Turkish Journal of Agriculture - Food Science and Technology, 10(6): 1019-1025, 2022
DOI: https://doi.org/10.24925/turjaf.v10i6.1019-1025.4783

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Mathematical Modelling of Drying Characteristics of Lemon Grass Leaves (*Cymbopogon citratus*)

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ARTICLE INFO

Research Article

Received : 25/10/2021
Accepted : 30/12/2021

Keywords:
Lemon grass leaves
Oven drying
Modelling
Drying rate
Drying models

ABSTRACT

Drying characteristics of Lemon grass leaves using an oven dryer was studied at four different temperatures (40, 50, 60 and 70°C). The effect of the drying temperatures on moisture content of the leaves was investigated. Thirteen drying models were fitted to the drying data to establish the model that best describes the drying characteristics of Lemon grass leaves. The best model was determined by the model with the lowest value of SSE and root mean square error (RMSE), and the highest value of coefficient of determination (R^2). Hii et al. model satisfied the conditions for selecting the most suitable and reliable model with R^2, SSE and RMSE values of the model was 0.9964, 0.0250 and 0.0214 respectively. This model is most suitable at 40°C. The effective diffusivity (D_{eff}) values ranged from 8.92452×10^{-12} m²/s to 16.00657×10^{-12} m²/s and increases as temperature increases. It was further observed that the amount of energy required to eliminate moisture within the leaves was in the range of 19.85 kJ/mol - 19.86949 kJ/mol. Dried lemongrass leaves can be used in food preservation as an alternative to synthetic substances that have recently become less acceptable to consumers. Consumers accept natural food products that are universally acknowledged as safe, such as lemon grass with essential oils, and they also fit the standards for green processing.

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Introduction

Lemongrass (*Cymbopogon citratus*) is a tropical perennial grass that grows throughout Europe, India, Africa, and Australia (Nambiar et al., 2012). Lemongrass is high in vitamins A, B1 (thiamine), B2 (riboflavin), B3 (niacin), B5 (pantothenic acid), B6 (pyridoxine), C, and folate, as well as minerals including calcium, potassium, phosphorus, magnesium, copper, iron, and zinc (USDA National Nutrient Data Base, 2019). It's a medicinal, aromatic herb with a strong lemony scent and antibacterial properties, used in suppression of a number of important postharvest pathogenic and spoilage microorganisms (Leite et al., 2016; Athayde et al., 2016; Ekpenyong and Akpan, 2017). Lemongrass oil has also been reported to extend the shelf life of guava (Murmu and Mishra, 2018), strawberries (Kahramanoglu, 2019), table grapes (Sonker et al., 2014), and apples (Frankova et al., 2016).

In general, aromatic plants like lemon grass require the best preservation technique to maintain their nutritious content throughout time. The drying of fragrant plants, vegetables, fruits, and other perishable agricultural items is a typical method of preservation (Wankhade, et al., 2013). The presence of moisture in foods encourages microbial development and degradation over time; however, moisture that can cause deterioration is removed during the drying process. Drying foods used to be done mostly by exposing them to the open sun, which exposed them to harsh climatic conditions as well as pollutants. Mechanical and solar dryers, on the other hand, are increasingly and widely used in the food business for drying agricultural products (Doymaz, 2009).

The complexity of the drying process as a result of simultaneous mass and unsteady heat transfer necessitates a better understanding of the parameters that govern the complex process Techniques such as mathematical simulation and modeling of drying processes have been used to develop a suitable drying system for a specific agricultural product. Thin layer drying models have been widely and preferentially used to determine the drying characteristics of vegetables, fruits, and plants. Previously, researchers investigated the drying properties of agricultural products such as moringa leaves, coriander leaves, and rambutan (Ali et al., 2014, Olabinjo et al., 2020, Rahman et al., 2015). Previous studies have investigated the drying characteristics of lemon grass leaves under various conditions; however, there appears to be a limitation in either the applicability of the drying method on an industrial scale or the number of drying models used. Coradi et al., (2014) had used limited number of models that explore the drying kinetics of lemon grass (midilli, logarithmic, two-term and models and modified Page). Simha (2016) investigated the drying characteristics of lemon grass using a microwave drier. The experimental data employed ten models. The Midili model was found to be the most appropriate. However, the microwave drying power requirements make it impractical for industrial use. Nguyen et al. (2019) established the best model for drying lemon grass with hot air using only seven different drying models. From the result, it was shown that Weibull model was the most suitable model for describing the drying process. This study therefore investigates the best drying model to describe the drying characteristics of lemon grass using thirteen (13) typical thin layer models. Furthermore, it establishes the effect of drying air temperature on the rate of moisture removal, the effective diffusion coefficient and activation energy.

