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Drying Kinetic Behavior of Dried Salam Leaves (*Syzygium polyanthum*) Based on Forced Convective Solar Drying and Open Sun Drying

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ABSTRACT

Salam leaves, a traditional food flavoring spice, are a widely recognized herb in Indonesia and are used in many regions. This study aimed to investigate the drying kinetics of salam leaves, comprising mathematical modeling, moisture diffusivity, and other nutritional values as qualitative parameters. The drying process was examined using a forced convective system (CSD) and open sun drying (OSD). The drying behavior was examined by observing the drying kinetics characteristics using 12 thin-layer semi-theoretical mathematical for drying of agricultural products, determining the moisture diffusivity, as well as measuring the content of chlorophyll a, b, and total dissolved solids as nutritional quality indicators of the drying products. According to the obtained results from the non-linear regression analysis, the Midilli model demonstrates the highest degree of appropriateness for drying salam leaves. The moisture diffusivity of CSD is greater than that of open-air solar drying. Regarding nutritional composition, the study revealed that chlorophyll a, b, and carotenoid levels in the dried leaves obtained through CSD were more significant than those obtained by OSD. As an environmentally friendly dryer, CSD can potentially be applied in herb-drying industries, especially salam leaves.

Keywords: leaves, drying, kinetics, modelling, convective drying.

INTRODUCTION

Syzygium plyantum, a well-known herb and seasoning, is used to season meat, fish, and coconut in a variety of Indonesian recipes. Numerous names, including salam, ubar serai, meselengan (Sumatra), samak, samak kelat, and manting, are used locally to refer to it (Dewijanti et al., 2019). The fragrant flavor of salam leaves is used to season meat, fish, and coconut soup recipes. It is comprised of natural pigments and antibacterial essential oils, including eugenol and methyl chavicol. (Dewijanti et al., 2020). In addition, the leaves are rich in tannins, terpenoids, alkaloids, carbohydrates, steroids, tripenoids, and flavonoids. Fresh and dried salam leaves are both commonly utilized. According to Pratama et al., (2022) drying salam leaves at 40 °C resulted in the maximum concentration of β-ocimene, reaching 139.62 μg/mL in the essential oil. The shelf life of fresh salam leaves is less than three days. During this time period, drying salam leaves was a popular activity among traditional farmers, although it was rarely carried out to high standards. Typically, they are moderately dry and prone to contamination by dust or bacteria. Therefore, salam leaves must be dried in a way that is both eco-friendly and capable of preserving their bioactivity.

Along the drying process, water flows from the inner part of the product to the surface continued by evaporation process which removing the water from the material surface to the environment (Fillet et al., 2021; Babu et al., 2018). Moving heat and mass to and through the object being dried is how drying is accomplished (Chaurasiya & Singh, 2022). In order to prepare spices and herbs for long-term storage or practical usage, drying is typically employed to lower the moisture content from 75–80% to less than 15%. On a small scale, drying spices and herbs is accomplished by aerating in a well-ventilated shade, but on a large scale, convection ovens are typically used to complete the task (Alwafa et al., 2021). By drying herbs and spices, it is possible to stop both the growth of microorganisms and the loss of bioactive chemicals. However, the process of drying can potentially decrease the quality of spices due to changes in color, shape, and aroma caused by the loss of volatile components or the formation of new volatile compounds due to oxidation, hydrolysis, or esterification.

