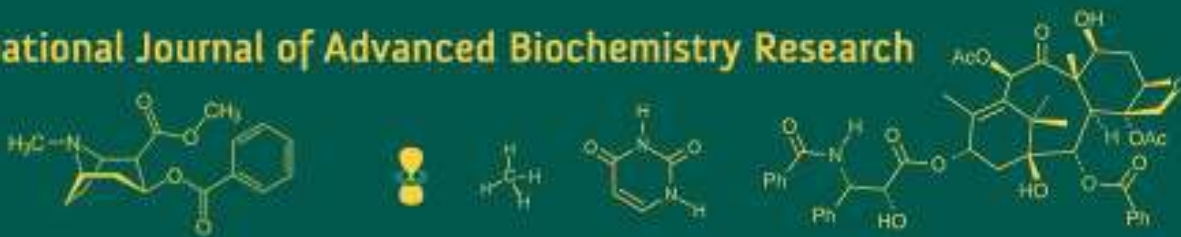


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Thin layer drying of fenugreek leaves in a solar tunnel dryer: Performance and analysis

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Abstract

This study explores the drying behaviour of fenugreek leaves (*Trigonella foenum-graecum*) in a solar tunnel dryer, comparing two drying methods (solar tunnel drying and sun drying) and varying blanching times (0 min, 3 min, 5 min), with the goal of identifying the most effective model for predicting moisture content dynamics. Experimental data were transformed into moisture ratio values and analysed using six well-established drying models. Statistical evaluation, based on parameters such as the coefficient of determination (R^2), chi-square (χ^2), and root mean square error (RMSE), was conducted to assess the goodness of fit. Among the models tested, the Midilli model showed the best performance, with R^2 values ranging from 0.9944 to 0.9999, and the lowest χ^2 and RMSE values. Residual analysis indicated minimal discrepancies between the actual and predicted moisture ratios, ranging from 0.00010 to 0.00138, demonstrating the model's accuracy and reliability in describing the thin-layer drying kinetics of fenugreek leaves. By effectively capturing moisture removal behaviour, the Midilli model offers a strong framework for optimizing drying processes, particularly those using renewable energy methods. This study highlights the potential of the Midilli model in guiding the development of energy-efficient and sustainable drying techniques, which not only minimize energy consumption but also help preserve product quality. The results are especially relevant for renewable energy engineering, where efficient drying methods play a key role in reducing post-harvest losses and increasing the value of agricultural products. By incorporating precise modeling into the design of drying systems, this research contributes to advancing environmentally friendly practices and supports the creation of innovative solutions for agricultural preservation. The findings emphasize the importance of accurate models in achieving sustainable and cost-effective drying strategies, driving progress in both renewable energy applications and agricultural engineering.

Keywords: Solar tunnel drying, fenugreek leaves, thin layer drying, Moisture ratio, Renewable energy

1. Introduction

In recent years, the use of green leafy vegetables as nutritional supplements and ingredients in functional foods has seen significant growth. The consumption of these vegetables is linked to various health benefits and mechanisms for disease prevention [1, 2]. These vegetables are rich in essential nutrients, but their seasonal availability and perishable nature limit their widespread use. The high surface area-to-volume ratio and tender texture of the leaves contribute to substantial post-harvest losses, which begin as early as the harvesting stage. Fenugreek (*Trigonella foenum-graecum* L.) is an annual herb commonly found across Africa, Asia, and Europe, with India being the largest producer globally [3]. There are two types of fenugreek: *Trigonella foenum-graecum* and *Trigonella corniculata* (Champa or Kasturi Methi), both belonging to the *Leguminosae* family. Fresh leaves of fenugreek leaves contain 4% protein, 1% fat, and 6% carbohydrate [4]. The distinctive aroma and flavor of these leaves, due to compounds like anethol and sotolone, make them a popular culinary herb [5, 6]. Fenugreek leaves, along with the stems, are commonly used as vegetables, similar to spinach [7], while dried leaves are valued for their health benefits, such as reducing blood sugar and cholesterol levels [9], owing to active ingredients like ascorbic acid, potassium, niacin, saponins, alkaloids, lysine, diosgenin, trigonelline, fenugreekine, galactomannan, 4-hydroxy isoleucine, and L-tryptophan [10, 11]. However, the seasonal availability and perishable nature of fenugreek leaves hinder their broader application in the food industry. Therefore, there is a critical need for processing methods that can extend their shelf life. Traditionally, fenugreek leaves are sun-dried to improve storability, though contamination

during sun drying remains a significant concern ^[12]. Additionally, drying at high temperatures can lead to undesirable changes in the quality of the product. Controlled heat processes are thus necessary to remove moisture to the desired level while preserving nutrients ^[13]. Naidu *et al.* ^[14] attempted to dry fenugreek leaves at 40°C in a controlled environment, resulting in a high-quality product with maximum nutrient retention. Blanching is a widely used technique to extend shelf life by inactivating enzymes such as polyphenol oxidase (PPO), ensuring better quality retention in dried products ^[15]. Various types of thermal blanching, including water, steam, superheated steam, ohmic, microwave, and superheated steam impingement blanching (SSIB), are employed to simultaneously reduce processing time and increase energy efficiency ^[22]. Mathematical modeling is a valuable approach for optimizing the drying process, providing ideal operating conditions for equipment design to dehydrate products with improved rehydration properties. This study aims to assist industries, particularly those focused on fenugreek leaf powder production, in designing cabinet dryers. The dried powder can be utilized as a functional ingredient in various food products, such as bakery items, soups, curries, instant vegetables, and beverages. Considering the broad usage and significance of fenugreek leaves, this study was designed to examine the effect of different blanching pre-treatments on the quality of dried leaves. Mathematical modeling has been employed to identify the optimal drying conditions.