Materials and Methods

Material

Lemon grass leaves were collected from Ilara-mokin, a village close to Akure, the capital of Ondo State and were thoroughly washed and sorted. A hot air convection dryer at the department of Agricultural and Environmental Engineering of the Federal University of Technology, Akure, Ondo State Nigeria was utilized to dry the leaves according to the selected temperatures.

Drying Method

Upon collection, the leaves were cleaned and sorted to remove any form of impurity and dirt. AOAC (2000) method was adopted to determine the initial moisture content of the leaves by placing the leaves in oven at 105°C for 24h. 50g of the cleaned lemon grass leaves was used for each experimental run. The leaves were placed on the tray in the dryer at 40, 50, 60 and 70°C temperature. At an interval of 30mins, readings were taken to monitor changes on the leaves during the drying process. When the leaves became fully dried, readings became constant since there was no more moisture loss. Dried leaves were subsequently cooled and preserved in the desiccator to prevent them from moisture absorption. Data were obtained and then fitted to thirteen (13) different drying models to determine the drying characteristics of the leaves.

Mathematical Modelling

Moisture ratio (MR) and the drying rate (DR) were determined using equation 1 and 2 below. (Yaldiz et al., 2001).

$$MR = \frac{M_t - M_c}{M_0 - M_e} \quad (1)$$

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

Where MR is the dimensionless moisture ratio, M_t is the moisture content at time t of the drying process (g/g dry solid), M_e is the equilibrium moisture content (g/g dry solid), and M_o is the initial moisture content (g/g dry solid). The equilibrium moisture content (Me) was assumed to be 0 g/g dry solid for microwave drying since it is relatively small compared to M_t and M_o (Roberts et al., 2008). Therefore, equation 1 was simplified to

$$MR = \frac{M_t}{M_0} \quad (3)$$

From equation 2 expressed above, M_{t+dt} is the moisture content at time t+dt, while M_t is the moisture content at specific time t. M_0 and M_e remains the initial moisture content and equilibrium moisture content respectively. Different mathematical models as expressed in Table 1 were applied in fitting the drying curves.

Microsoft Excel was used in performing the non-linear regression analysis of each mathematical model which represents the coefficient of determination, chi square, root mean square error, and reduced sum square error respectively were also calculated. The best drying model was selected based on the lowest value of chi-square (χ^2), root-mean square error (RMSE) and sum of square error (SSE) and highest value of coefficient of determination (R^2).

Table 1. Mathematical models applied to the microwave oven drying curves of Lemon grass leaves

S/N	Model	Equation	References
1	Newton	$MR = \exp^{-kt} j$	Pangavhane, and Singh (1999)
2	Henderson and pabis	$MR = aexp^{-kt}$	Ceylan, (2007)
3	Page	$MR = exp\,(-kt^n)$	Guiné et al. (2011)
4	Logarithmic	$MR = aexp^{-kt} + c$	Ganesapillai et al. (2011)
5	Two term model	$MR = aexp^{-kt} + cexp^{-gt}$	Doymaz (2009)
6	Verma et al	$MR = aexp^{-kt} + (1-a)\exp^{-gt} f$	Verma et al. (1985)
7	Diffusion approach	$MR = aexp^{-kt} + (1-a)\exp^{-kgt}$	Yaldız et al. (2001)
8	Midili kucuk	$MR = aexp^{-kt^n} + bt$	Midilli, Kucuk et al. (2002)
9	Wang and singh	$MR = 1 + at + bt^2$	Miranda et al. (2009)
10	Hii et al.	$MR = aexp^{-k_1 t^n} + c\exp^{-gt^n}$	Hii et al. (2008)
11	Modified Henderson Pabis	$MR = aexp^{-kt} + b\exp^{-gt} + cexp^{-ht}$	Karathanos (1999)
12	Modified Page I	$MR = \exp^{-kt^n} j$	Overhults (1973)
13	Modified Page II	$MR = \exp^{-k\left(\frac{t}{l^2}\right)^n} j$	Diamante (1993)

Effective Moisture Diffusivity and Activation Energy Determination

Fick's second law of diffusion was utilized in determining the effective diffusivity. Equation 4 (Doymaz, 2005) was used in determining the effective moisture diffusivity of the samples as described.