According to several studies, the freeze drying technology provides dry spices with good bioactive content (Chaurasiya & Singh, 2022), but it also consumes a lot of energy and is expensive, making it unproductive from an economic and environmental viewpoint (Karwacka et al., 2022). Using solar energy is a drying solution that is more affordable and environmentally beneficial. Numerous studies have been done to evaluate various solar energy-based drying techniques on herbs and spices (Mohana et al., 2020). To analyze the drying behavior of a herb products, thin layer drying is widely used because of their simplicity. The models accurately represent drying phenomena in order to estimate drying times for various items and generalize drying curves. Various systems within the operational unit influence the quality of drying products. Drying on an industrial scale must ensure consistent quality with hygienic and uniform drying results (Hawa et al., 2021). The industrial drying processes must be rapid and efficient and provide uniform and hygienic dried product (D. Pagukuman & Wan Ibrahim, 2022). Previous studies regarding drying of herbs have been reported by various authors (Bhaskara Rao & Murugan, 2021; Thamkaew et al., 2021); However, limited information is provided about the drying kinetics of salam leaf. This research was aimed at observing the drying kinetics behavior of salam leaves including mathematic modeling, moisture diffusivity and some quality attributes of salam leaves using forced convective drying system compared to open sun drying.

RESEARCH METHODS

Drying implementation

Salam leaves samples were selected manually. The salam leaves used in this study were chosen based on the homogenous color (dark green) and shapes. The leaves were dried in a convective system using a convective solar dryer designed by (Mardiyani et al., 2018). The forced convective drying use a solar dryer based on solar collectors and solar photovoltaic panels consisting of four main parts: a black painted solar collector, a 100 WP solar photovoltaic, a drying unit using a silo model as the drying chamber, and a DC blower generated by the photovoltaic. This study used some measuring tools, including thermo-hygro meter, lux meter, wind meter, and digital balance.

The black-painted solar collector is made of 0.55 mm thick V-groove iron plate. To generate a greenhouse effect in the collector, a piece of 4 mm clear glass was placed on top of the absorber. Open sun drying (OSD) and CSD application drying processes were placed side by side for comparison purposes. The drying chamber inlet temperature of the CSD ranged from 45 to 55 °C, depending on the weather. In CSD, the airflow remained steady constant at 3 m/s. Meanwhile, the application of OSD drying process was done by spreading out the salam leaves on an open tray and exposing the

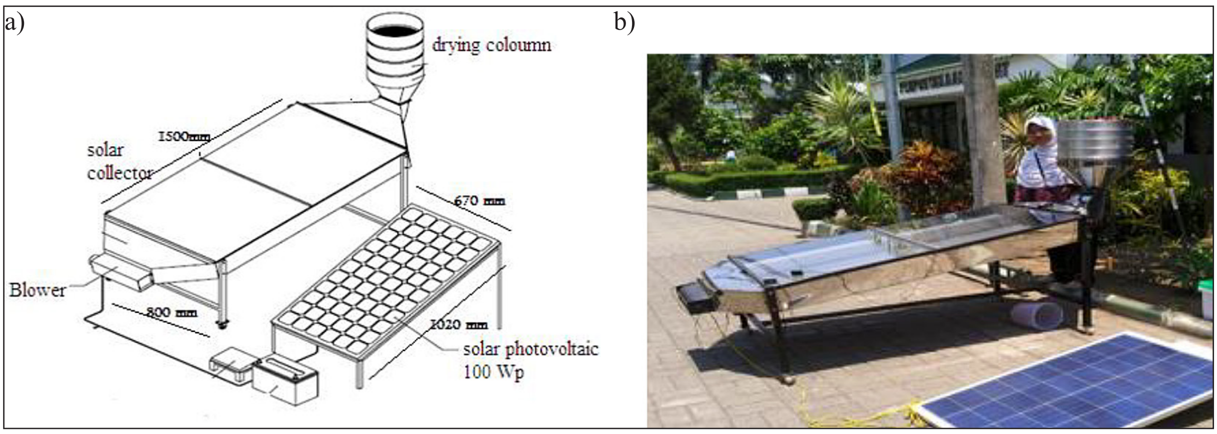

Figure 1. a) Schematic preview of Convective Solar Drying (CSD));
b) Drying implementation using convective solar drying (CSD) system

leaves to the direct sunshine. Some parameters related to the environment condition were measured, including solar radiation (digital lux meter), ambient humidity, inlet humidity (thermohygrometers), ambient temperature, and inlet temperature (thermometer). The leaves were weighed every 1 hour (60 minutes) to determine the moisture content reduction of the leaves during the drying process using the gravimetric method in dry basis. Figure 1 shows the schematic preview of CSD (a) and drying implementation process.