2. Materials and Methods

2.1 Description of the indirect solar dryer

The drying system used in this study is a natural convection type solar tunnel dryer, with dimensions of 10 meters in

length, 5 meters in width, and 2.5 meters in height, designed in a hemi-cylindrical shape. The dryer consists of 64 trays, each measuring 0.70 meters by 0.70 meters by 0.05 meters, with 16 trays per stand arranged in two tiers, and a total of 4 tray stands. The total volume of the 64 trays is 1.57 cubic meters. To ensure adequate airflow, the dryer is equipped with five air vents, each with dimensions of 16.5 cm by 16.5 cm. Additionally, the system includes two turbo fans, each with a size of 16.5 cm by 16.5 cm, and two exhaust fans, each with a power rating of 0.557 hp and a speed of 1400 rpm. The solar tunnel dryer is covered with a UV-stabilized 200 μ polyethylene sheet, ensuring durability and optimal performance in preserving the quality of the dried material.

2.2. Experimental Details

2.2.1. Procurement of Fenugreek Leaves

The medicinal plants namely, *Trigonella foenum-graecum* (fenugreek) leaves, was procured from the local farm of the Junagadh, Gujarat. *Trigonella foenum-graecum* (fenugreek) was harvested by a wooden rod with a sharp stainless-steel knife at the top for cutting the leaves. Then after, damaged and discoloured leaves were separated manually by hand picking.

2.2.2. Pre-Treatments

The freshly harvested *Trigonella foenum-graecum* leaves were treated with pre-treatment durations (*i.e.*, steam blanching for 3 and 5 minutes) before being subjected to solar tunnel drying and sun-drying. Several studies have indicated that steam blanching before drying enhances sensory attributes (such as color, flavor, taste, fragrance, and aroma), allows for extended shelf life, and reduces the overall drying time.

Table 1: Treatment combination details of fenugreek leaves for different drying methods and drying times.

Treatment No.	Treatment Details	Combinations
1	Fenugreek Leaves (C) + 0 min Steam blanching(S ₁) + Solar Tunnel Drying (D ₁)	CS ₁ D ₁
2	Fenugreek Leaves (C) + 3 min Steam blanching(S ₂) + Solar Tunnel Drying (D ₁)	CS ₂ D ₁
3	Fenugreek Leaves (C) + 5 min Steam blanching(S ₃) + Solar Tunnel Drying (D ₁)	CS ₃ D ₁
4	Fenugreek Leaves (C) + 0 min Steam blanching(S ₁) + Sun Drying (D ₂)	CS ₁ D ₂
5	Fenugreek Leaves (C) + 3 min Steam blanching(S ₂) + Sun Drying (D ₂)	CS ₂ D ₂
6	Fenugreek Leaves (C ₂) + 5 min Steam blanching(S ₃) + Sun Drying (D ₂)	CS ₃ D ₂

2.3 Analysis of drying characteristics

2.3.1 Moisture Content

Moisture content was measured using the hot air oven method as described by Ranganna. Freshly harvested medicinal leaves, as well as solar tunnel dried and sun-dried leaves, were placed in pre-weighed petri dishes and dried in a hot air oven at 70°C for 16 hours. Post drying, the petri dishes with samples were weighed to determine the moisture loss. This moisture loss, when divided by the total or dry weight, gives the moisture content on a wet and dry basis.

The initial water content is calculated using the following equation:

$$M = \frac{M_1 - M_2}{\text{total weight of the sample or dry weight of the sample}} \times 100 \quad (2.1)$$

Where,

M = Initial water content in the product, kg

M_1 = Weight of the sample before drying, kg

M_2 = Weight of the sample after drying, kg

2.3.2 Moisture Ratio

Moisture ratio was computed as per the method suggested by Singh *et al.* (1996):

$$MR = \frac{M - M_e}{M_o - M_e} = e^{-k\theta} \quad (2.2)$$

Where, MR = Moisture ratio

M = Moisture content at any time, % (db)

M_e = Equilibrium moisture content, % (db)

M_o = Initial moisture content, % (db)

k = Drying constant,

2.3.3 Drying Rate

The moisture content data recorded during experiments was analysed to determine the moisture lost by dried fenugreek and fenugreek leaves at a different interval of time.

The drying rate of the samples was calculated using the following equation,

$$\text{Drying rate, \%} = \frac{dm}{dt} \quad (2.3)$$

Where, dm = Moisture removed per hour, % (wb)
 dt = Drying time, h

$$K_o = \frac{\pi^2 D_{eff}}{4L_o^2} \quad (2.4)$$

$$D_{eff} = \frac{L_o^2}{4K_o} \quad (2.5)$$

2.4 Mathematical Modeling Analysis

Modeling of the drying process is important for characterizing the process with different drying methods and conditions so, fenugreek leaves and fenugreek were dried in sun and solar tunnel dryer for different blanching pretreatments 0min., 3 min., 5 min. To determine the most suitable drying equation, the experimental drying data were fitted in the various drying models (Table 2.2) and the performance was determined by the coefficient of determination (R^2). These selected models were used to describe the drying curve equations during drying. These are explained here under.