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{\pi^2(2n+1)^2}{4L^2}D_{eff}t\right) \quad (4)$$

Upon plotting a graph of ln (MR) against time, the slope in equation 5 is used in computing the moisture diffusivity of the samples.

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}t\right) \quad (5)$$

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4L^2}$$

Where D_{eff} is the effective moisture diffusivity (m^2/s), MR is the moisture ratio and L is the half-thickness (m) of the samples.

Activation energy was calculated using the Arrhenius equation presented in equation 6 (Roberts et al., 2008).

$$D_{eff} = D_0 exp\frac{(-E_a)}{RT} \quad (6)$$

Results and Discussion

Effect of Drying Temperature on Drying Time of Lemon Grass Leaves

Figure 1 and 2 presents the drying curves of Lemon grass leaves at oven temperatures 40, 50, 60 and 70°C. Moisture content during the drying process was measured every 30 min at various drying air temperature until it attains equilibrium moisture content. The initial moisture content of the fresh leaves was observed to be 73.80% (wb) indicating a perishable fruit with high amount of water that permits the deterioration. However, upon drying, the moisture content was reduced to 2.00%, 2.00%, 1.99%, and 1.99% for 40, 50, 60 and 70°C air drying temperatures respectively. From the curve, it can be deduced that the leaves were completely dried at 750, 540, 480, and 450mins for 40, 50, 60 and 70ºC respectively under hot air drying. Therefore, moisture content in the leaves decreased to a constant point in a time that was dependent on drying temperature, being lowest at 70ºC (450 min) and highest at 40°C (750 min). Thus, an increase in drying air temperature resulted in decrease in the drying time. The lower moisture content of lemon grass in the dried samples shows decrease in volume and ease in conveying the dried sample during processing and storage. The reduction in moisture content reduces their water content which also result in minimizing microbial spoilage and deterioration reaction during storage. With increase in drying temperature from 40℃ to 70℃, the higher drying temperature resulted in lower moisture content. It can be observed that the lowest moisture content for safe storage and to minimize the growth of microbial organism in the lemon grass was obtained at a drying temperature of 70℃ at least drying time of 450minutes. The dried lemon grass will be more stable as a product, thus enhance food supply and improve seasonal food choice.

As indicated by the curves in figure 3, the drying processes occurred in falling rate for all the temperatures. Figure 3 shows that no constant rate drying period was observed and that drying rate decreased with decreasing moisture content or increased drying time. However, the drying processes occurred in falling rate for all the temperatures, similar to the results obtained in previous research (Ertekin et al., 2004; Sobukola et al., 2006; Sarimeseli, 2011; Ali et al., 2014). During falling rate period, rate of water diffusing from inside the leave to the surface is less than rate of water being evaporated from the surface to the surrounding air. Hence, there is an increased heat transfer quotient between the air and the leaves more than that between the surface and inside the leave which improves water evaporation from the leaves.

Modelling of Drying Curves

The 13 different models to which the data obtained from drying lemon grass leaves were fitted are presented in Table 1. The curves were obtained by plotting moisture ratios against oven drying time. Table 2 presents the result from the statistical analysis of the curve fits. The best model was determined by the model with the lowest value of SSE and RMSE, and the highest value of R^2. These statistical parameters have constantly been used in previous studies to evaluate models by (Meisami-asl and Rafiee, 2009; Olabinjo and Adeniyan 2020; Sobowale et al., 2020). From the result the value of R^2, SSE and RMSE ranged from 0.9151 - 0.9964, 0.0250 - 0.1325 and 0.0214 - 0.1288 respectively. Satisfying the conditions for selecting the most suitable and reliable model, Hii et al. model met all the criteria. R^2, SSE and RMSE values of the model was 0.9964, 0.0250 and 0.0214. Therefore, it can be concluded that at 40ºC Hii et al. model optimally describes the drying characteristics of Lemon grass leaves and gives better prediction than other models since it has the highest R^2 value (0.9966) at that temperature. The correlation between the predicted and experimented values for the best model oven drying methods at different temperature is presented in Figure 4. The selected models were validated by plotting graphs of the predicted moisture ratio against the experimental moisture ratio of the sample at the different drying temperatures. Validation is necessary to scrutinize the fitness of the models in predicting the drying kinetics of the lemon grass leaves and to obtain a valid model, the coefficient of determination (R^2) generated from the graph should be ≥ 0.75 (Olabinjo and Adeniyan, 2020). From the figure 4. the values of the coefficient of determination (R^2) are greater than 0.75, indicating a good fit. This reveals that all the models derived for drying of lemon grass leaves under oven drying methods are valid and can correctly predict its drying kinetics.