Drying characteristics

Mathematic modelling

The moisture ratio of salam leaves was measured using Eq. 1 as follows:

$$MR = \frac{Mt}{M0} \quad (1)$$

where: MR – Moisture ratio (dimensionless);
Mt – Moisture content, dry basis after a period of time (%);
$M0$ – Moisture content, dry basis at the beginning of the drying period at time zero (%).

Table 1 describes in detail the twelve drying kinetics models used in this study. The coefficient of determination (R^2), the reduced mean square deviation (2), and the Root Mean Square Error (RMSE) were used to assess the mathematical model's ability to describe drying conditions. A non-linear regression analysis was conducted to ascertain the value of the constant. When selecting a modeling equation to precisely describe the drying material/sample curve, the coefficient of determination is one of the most important factors to consider. When the value of R^2 is significant and (χ^2) and RMSE are lower, the validation value of the utilized prediction model is considered to be of higher quality. The determination coefficient was calculated using the following equation:

$$R^2 = \frac{\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})^2}{\sqrt{\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})^2 * * (\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})^2}} \quad (2)$$

The value of χ^2 and Root Mean Square Error (RMSE) was determined using the following equation:

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})}{N - z} \quad (3)$$

$$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{N}(MR_{pred,i} - MR_{exp,i})}{N}\right]} \quad (4)$$

where: $MR_{exp,i}$ – experiment moisture ratio – i;
$MR_{pred,i}$ – predicted moisture ratio – i;
N – the amount of observational data;
z – the amount of constant .

The considered drying kinetic models used in this study were listed in Table 1.

Determination of moisture diffusivity

A formulation based on Fick's second law was used to determine moisture diffusivity (Henderson and Perry, 1976), with the following formulations steps and equations:

$$\frac{M}{M0} = \frac{8}{\pi^2} e[\frac{\mathrm{Deff.t}}{4L^2}] \quad (5)$$

Table 1. The considered drying kinetics models

No	Model name	Model
1.	Newton	MR = exp (-kt)
2.	Page	MR = exp (-kt^n)
3.	Modified Page	MR = exp (-(kt)^n)
4.	Henderson-Pabis	MR = a·exp (-kt)
5.	Logarithmic	MR = a·exp (-kt) + c
6.	Midilli et al.	MR = a·exp (-kt^n) + bt
7.	Two term	MR = a·exp (-k0t) + b·exp (-k1t)
8.	Two term Exp.	MR = a·exp (-kt) + (1-a)·exp (-kat)
9.	Mod. Henderson-Pabis	MR = a·exp (-kt) + b·exp(-k1t) + c·exp (-k2t)
10.	Wang-Singh	MR = 1 + a·t + b·t^2
11.	Diffusion approach	MR= a·exp (-k·t) + (1-a)·exp (-k·b·t)
12.	Verma et al.	MR= a·exp (-k·t) + (1-a)·exp (-g·t)

In the form of logarithms, equation (1) can be written as:

$$ln\left(\frac{M}{M_0}\right) = ln\frac{8}{\pi^2} - \left(\frac{\text{Deff.}}{4L^2}\right)t \quad (6)$$

Effective diffusivity value is determined by making data plot of: $ln\left(\frac{M}{M_0}\right)$ with time (t), so the slope is obtained that describes the value of K (constant drying)

$$K = \frac{\pi^2\ Deff}{4L^2} \quad (7)$$

where: M – Moisture content, dry basis after a period of time (%);
M_0 – Moisture content, dry basis at the beginning of the drying period at time zero (%);
L – Half slab thickness (m);
$Deff$ – Moisture diffusivity (m²/s);
K – Drying constant;
T – Time (s).