Table 2: Name of the mathematical models

Name of the model	equation
Newton	$Y = \exp(-kt)$
Page	$MR = \exp(-kt^N)$
Modified Henderson & Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$
Wang & Singh	$MR = 1 + at + bt^2$
Logarithmic	$MR = a \exp(-kt) + c$
Midilli	$Y = a \exp(-k(t^n)) + bt$

2.4.1 Thin layer drying analysis

In this study, the experimental drying data of *Trigonella foenum-graecum* at different blanching times (0 min, 3 min, 5 min) were fitted into different models used in thin layer drying models. The experimental values of moisture ratio different interval of time was plotted against drying time for different blanched turmeric rhizomes. The goodness of fit of the selected mathematical models to the experimental data was evaluated with the correlation coefficient R^2 , the reduced chi-square (χ^2) and the root mean square error (RMSE). The goodness of fit will be better, if R^2 values are higher and χ^2 and RMSE values are lower. The reduced chi-square (χ^2) and the RMSE were calculated using the following expressions.

2.4.2 Calculation of effective diffusivities

Effective diffusivities for different blanching times were found by plotting the graph of moisture ration on logarithmic scale versus drying time t . The calculation of slope, k_0 and effective diffusivity was followed as:

3. Results and Discussion

3.1 Drying characteristics of fenugreek leaves

3.1.1 Drying characteristics of sun tunnel dried fenugreek leaves

Figure 1, 2 and 3 presents the moisture content, drying rate, and moisture ratio at various intervals during the drying process of 0 min, 3 min and 5 min blanched fenugreek leaves using a solar tunnel dryer. The drying process begins with the fenugreek leaves having an exceptionally high initial moisture content. In the initial drying phase (0-60 minutes), a rapid reduction in moisture content is observed, with the moisture level decreasing from 611.74% to 410.51%, 380.65%, 301.85%, respectively for 0 min, 3 min and 5 min. This early stage of drying is marked by a very high moisture evaporation rate, as the material loses water rapidly. The drying rate reaches its peak during the first 10 minutes, with a maximum value of 6.17%, 6.88%, 7.04% per minute for 0 min, 3 min and 5 min respectively, highlighting the intense moisture loss that occurs at the start. This high rate of moisture removal is typical of the first stage of drying, where free water in the product is quickly removed, contributing to the large decrease in moisture content as the drying process moves into the intermediate phase (60-180 minutes), the reduction in moisture content continues, but at a much slower rate. The moisture content decreases to 275.22%, 170.15%, 66.25%. during this period, which indicates a slower rate of moisture removal as the drying process enters the next stage. In the intermediate phase, the drying rate is governed by the diffusion of water from the interior of the material to the surface, where it can evaporate. Finally, in the later drying phase (180-300 minutes), the rate of moisture loss decreases significantly, with the moisture content approaching the equilibrium value. During this phase, the moisture content drops to 10.84%, 8.71%, 8.21%, which signifies that most of the water has been removed from the fenugreek leaves. The drying rate continues to decrease further, reaching a minimum of 1.07%, 1.14%, 1.23% per minute for 0 min, 3 min and 5 min respectively, indicating that the fenugreek leaves are nearing their final moisture content and the drying process is approaching completion. At this point, the material is almost completely dried, and only a small amount of bound water remains.