Effective Moisture Diffusivity and Activation Energy

Since all the samples of the Lemon grass leaves showed a falling rate period in their drying characteristics, Fick's second law of diffusion was utilized in determining the effective diffusivity. Table 3 shows the estimated diffusivity constant, D_0, and activation energy, E_a for the different temperatures. It was observed that the calculated values of effective moisture diffusivity fall within the general range of 10^{-9} to 10^{-12} m^2/s for food samples and agricultural crops.

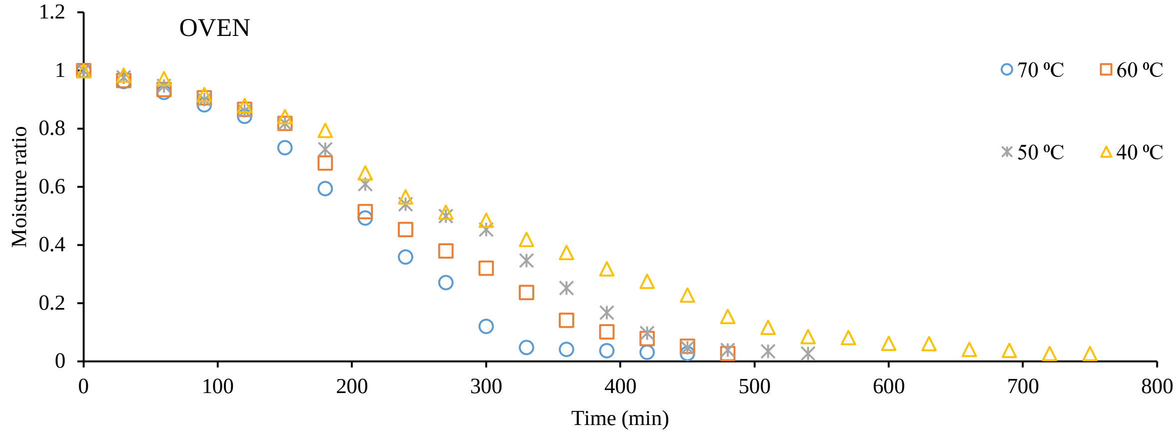

Figure 1. Moisture ratio against drying time of Lemon grass leaves at 40, 50, 60 and 70°C.

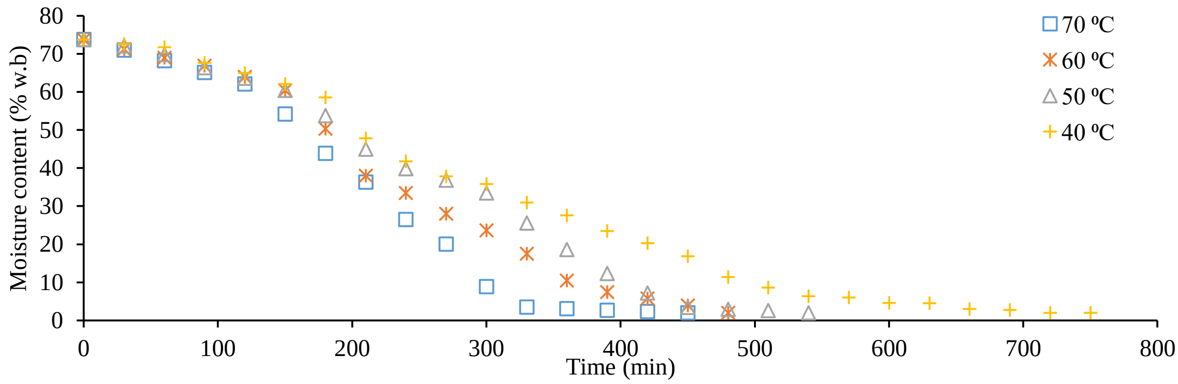

Figure 2. Moisture content (% wb) against drying time of Lemon grass leaves at 40, 50, 60 and 70°C.