Measurement of quality attributes

The analysis of chlorophyll was adapted from Etemadian et al. (2017) with the following steps: 1. An amount of 2.5 mg of dried salam leaves was placed in 5 ml of 100% methanol and centrifuged for 10 minutes at 5000 rpm. 2. The supernatant was filtered using Whatman filter paper A UC Davis 3. The absorbance value was read using the UC Davis Spectrofotometer at 645, 663, and 470 nm wavelengths. The chlorophyll content (μg/ml) was measured using the following formulation:

$$\text{Chlorophyll a } (\mu g\ ml\ ) = = (11.47 * A664) - (0.40 * \text{A630}) \quad (8)$$

$$\text{Chlorophyll b } (\mu g\ ml) = = 27.05 * A664) - (0.40 * \text{A630}) \quad (9)$$

$$\text{Carotenoids } (\mu g\ ml) = 1000\ \text{A470} - - 2.860\ \text{Ca} - 129.2\ \text{Cb} / 245 \quad (10)$$

where: $A664$ – The absorbance value in 664 wavelength;
$A630$ – The absorbance value in 664 wavelength;
$A470$ – The absorbance value in 664 wavelength;
Ca – Chlorophyll a;
Cb – Chlorophyll b.

Total soluble solids analysis was performed on 1 g of fresh material weighed using a watch glass. The substance was crushed with a mortar, then the liquid was extracted with a pipette and dropped on the refractometer. The value obtained was the total dissolved solids of the sample in degrees Brix.

RESULT AND DISCUSSION

Drying characteristic

A decrease in the moisture ratio demonstrates the effectiveness of a drying operation. The moisture ratio significantly falls as agricultural products start to dry because mass rapidly transfers water from the substance. Along with temperature, humidity and air velocity also influence this

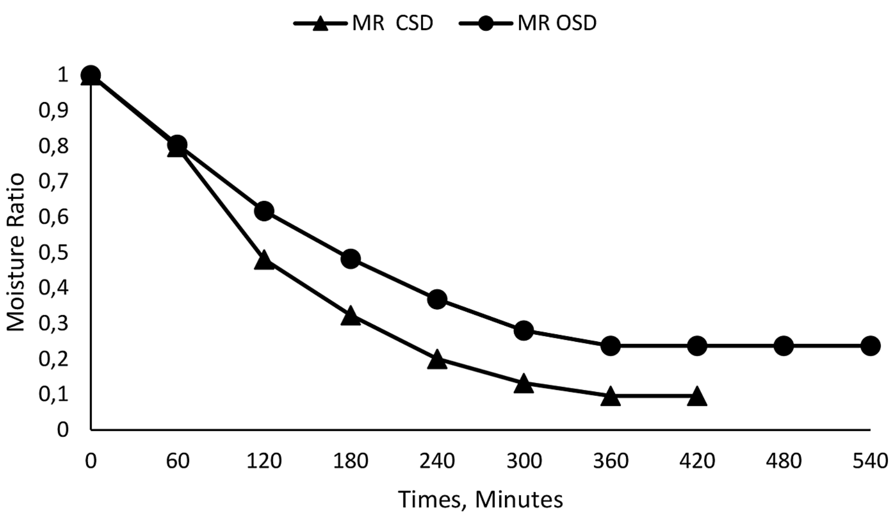

Figure 2. The phenomenon of moisture ratio decrease of salam leaves in CSD and OSD

phenomenon. The results of this study, in which the drying time required is 420 minutes for CSD and 540 minutes for OSD, are not substantially different from the study of Lakshmi et al., (2019), who applied a drying of *Curcuma zedoaria* with MFSCD (Mixed Mode Forced Solar Convective Drying) compared to OSD (Fig. 2). Drying with MFCSD took 330 minutes, shorter than drying with OSD, to achieve a moisture level suitable for storage (0.053 (db)).