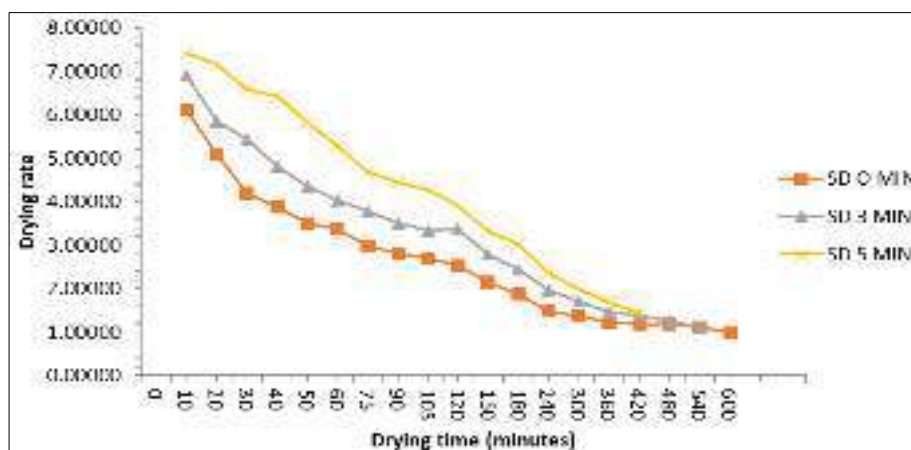


Fig 1: Drying rate vs Drying time for sun dried fenugreek leaves

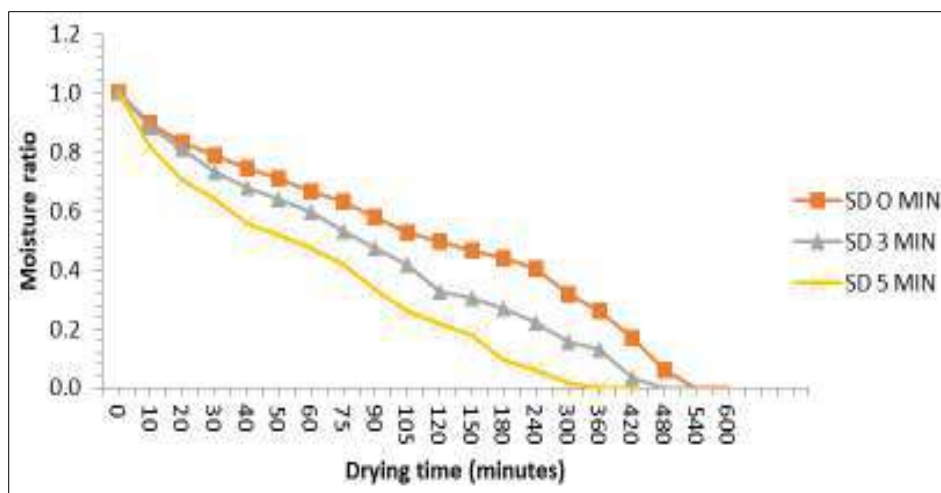


Fig 2: Moisture ratio vs Drying time for sun dried fenugreek leaves

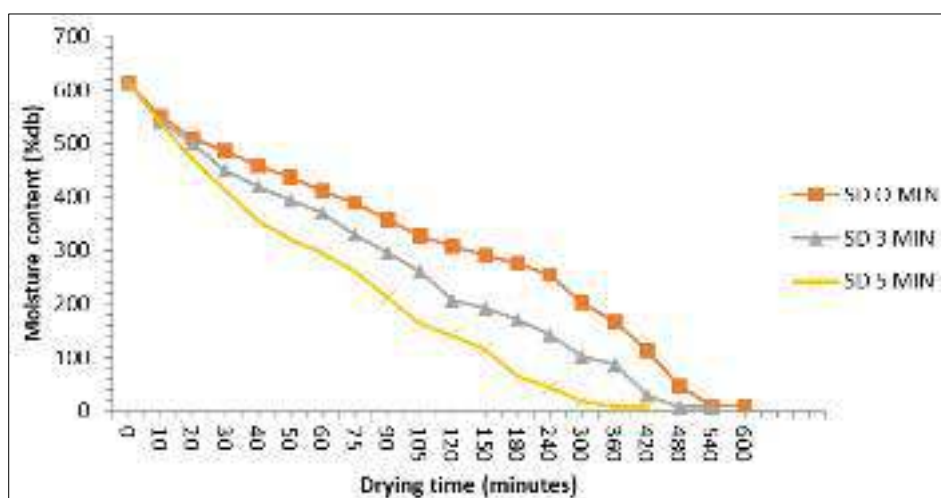


Fig 3: Moisture content vs Drying time for sun dried fenugreek leaves

3.1.2 Drying characteristics of sun tunnel dried fenugreek leaves

Figures 4, 5, and 6 show the moisture content, drying rate, and moisture ratio at various intervals during the drying of fenugreek leaves that were blanched for 0 minutes, 3 minutes, and 5 minutes using a solar tunnel dryer. The drying process begins with fenugreek leaves having a very high initial moisture content. In the initial drying phase (0-60 minutes), a sharp decrease in moisture content is observed, with the moisture levels dropping from 611.74% to 348.74%, 281.68%, and 252.25% for 0 min, 3 min, and 5 min blanched leaves, respectively. This early stage of drying is characterized by a rapid evaporation of moisture, as the material loses water quickly. The drying rate peaks within the first 10 minutes, with a maximum value of 6.8%, 8.3%, and 9.02% per minute for 0 min, 3 min, and 5 min, respectively, reflecting the intense moisture loss at the start. This high moisture removal rate is typical of the initial drying stage, where free water is quickly expelled, causing a significant reduction in moisture content. As the drying progresses into the intermediate phase (60-180 minutes), moisture content continues to decrease, but at a slower rate. During this period, the moisture content reduces to

185.32%, 108.25%, and 77.25%, indicating a deceleration in moisture removal as the drying enters the next phase. The drying rate also slows down during this time, stabilizing to 2.39%, 2.70%, and 3.15% per minute for the 0 min, 3 min, and 5 min blanched leaves, respectively. This decline in the drying rate reflects the reduced availability of free water for evaporation, as most of the easily accessible moisture has already been removed. In this intermediate phase, the drying rate is primarily controlled by the diffusion of water from the inner layers to the surface, where it can evaporate. Finally, in the later drying phase (180-300 minutes), the moisture loss rate significantly slows, with the moisture content approaching its equilibrium value. During this phase, the moisture content decreases to 9.30%, 7.92%, and 7.04%, indicating that the majority of the water has been removed from the fenugreek leaves. The drying rate continues to decrease, reaching a minimum of 1.00%, 1.21%, and 1.33% per minute for 0 min, 3 min, and 5 min, respectively, signifying that the fenugreek leaves are nearing their final moisture content and the drying process is almost complete. At this stage, the material is almost fully dried, with only a small amount of bound water remaining.