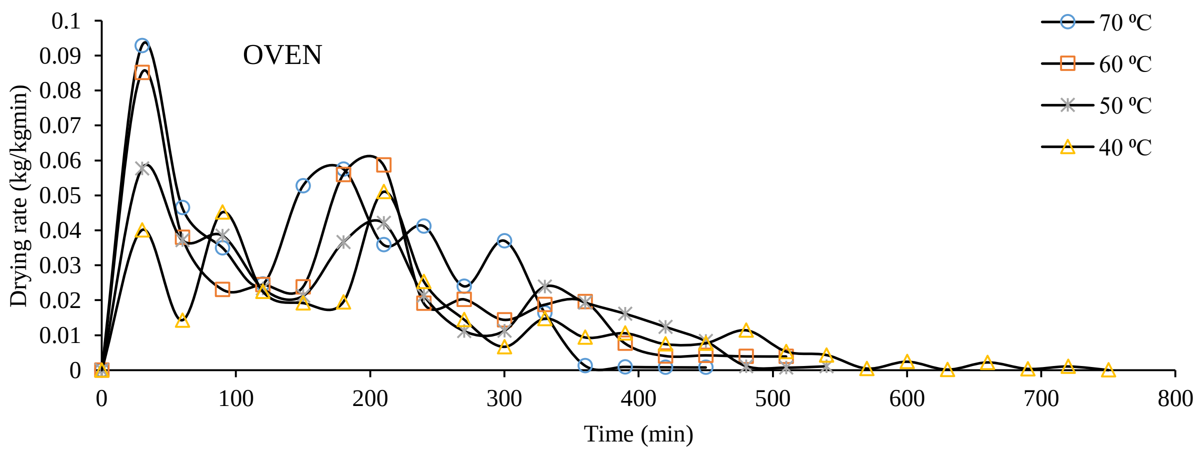

Figure 3. Drying rate vs time of Lemon grass leaves at 40, 50, 60 and 70°C.

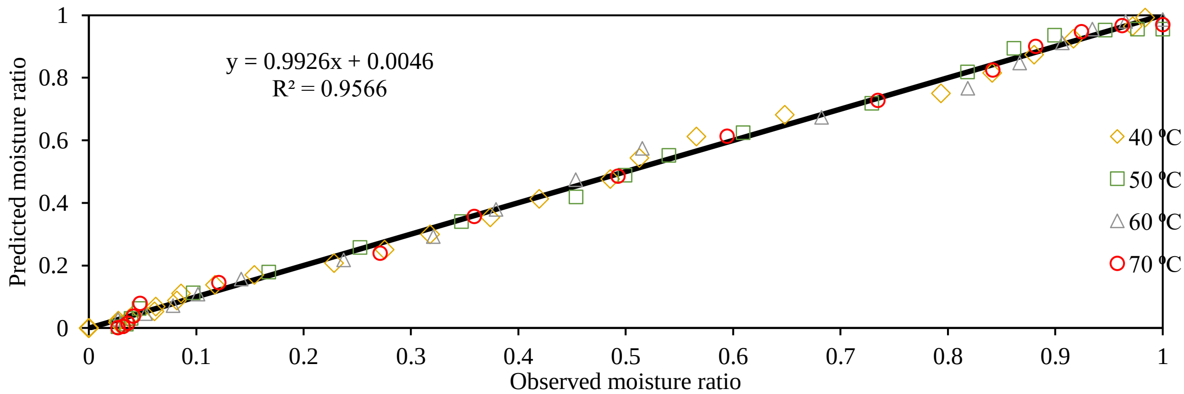

Figure 4. Calculated MR vs. experimental MR at drying temperatures of 40, 50, 60 and 70ºC