Mathematic modeling

The experimentally measured moisture ratio data from both OSD and CSD were fitted into twelve drying kinetics models listed in Tables 2 and 3. They were comprised of model constants of nonlinear regression statistical parameters. The most suitable drying kinetics for salam leaves drying based on OSD and CSD were obtained to the highest R^2 the lowest χ^2 and *RMSE* values. The coefficient of determination value of OSD were varied between 0.834733 to 0.998851 while R^2 of CSD were varied between 0.831779 to 0.998129. The RMSE of OSD were varied between 0.000443 and 0.0020064 while CSD varied between 0.000231 to 0.0095819. The χ^2 of OSD varied between 0.00005802 and 0.0,000442656 while CSD varied between 0.0000317 and 0.009541. Those parameters value indicated that all the models can be used to predict the experimental moisture ratio of salam leaves dried using OSD and CSD.

On the basis of the constant values and statistical parameters derived from the results of the non-linear regression analysis as provided in Tables 1 and 2, it is known that the Midilli model has the highest level of suitability for drying bay leaves using either an OSD or CSD drying method (Fig. 3). The constant value of OSD is 0.00039, while the R2 and RMSE values are 0.998851 and 0.003822, respectively. In the CSD drying system, the constant value is. 0.000183; R2 is 0.998229 and RMSE is 0.005416. The convergence between MR and MR predictions made by the Midili model is illustrated in Figure 1. The Midilli model is a semi-empirical model established by Midilli & Kucuk, (2003). It is frequently used for analyzing the drying kinetics of a variety of agricultural products using a variety of drying processes, in particular, drying that is dependent on solar energy. In a recent report, (Essalhi et al., 2017) and (Hawa et al., 2021) conducted the drying process of grapes and cabya under an indirect solar dryer and open sun drying. In their study, they found that the Midilli model was able to satisfactorily describe the drying kinetics of agricultural products using solar energy based drying. The findings of this study are in accordance with the results of a study on the use of a solar-electric hybrid drier for the drying of thyme leaves that was carried out by (Karami, et al., 2021). The Midilli model provided the most accurate description of the drying kinetics of thyme leaves in this study when used at temperatures of 40, 50, 60, and 70 °C with air flow rates of 1, 1.5, and 2 m/s.

Table 2. Model constant and statistical parameters of salam leaves under open sun drying (OSD)

Model name	Model formulation	Constant	R^2	RMSE	χ^2
Newton	MR = exp (-kt)	k:0.00371931	0.972481	0.020435	0.0004256
Page	MR = exp (-kt^n)	k:0.00889702;n:0.84393	0.977361	0.017055	0.0003023
Modified Page	MR = exp (-(kt)^n)	k:0.00371931;n:1	0.972481	0.020435	0.000434
Henderson-Pabis	MR = a·exp (-kt)	k:0.00361627;a:0.97717	0.970472	0.020064	0.0004184
Logarithmic	MR = a·exp (-kt) + c	k:0.00571672;a:0.86014;c:0.03213	0.970472	0.020064	0.0001292
Midilli et al.	MR = a·exp (-kt^n) + bt	k:0.00141263;n:1.2472;a:0.9965; b:0.00039	0.998851	0.003822	1.58E-05
Two term	MR = a·exp (-k0t) + b·exp (-k1t)	k:0.00361433;b:4.46465	0.970469	0.020064	0.0002626
Two term Exp.	MR = a·exp (-kt) + (1-a)·exp (-kat)	k:0.00853737;a:0.31462	0.980419	0.015896	0.0002626
Mod. Henderson-Pabis	MR = a·exp (-kt) + b·exp (-k1t) + c·exp (-k2t)	k:0.00284969;k1:0.01429;k2:0.001557 a:1.42228;b:-5.8775;c:5.46221	0.998355	0.01235	2.36E-05
Wang-Singh	MR = 1 + a·t + b·t^2	a:-0.0018;b:1.2E-07	0.834733	0.063217	0.0041531
Diffusion approach	MR= a·exp(-k·t) + (1-a)·exp(-k·b·t)	k:0.0037195;a:0.00372;b:1	0.972482	0.020435	0.0004427
Verma et al.	MR= a·exp(-k·t) + (1-a)·exp(-g·t)	k:0.00371912;a:-1.6783;g:0.00372	0.972482	0.000443	0.0004427