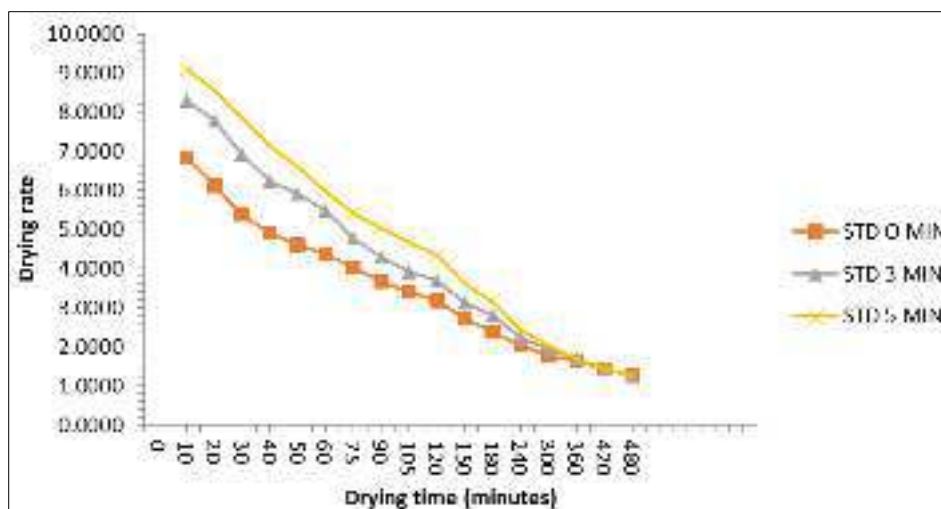


Fig 4: Drying rate vs Drying time for solar tunnel dried fenugreek leaves

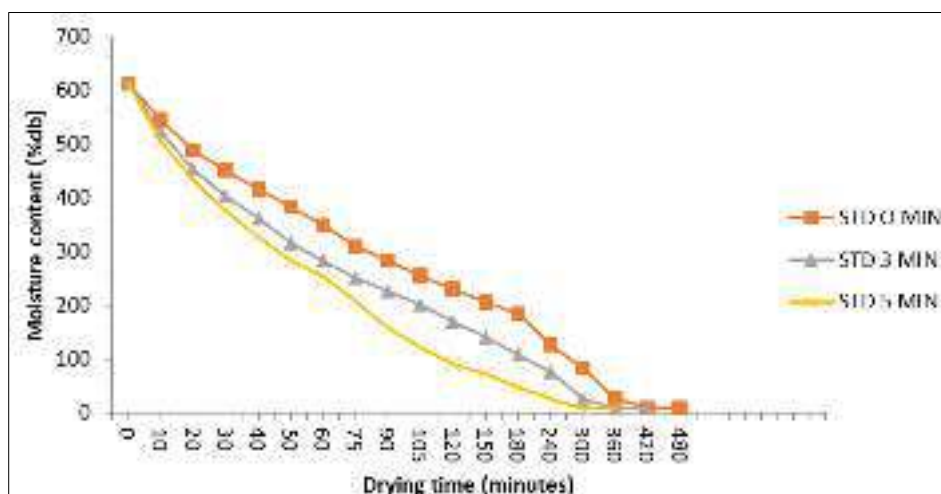


Fig 5: Moisture content vs Drying time for solar tunnel dried fenugreek leaves

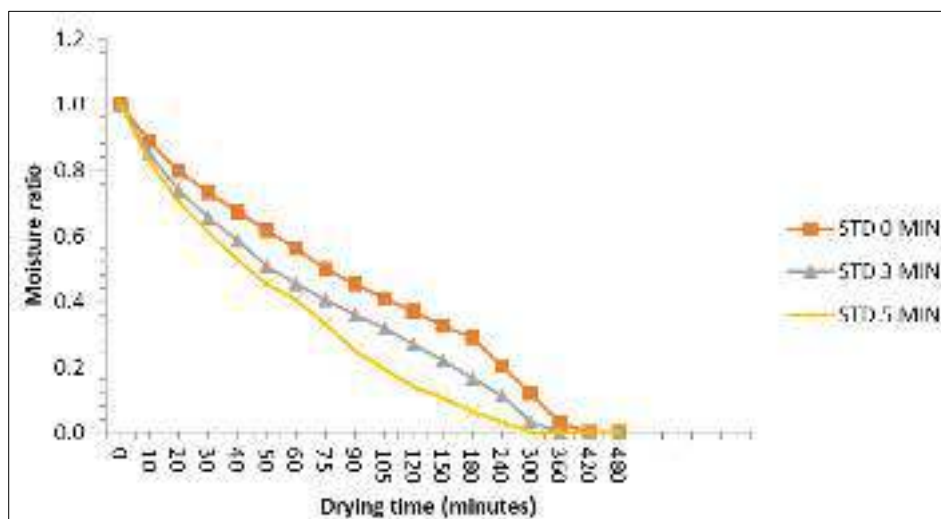


Fig 6: Moisture ratio vs Drying time for solar tunnel dried fenugreek leaves

3.2 Fitting of mathematical models

3.2.1 Fitting of models for sun dried fenugreek leaves

The experimental data on the moisture content at various time intervals were calculated into moisture ratio for the entire drying process. These moisture ratio values were subsequently fitted to six different drying models, as outlined in Table 2.2. The fitting process involved

determining the drying constants for each model, and the results are presented in Table 2.3 which showcase the effects of different drying methods and blanching times on the drying behaviour of the fenugreek leaves. The drying models were evaluated for their goodness of fit, and the statistical parameters such as the coefficient of determination (R^2), chi-square (χ^2), and root mean square

error (RMSE) were used for comparison. These values are also summarized in Table 2.3, providing a comprehensive view of the models' performance under varying drying methods and blanching conditions.

Among the various models tested, the Midilli model demonstrated the best performance in describing the drying kinetics of the fenugreek leaves. The coefficient of regression (R^2) for this model ranged from 0.9944 to 0.9991, which indicates an excellent fit between the experimental

data and the model predictions. The Midilli model outperformed the other models, as it yielded the highest R^2 values, the lowest χ^2 values, and the smallest RMSE values. These statistical indicators clearly suggest that the Midilli model is the most suitable for representing the drying behaviour of fenugreek leaves in the conditions tested. Moreover, the residual sum of actual and predicted moisture ratio values varied between 0.00012 to 0.00135, which were the smallest values among all the models evaluated.