Table 2. Modelling of drying curves of Lemon Grass

(°C)	Model constants		R^2	RMSE	SSE	X^2
	Newton	Average	0.9340	0.1288	0.1325	0.0178
40	k = 0.2135		0.9641	0.1051	0.1071	0.0115
50	k = 0.1121		0.9289	0.1316	0.1352	0.0183
60	k = 0.2135		0.9283	0.1313	0.1353	0.0183
70	k = 0.2569		0.9147	0.1473	0.1522	0.0232
	Henderson and perbis	Average	0.9151	0.1078	0.1142	0.0134
40	k = 0.2544, a = 1.1804		0.9496	0.0823	0.0856	0.0073
50	k = 2.1305, a = 0.1395		0.9083	0.1111	0.1175	0.0138
60	k = 0.2544, a = 1.1804		0.9086	0.1104	0.1175	0.0138
70	k = 0.3044, a = 1.1914		0.8938	0.1274	0.1362	0.0185
	Page	Average	0.9954	0.0249	0.0264	0.0007
40	k = 0.0347, n = 2.2169		0.9966	0.0202	0.021	0.0004
50	k = 0.1286, n = 0.9412		0.9933	0.0298	0.0315	0.001
60	k = 0.0347, n = 2.2169		0.9954	0.0242	0.0258	0.0007
70	k = 0.0307, n = 2.5533		0.9961	0.0253	0.0271	0.0007
	Logarithmic	Average	0.9721	0.0589	0.0644	0.0043
40	k = 0.0253, a = 6.1841, c = -5.1015		0.9797	0.0495	0.0526	0.0028
50	k = 0.1386, a = 1.0011, c = 0.0545		0.9796	0.0502	0.0547	0.003
60	k = 0.0253, a = 6.1841, c = -5.1015		0.9731	0.0576	0.0635	0.004
70	k = 0.0516, a = 3.7115, c = -2.6202		0.9561	0.0783	0.0868	0.0075
	Two term model	Average	0.9553	0.0740	0.0839	0.0078
40	k = 0.2544, g = 0.2476, a = 1.1702, c = 0.0102		0.9803	0.0488	0.053	0.0028
50	k = 0.1614, g = 0.0403, a = 0.8671, c = 0.1982		0.9758	0.0589	0.0663	0.0044
60	k = 0.2544, g = 0.2476, a = 1.1702, c = 0.0102		0.9086	0.1104	0.1262	0.0159
70	k = 0.0386, g = 0.0306, a = 20.7944, c = -19.6937		0.9566	0.0778	0.0899	0.0081
	Verma et al	Average	0.9669	0.0687	0.0750	0.0058
40	k = -0.0254, g = -0.0019, a = -5.1446		0.9747	0.0618	0.0657	0.0043
50	k = 0.0237, g = 0.1344, a = 0.0974		0.9723	0.0594	0.0647	0.0042
60	k = -0.0254, g = -0.0019, a = -5.1446		0.9691	0.0661	0.0728	0.0053
70	k = 0.0004, g = 0.0035, a = -48.1374		0.9515	0.0873	0.0969	0.0094
	Diffusion approach	Average	0.9694	0.0692	0.0757	0.0059
40	k = 0.0016, g = -0.4961, a = 54.2284		0.9752	0.0614	0.0653	0.0043
50	k = 0.1121, g = 1, a = 3.0345		0.9794	0.0603	0.0658	0.0043
60	k = 0.0016, g = -0.4961, a = 54.2284		0.9722	0.0677	0.0746	0.0056
70	k = 0.0003, g = -1.4472, a = 229.2136		0.9509	0.0874	0.0969	0.0094
	Midili kucuk	Average	0.9958	0.0228	0.0257	0.0007
40	k = 0.0304, b = 0.001, a = 0.9847, n = 2.3042		0.9966	0.0202	0.0219	0.0005
50	k = 0.1266, b = 0.0016, a = 1.0457, n = 1.0047		0.9942	0.027	0.0304	0.0009
60	k = 0.0304, b = 0.001, a = 0.9847, n = 2.3042		0.9955	0.0235	0.0268	0.0007
70	k = 0.0211, b = 0.0017, a = 0.9641, n = 2.8092		0.997	0.0206	0.0238	0.0006
	Wang and smith	Average	0.9702	0.0681	0.0721	0.0054
40	a = -0.1298, b = 0		0.9788	0.0594	0.0618	0.0038
50	a = -0.0776, b = 0.0015		0.978	0.0579	0.0612	0.0038
60	a = -0.1298, b = 0		0.9721	0.0676	0.072	0.0052
70	a = -0.1498, b = 0.0004		0.9517	0.0873	0.0934	0.0087
	Hii et al.	Average	0.9964	0.0214	0.0250	0.0006
40	k = 0.0321, g = 0.0396, a = 1.0728, c = -0.0861, n = 2.2687		0.9966	0.0201	0.0224	0.0005
50	k = 0.0575, g = 0.0046, a = 0.6804, c = 0.3086, n = 1.723		0.9965	0.021	0.0245	0.0006
60	k = 0.0321, g = 0.0396, a = 1.0728, c = -0.0861, n = 2.2687		0.9955	0.0236	0.0281	0.0008
70	k = 0.014, g = 0.1533, a = 0.9033, c = 0.0664, n = 3.0243		0.9971	0.0208	0.0251	0.0006
	Modified Henderson Pabis	Average	0.9716	0.0596	0.0728	0.0055
40	k = -2.5161, a = 0.0001, g = -2.5161, b = 0.0001, h = 6.1151, c = 0.0257		0.9799	0.0492	0.0561	0.0031
50	k = 0.05, a = 0.0015, g = 0.05, b = 0.0015, h = 0.05, c = 0.1		0.9771	0.0532	0.0644	0.0041
60	k = -2.5161, a = 0.0001, g = -2.5161, b = 0.0001, h = 6.1151, c = 0.0257		0.9731	0.0576	0.0716	0.0051
70	k = -4.2168, a = 0.0381, g = -4.2164, b = 0.0381, h = 9.5491, c = 0.0562		0.9562	0.0782	0.099	0.0098
	Modified Page I	Average	0.9954	0.0249	0.0264	0.0007
40	k = 0.2197, n = 2.2169		0.9966	0.0202	0.021	0.0004
50	k = 0.1959, n = 1		0.9933	0.0298	0.0315	0.001
60	k = 0.2197, n = 2.2169		0.9954	0.0242	0.0258	0.0007
70	k = 0.2555, n = 2.5534		0.9961	0.0253	0.0271	0.0007
	Modified Page II	Average	0.9958	0.0230	0.0260	0.0007
40	k = 0.9864, a = 0.0511, n = 2.2761, L = 1.242		0.9966	0.0201	0.0219	0.0005
50	k = 1, a = 0.8, n = 0.9, L = 0.7		0.9941	0.0273	0.0307	0.0009
60	k = 0.9864, a = 0.0511, n = 2.2761, L = 1.242		0.9955	0.0235	0.0269	0.0007
70	k = 0.9673, a = 0.0014, n = 2.7498, L = 0.3621		0.9968	0.0212	0.0245	0.0006