Table 3. Model constants and statistical parameters of salam leaves under convective solar drying (CSD)

Model name		Model constant	R^2	RMSE	χ^2
Newton	MR = exp (-kt)	k:0.005947	0.987275	0.015938	0.000259
Page	MR = exp (-kt^n)	k:0.003239;n:1.115991	0.99118	0.01216	0.000154
Modified Page	MR = exp $(-(kt)^n)$	k:0.003239;n:1	0.987275	0.015938	0.000264
Henderson-Pabis	MR = a·exp (-kt)	k:0.006145;a:1.011034	0.98709	0.014652	0.000223
Logarithmic	MR = a·exp (-kt) + c	k:0.006716;a:1.011034;c:0.03213	0.985407	0.015679	0.000223
Midilli et al.	MR = a·exp $(-kt^n)$ + bt	k:0.000867;n:1.404807;a:1.004696 ;b:0.000183:	0.998129	0.005416	3.17E-05
Two term	MR = a·exp (-k0t) + b·exp (-k1t)	k:0.006476;k1:0.006451;b:14.3938	0.987143	0.000231	0.000264
Two term Exp.	MR = a·exp (-kt) + (1-a)· exp (-kat)	k:79.33489;a: 7.49E-05	0.987268	0.015946	0.000264
Mod. Henderson-Pabis	MR = a·exp (-kt) + b·exp (-k1t) + c·exp (-k2t)	k:0.00029;k1:0.000545;k2:0.00120;a:6.300 0;b:6.300805;c:14.74988	0.991822	0.011377	0.000146
Wang-Singh	MR = 1 + a·t + b·t^2	a:-0.00161;b: -9.9E-07	0.831779	0.095819	0.009541
Diffusion approach	MR= a·exp(-k·t) + (1-a)·exp(-k·b·t)	k:0.009387;b:0.980604	0.990755	0.012233	0.000159
Verma et al.	MR= a·exp(-k·t) + (1-a)·exp(-g·t)	0.006292;a:-13.1556;g:0.006266	0.987325	0.015911	0.000268