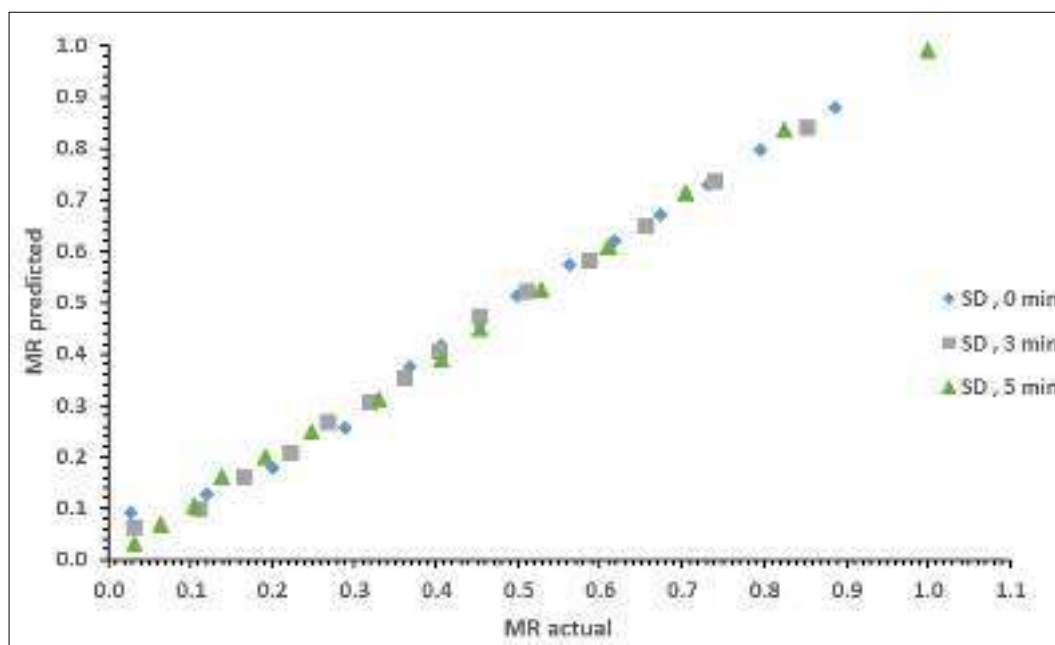


Fig 7: Experimental vs Predicted values for fenugreek leaves at drying methods SD and different blanching times using the Midilli model.

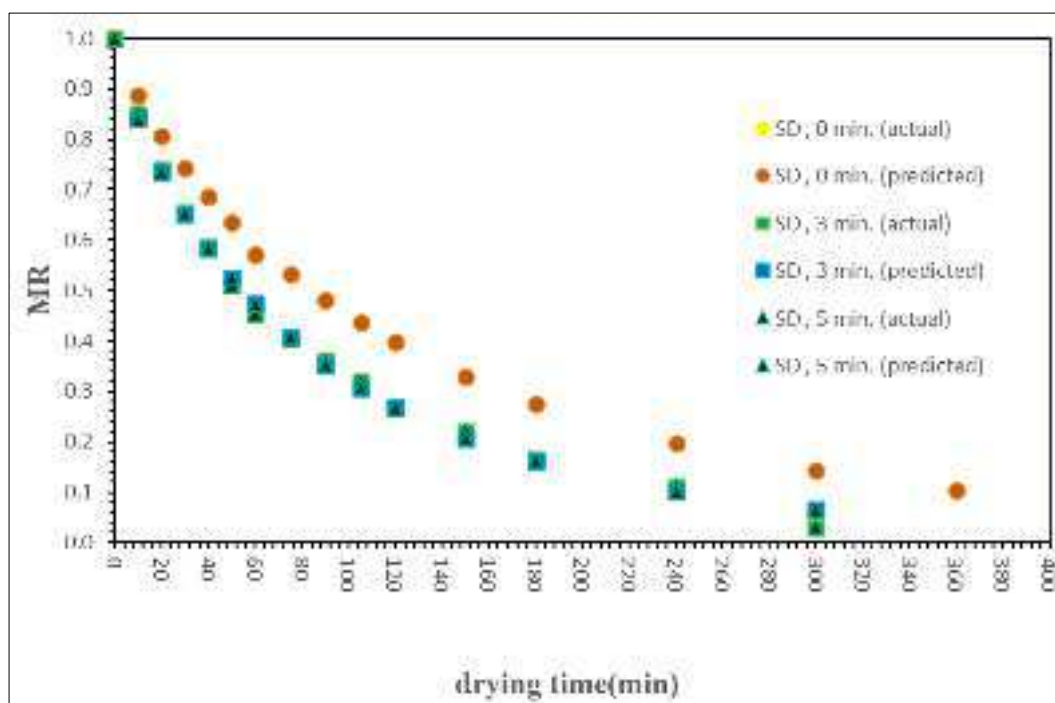


Fig 8: fitting of Midilli model on actual values of Fenugreek leaves at drying method SD and different blanching times

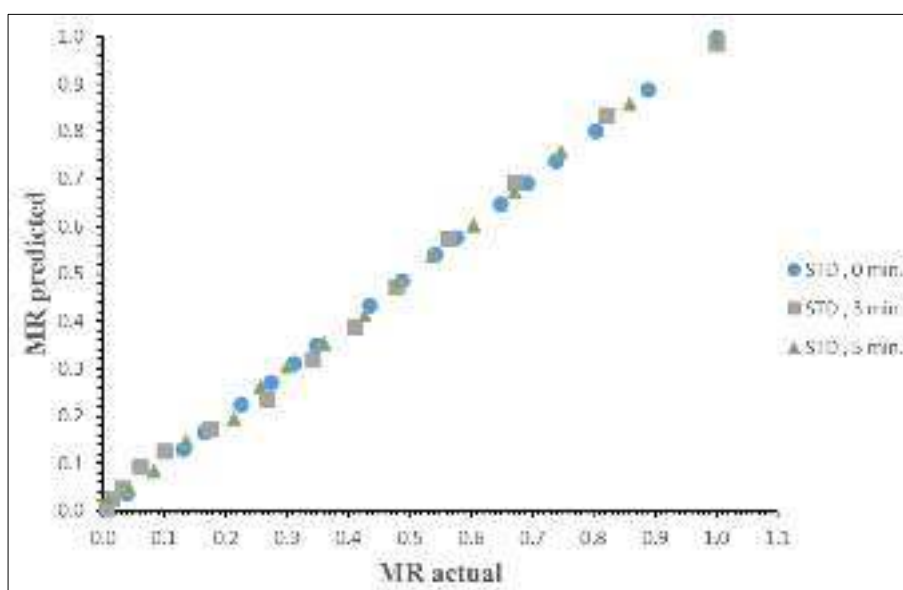
Table 3: Drying constant and Statistical comparison of different drying models for sun drying method and different steam blanching time for fenugreek leaves.

