar thermal energy for its functioning and can be used for small-scale batch drying of mint leaves. Future work could be directed towards conducting experiments using the same set-up to study the drying behaviour of other leaves and at different locations to check its consistency and reliability.

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