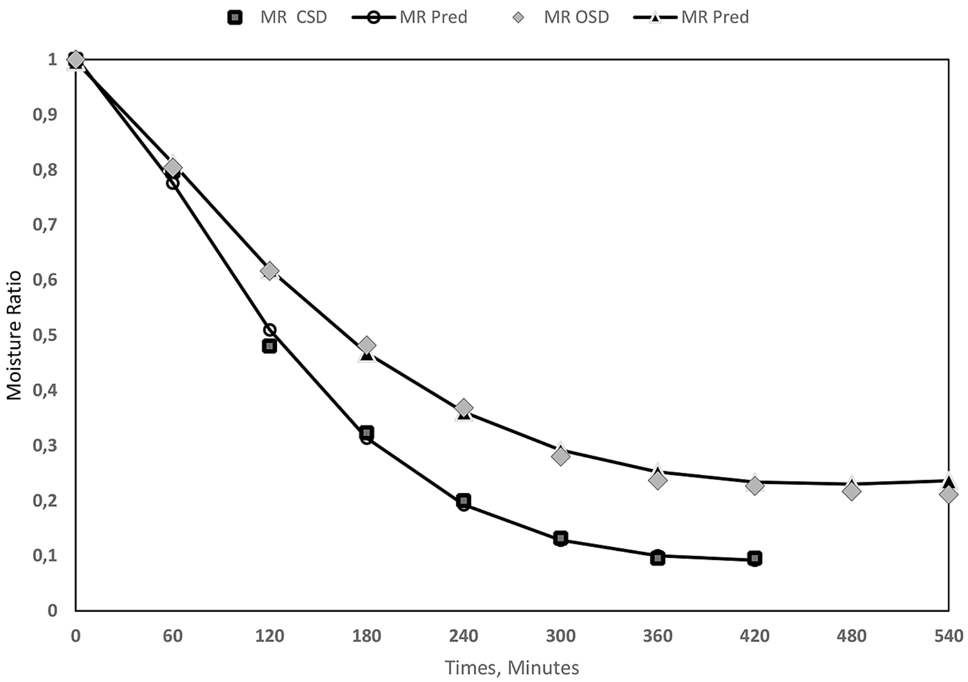

Figure 3. Modeling the drying of bay leaves using the Midili equation on the OSD and CSD drying system

Moisture diffusivity

The concept of moisture diffusivity pertains to the process by which unbound moisture is removed from the inside of a product until it reaches a predetermined threshold. Diffusion serves as the prevailing mechanism during the process of drying. The diffusion mechanism, which is the primary mechanism in a drying process, is influenced by the structure of drying products and the moisture level. The mechanism would undergo continuous changes throughout the drying process. On the basis of the data shown in Figure 4, it can be observed that the moisture diffusivity of CSD is higher (2.547×10^{-10} m²/s) compared to the moisture diffusivity of open sun drying (4.238×10^{-10} m²/s). The findings of this investigation align with other studies on bay leaves utilizing hybrid dryers powered by conventional solar and electric energy. Karami et al. (2021) stated that reported effective diffusivity (OSD) of thyme leaves values ranged from 2.172×10^{-10} to 1.23×10^{-10} m²/s. According to Mardiyani et al. (2021), the moisture diffusivity value for the drying of red pepper using the open sun drying method was found to be the lowest (4.21×10^{-9} m²/s) when compared to

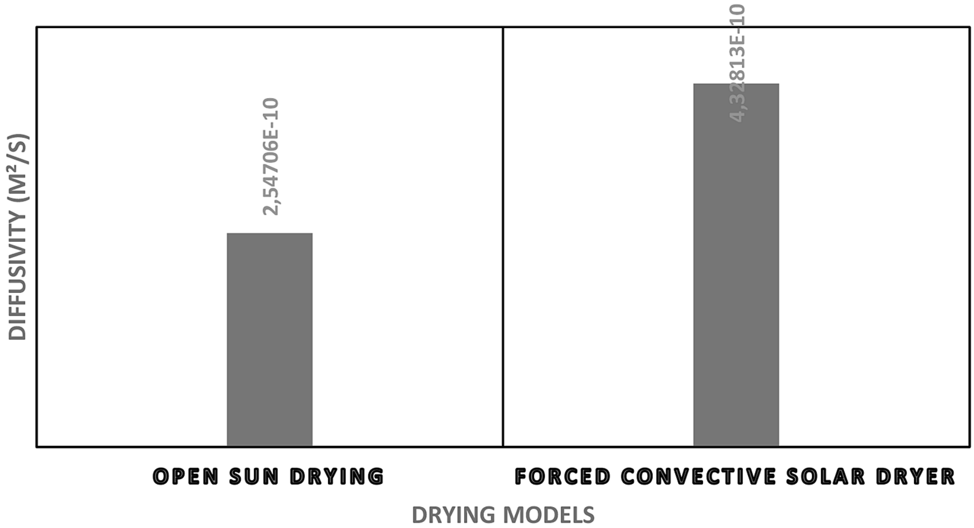

Figure 4. The value of the effective diffusivity of drying bay leaves in the CSD and OSD drying systems

both the oven drying and convective solar drying systems. Additionally, it was mentioned that there is a direct relationship between temperature and effective diffusivity values, whereby an increase in temperature leads to higher effective diffusivity values. Concerning the environmental state, the temperature differential observed between the OSD and CSD chambers ranged from 10–20 °C.