Sr. No.	Model	steam blanching time, min	Constants						R ²	χ^2	RMSE
			1 st	2 nd	3 rd	4 th	5 th	6 th			
1	Lewis		k								
		0	0.005						0.9666	0.2103	0.0634
		3	0.008						0.9907	0.2009	0.0210
		5	0.012						0.9970	0.1107	0.0225
2	Logarithmic		k	a	b						
		0	0.0117	0.9013	0.0457				0.9808	1.6000	0.1417
		3	0.0106	0.8854	0.0765				0.9887	0.0970	0.0340
		5	0.0104	0.8790	0.0677				0.9964	0.3640	0.0560
3	Modified Henderson and Pabis		k	a	g	b	h	c			
		0	0.1522	-0.0024	0.0152	0.9863	0.1622	0.1053	0.8470	0.0355	0.2919
		3	0.1496	-0.0029	0.0147	0.9921	0.1529	0.1173	0.9441	6.3670	0.1672
		5	0.1642	-0.0025	0.0164	0.9921	0.1423	0.1239	0.9687	2.5139	0.0945
4	Midilli		a	k	n	b					
		0	0.9879	0.0156	0.7681	0.0000160			0.9944	0.1115	0.0067
		3	1.0030	0.0191	0.8116	0.000018			0.9947	0.0400	0.0200
		5	0.9951	0.0190	0.8888	0.000021			0.9991	0.0168	0.0091
5	Wang and Singh		a	b							
		0	-0.0085	0.0000150					0.9380	0.3483	0.0814
		3	-0.0085	0.000015					0.9270	0.8765	0.1879
		5	-0.0068	0.000013					0.9589	0.7449	0.1355
6	Page		k	n							
		0	0.0118340	0.87653					0.9707	0.3674	0.0666
		3	0.010423	0.987530					0.9910	0.8797	0.0677

Fitting of models for solar tunnel dried fenugreek leaves

The experimental data on the moisture content at various time intervals were calculated into moisture ratio for the entire drying process. These moisture ratio values were subsequently fitted to six different drying models, as outlined in Table 2.2. The fitting process involved determining the drying constants for each model, and the results are presented in Table 2.4 which showcase the effects of different drying methods and blanching times on the drying behaviour of the fenugreek leaves. The drying models were evaluated for their goodness of fit, and the statistical parameters such as the coefficient of determination (R^2), chi-square (χ^2), and root mean square error (RMSE) were used for comparison. These values are also summarized in Table 2.4, providing a comprehensive view of the models' performance under varying drying methods and blanching conditions.

Among the various models tested, the Midilli model demonstrated the best performance in describing the drying kinetics of the fenugreek leaves in solar tunnel drying. The coefficient of regression (R^2) for this model ranged from 0.9944 to 0.9999, which indicates an excellent fit between the experimental data and the model predictions. The Midilli model outperformed the other models, as it yielded the highest R^2 values, the lowest χ^2 values, and the smallest RMSE values. These statistical indicators clearly suggest that the Midilli model is the most suitable for representing the drying behaviour of fenugreek leaves in the conditions tested. Moreover, the residual sum of actual and predicted moisture ratio values varied between 0.00011 to 0.00138 which were the smallest values among all the models evaluated. This indicates a high degree of accuracy in the model's predictions, further validating its reliability.

**Fig 9:** Experimental vs Predicted values for fenugreek leaves at drying methods STD and different blanching times using the Midilli model.

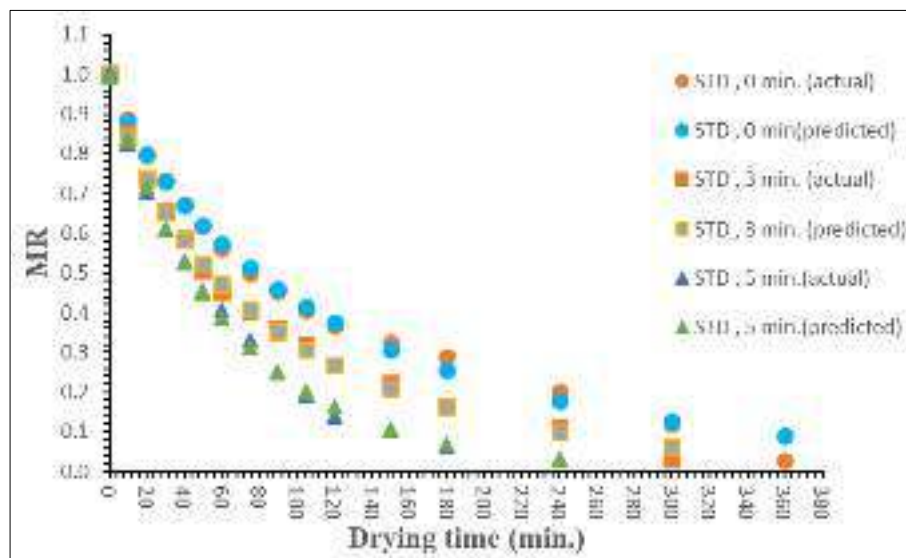


Fig 10: Fitting of Midilli model on actual values of Fenugreek leaves at drying method STD and different blanching time

Table 4: Drying constant and Statistical comparison of different drying models for solar tunnel drying method and different steam blanching time for fenugreek leaves.