An increase in the drying temperature led to increase in the effective moisture diffusivity similar observations were made by Alara et al. (2019), Sabat et al. (2018). The highest effective moisture diffusivity was found to be 16.007×10^{-12} m^2/s at oven drying temperatures of 70°C, while the lowest effective moisture diffusivity was estimated to be 8.92×10^{-12} m^2/s at oven drying temperatures of 40°C. The effective moisture diffusivity of the lemon grass leaves was found to be higher than *vernonia amygdalina* leaves (5.48×10^{-12} m^2/s) oven dried at 60°C (Alara et al., 2019).

Table 3. Estimated diffusivity constant and activation energy for 40, 50, 60 and 70°C

°C	D_{eff} (10^{-12}) m^2/s	D_o	E_a (kJ/mol)
70	16.00657	15.89542	19.86949
60	12.11538	12.02878	19.86196
50	11.93916	11.85121	19.85745
40	8.92452	8.856618	19.85

Conclusion

The drying characteristics of Lemon grass leaves were investigated in this study using four different temperatures (40, 50, 60, 70°C). Thirteen drying models were used by the experimental data from the drying process to fit the drying curves. It was observed that an increase in drying air temperature resulted in decrease in the drying time and the drying processes occurred in falling rate for all the temperatures. Hii et al. model optimally describes the drying characteristics of Lemon grass leaves and gives better prediction than other models since it has the highest R^2 value (0.9966) at 40°C. The D_{eff} values ranged from 16.00657×10^{-12} m^2/s to 8.92452×10^{-12} m^2/s and increases as temperature increases. It was further observed that the amount of energy required to eliminate moisture within the leaves increased in the range of 19.85 kJ/mol - 19.86949 kJ/mol.

Lemongrass is used as a food flavoring and can be used fresh or dried. Lemongrass essential oil has been effectively produced from both dry and fresh lemongrass in recent years. Dried lemongrass leaves can be used in food preservation as an alternative to synthetic substances that have recently become less acceptable to consumers. Consumers accept natural food products that are universally acknowledged as safe, such as lemon grass with essential oils, and they also fit the standards for green processing.

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