Quality Attributes

Figure 5 shows the values of chlorophyll a, chlorophyll b, carotenoids and total soluble solids of dried salam leaves resulted from OSD and CSD system. The figure shows that the chlorophyll a, b and carotenoid content of dried salam leaves from CSD were slightly higher (7.515 µg/ml, 2.925 µg/ml and 2.02 µg/ml) than the chlorophyll content of dried leaves from OSD (7.155 µg/ml, 2.870 µg/ml l and 1.753 µg/ml). The decrease in chlorophyll during drying is the main cause of discoloration (Hidar et al., 2020). Schmid et al., (2022) stated that chlorophyll degradation was affected by the drying system. Drying with convection heat flow gives good results in terms of maintaining color. However, the drying process in the open sun in this study also had an impact that was not much different from the CSD drying results in decreasing chlorophyll. Meanwhile, the dry leaves resulting from OSD had a higher total soluble solids value (1.95° brix) compared to the dried leaves produced from the CSD (1.00°

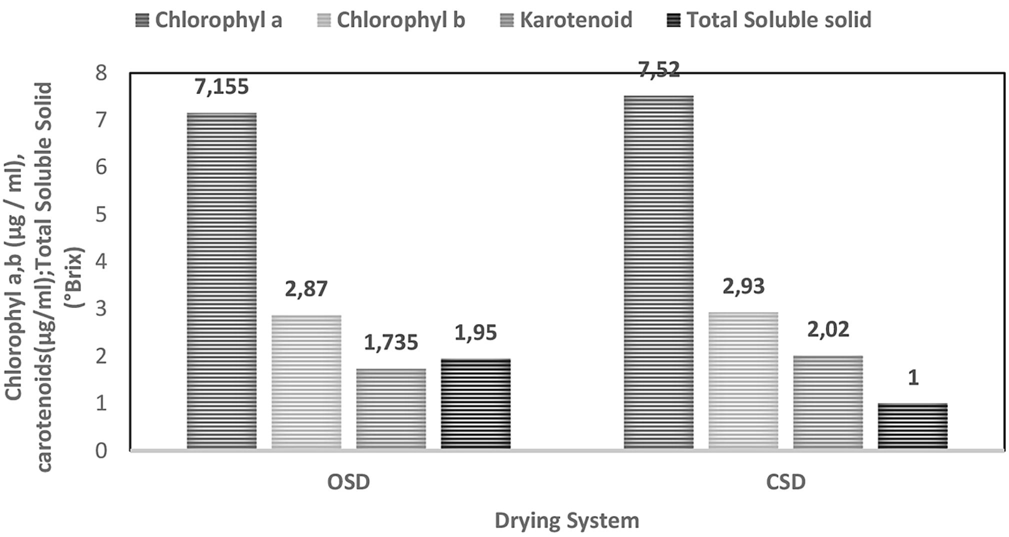

Figure 5. Total content of chlorophyll a, b, carotenoids and total soluble solids in dried leaves from OSD and CSD drying systems

brix). This value is not too much different from the extraction value of fresh bay leaves with various extraction models at 70 °C (1.13–2.33° Brix) conducted by Masaki et al. (2022). The phenomena showed that the drying process using both the CSD and OSD methods did not affect the total soluble solids content in salam leaves.

CONCLUSIONS

A comparative study was conducted between a forced convection solar drier utilizing solar collectors and solar photovoltaic panels and an open sun drying process to investigate the drying process of salam leaves. The investigation examined the drying process using twelve equations to model the drying kinetics. The study also encompassed the determination of moisture diffusivity and measurement of the nutritional value of the dried salam leaves. On the basis of the result from the non-linear regression analysis, it showed that the Midilli Model the highest degree of accuracy predictor for drying salam leaves, whether the OSD or CSD drying method was employed. CSD had better moisture diffusivity values and produced dried salam leaves with better quality attributes of chlorophyll and total soluble solids than salam leaves produced from OSD drying. Therefore, the convective solar drying (CSD) system developed in this study has a reasonable prospect of being developed as an alternative to optimize solar energy use in drying herbaceous products, especially salam leaves.

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