Sr. No.	Model	Steam blanching time, min	Constants						R ²	χ^2	RMSE
			1 st	2 nd	3 rd	4 th	5 th	6 th			
			k								
1	Lewis	0	0.008						0.9885	0.15	0.0396
		3	0.012						0.9957	0.29	0.0210
		5	0.016						0.9983	0.58	0.0147
			k	a	b						
2	Logarithmic	0	0.0117	0.9013	0.0457				0.9808	0.4808	0.0028
		3	0.0119	0.9045	0.0654				0.9910	0.1413	0.0385
		5	0.0175	0.9532	0.0698				0.9964	0.0819	0.0317
			k	a	g	b	h	c			
3	Modified Henderson and Pabis	0	0.1752	-0.002987	0.0156	0.9361	0.1253	0.1283	0.9365	0.0045	0.1753
		3	0.1629	-0.002374	0.0147	0.9253	0.1632	0.1192	0.9875	0.1041	0.0833
		5	0.1852	-0.002873	0.0152	0.8942	0.1596	0.1258	0.9955	0.0126	0.0300
			a	k	n	b					
4	Midili	0	1.0000	0.0193	0.8214	0.000010			0.9944	0.0500	0.0067
		3	1.0041	0.0277	0.8070	0.000013			0.9979	0.0207	0.0125
		5	0.9912	0.0189	0.9535	0.000015			0.9999	0.0063	0.0107
			a	b							
5	Wang and Singh	0	-0.00615	0.0000146					0.9637	0.2521	0.0793
		3	-0.008243	0.0000256					0.9790	0.2669	0.0910
		5	-0.008630	0.0000357					0.9868	0.6522	0.1314
			k	n							
6	Page	0	0.0098	0.9950					0.9883	0.0045	0.0507
		3	0.0154	0.9840					0.9918	0.5254	0.0614
		5	0.0174	0.9754					0.9985	0.0073	0.0124

Effective diffusivity of fenugreek leaves

The effective diffusivity of fenugreek leaves blanched at different times was calculated by plotting the relation between the moisture ratio on a logarithmic scale and Drying time. The slope of the linear equation from the graph was used for the calculation of effective diffusivity. The effective diffusivity was varied between 4.82×10^{-9} to 9.68

$\times 10^{-9} \text{m}^2/\text{s}$. The effective diffusivity was increased with the increase in the blanching time as well as Table 2.4. The maximum effective diffusivity was found to be $9.68 \times 10^{-9} \text{m}^2/\text{s}$ for STD 3 min blanched was similar to the various food materials. This increase in effective diffusivity could be attributed to higher thermal energy to the sample blanched for a longer period.

Table 5: Effective moisture diffusivity (deff) and its linear equation for fenugreek leaves at different drying temperature and hot water blanching time

Drying method	Blanching time, min.	MR	R ²	Slope, k ₀	Deff, m ² /s
STD	0 min.	$Y = -0.0081x - 0.0171$	0.9397	0.0081	5.16×10^{-9}
	3 min	$y = -0.0032x + 0.1844$	0.9285	0.0032	6.12×10^{-9}
	5 min	$Y = -0.0081x - 0.0171$	0.9397	0.0081	8.20×10^{-9}
SD	0 min.	$y = -0.0058x + 0.3638$	0.9666	0.0058	2.45×10^{-9}
	3 min	$y = -0.0039x + 0.3827$	0.9217	0.0039	4.25×10^{-9}
	5 min	$y = -0.0042x + 0.236$	0.9301	0.0042	5.05×10^{-9}

4. Summary and Conclusion

The drying characteristics of fenugreek leaves using a solar tunnel dryer (STD) and sun drying (SD) were investigated with varying blanching times (0, 3, and 5 minutes). In both methods, the drying process exhibited three distinct phases: rapid moisture loss in the initial phase (0-60 minutes), a slower rate in the intermediate phase (60-180 minutes), and a significant reduction in the final phase (180-300 minutes). The Midilli model provided the best fit for both drying methods, with the highest R^2 values, lowest χ^2 , and smallest RMSE, indicating its suitability for describing the drying kinetics. The effective diffusivity of fenugreek leaves increased with blanching time, with the highest value of $9.68 \times 10^{-9} \text{ m}^2/\text{s}$ observed for the 3-minute blanching under solar tunnel drying.

The drying process for sun-dried fenugreek leaves followed a similar trend, with rapid moisture loss in the initial phase, a slower rate in the intermediate phase, and a minimal moisture decrease in the final phase. Again, the Midilli model showed the best fit, with R^2 values ranging from 0.9929 to 0.9944, confirming its reliability in predicting the drying behaviour of fenugreek leaves. The effective moisture diffusivity for fenugreek leaves increased with blanching time, with values for solar tunnel dried fenugreek ranging from $5.16 \times 10^{-9} \text{ m}^2/\text{s}$ to $8.20 \times 10^{-9} \text{ m}^2/\text{s}$ and sun-dried fenugreek leaves from $2.45 \times 10^{-9} \text{ m}^2/\text{s}$ to $5.05 \times 10^{-9} \text{ m}^2/\text{s}$. These results suggest that blanching enhances moisture diffusivity, leading to faster drying.

5. References

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