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Investigation of Drying Characteristics and Estimation of Mass Transfer Parameters of Sri Lankan Black Pepper Dried in a Batch Fluidized Bed Dryer

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Abstract

The drying of Sri Lankan black pepper was studied using a lab-scale batch fluidized bed dryer at three different temperatures of 55 °C, 65 °C, and 75 °C. Minimum fluidization velocities were determined for different bed weights. The effect of drying temperature and bed weight on the drying rate of black pepper in a fluidized bed was studied. Higher drying rates were observed at higher drying air temperatures and lower bed weights. Experimentally determined moisture ratios with time were fitted into twelve thin-layer drying models. Statistical indicators: Coefficient of determination (R^2), Root mean square error (RMSE) and reduced chi-square values ($\chi 2$) showed that the *Midilli et. al* model gives the best fit to the experimental values to describe the drying of black pepper in the fluidized bed. The absence of the constant drying rate period in drying curves shows the drying of black pepper lies totally in the falling rate period where the drying rate is controlled by moisture diffusion. Maximum drying rates observed were 1.7, 3.8, and 5.9 kg moisture/kg of dry material per minute at 55 °C, 65 °C, and 75 °C drying temperatures respectively. Results revealed drying rate constant and the effective moisture diffusivity values increase with the hot air temperature. Drying rate constants in the *Midilli et. al* model were 0.0055, 0.0109, and 0.0197 min^{-1} and the effective moisture diffusivity values were 1.071×10^{-10}, 2.032×10^{-10}, 2.844×10^{-10} m^2/s for 55 °C, 65 °C and 75 °C of drying temperatures respectively. The activation energy for moisture diffusivity was 46.518 kJ/mol.

Keywords: Black pepper, Fluidization, Drying, Diffusivity, Mass transfer, Activation energy

1. Introduction

Drying involves simultaneous heat and mass transfer which is used to improve the shelf life of many crops as a preservative method [1,2]. Other objectives of drying include the reduction of weight and volume which decreases storage and transport costs. Sun drying is the most traditional food preservation technique used since ancient time to reduce water activity by lowering the water content of food [3]. Recently it has been replaced with some modern drying techniques such as rotary drying, fluidized bed drying, convective drying, hybrid drying with infrared or microwaves, etc [4].

Hygienic and cost-effective food-preserving methods are important in the food industry to reduce crop losses and improve food quality [5]. Drying, as a post-harvesting technology, improves the quality of spice foods [2]. The method of drying depends on the nature of the feed and the particle size. Fluidized bed drying, packed bed drying, and spouted bed drying are the preferred methods investigated in recent research for granular food types. Fluidized bed drying has more advantages due to high thermal efficiency with uniform distribution of temperature in the bed, low drying time, ease of operation and maintenance of the dryer and easiness in automation of the dryer [5,6]. Fluidized beds can be operated at two modes as either batch or continuous.

The study of the drying behaviour of food materials became popular with the growing interest of many researchers over the years. As a result, various mathematical models have been developed to simulate the drying process, which can be categorized into empirical models, semi-empirical models, and fundamental models based on material and energy balances[5,7]. It has been widely used to optimize the drying process and design efficient dryers, as full-scale experimentation for drying various food products is highly expensive and time-consuming [3]. Prediction of moisture diffusion parameters and drying rates are the most essential parts of the simulation of drying processes.

Many researchers claim that the most accurate thin layer model to simulate biological material drying is *Page* model while some claim that the best model is the *Two-term* model [8]. Drying constants and the coefficients in the thin layer model equations are influenced by the properties of the material being dried and the hot air as the drying involves in transport phenomena of heat and mass [2].

Black pepper, botanically known as piper nigrum is widely used as a spice and as a part of traditional medicine. Sri Lankan black pepper is popular worldwide due to its high piperine content which lends it a distinct pungency [4]. Raw black pepper must be dried up to 12-14 % moisture dry basis before storing [9]. Drying black pepper using hot air is one of the cost-effective and common strategies that can effectively reduce the moisture content to the required level. The drying process which uses hot air, depends on factors such as air temperature, the velocity of air and relative humidity of the air, initial and final moisture contents of the material being dried [10].

The main objective of this research study is to fill the gap in understanding the drying behaviour of Sri Lankan black pepper in a fluidized bed dryer. This includes determining the most suitable thin-layer drying model for the process and calculating key mass transfer parameters, such as effective moisture diffusivity and activation energy for moisture diffusion, which have not been fully explored in previous studies. Additionally, the data obtained can be utilized in Computational Fluid Dynamics (CFD) models to further optimize and analyze the drying process.

2. Experimental Set up

Fluidized bed drying experiments were carried out in a laboratory-scale experimental setup as shown in Figure 1. The cylindrical drying chamber was 1 m high with 0.15 m internal diameter. The cylindrical section consisted of a conical bottom with a perforated plate to prevent the entering of pepper into the air inlet. The dryer unit consisted of an air blower to supply air, an air heater to heat air, and a cyclone separator for the retention of fine particles at the airflow outlet.

Inlet air velocity to the drying column was measured using a thermo-anemometer (EXTECH CFM) model 407113 with an accuracy of ±2 % while the air blower was operated by 2.2 kW motor. U tube water manometer was used to measure the pressure inside the drying column and two Pt100 thermometers were fixed at the inlet and outlet of the bed to measure the temperature to an accuracy of ±1 °C. Inlet and outlet air humidity were measured by Hygrometer (BALDR B0109TH) thermo-hydrometer to ± 5 % humidity accuracy.

3. Material and Methods

3.1. Material handling

Raw black pepper spikes consisted of a mixture of red and green coloured matured black pepper berries were provided by a local farmer from Matara in the Southern province of Sri Lanka. The maturity of the berries was around 4 months. Raw black peppers were stored in the refrigerator around 2-5 °C to prevent spoilage and taken out from the refrigerator around 1-2 hours prior to the experiment to bring them to room temperature. Raw black pepper berries were removed from their spikes manually, before feeding to the drying chamber.

3.2. Methodology

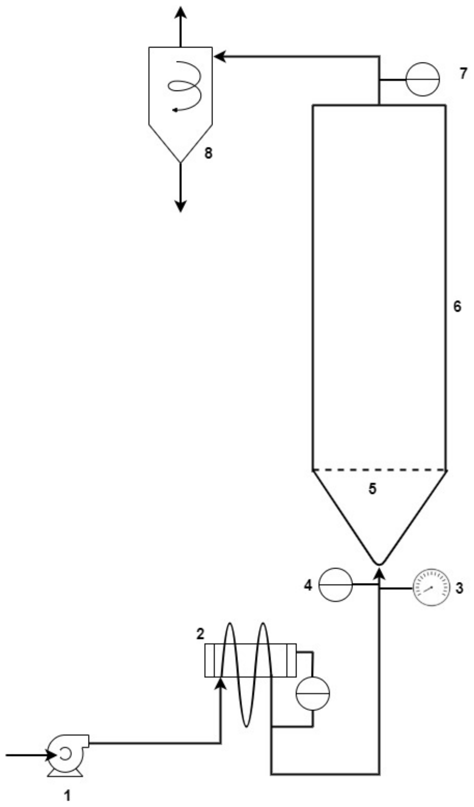
Preliminary experiments were conducted using dried black pepper to determine the minimum fluidization velocity at room temperature. Room temperature was chosen for the preliminary experiments as it provides a controlled, reproducible baseline for determining the minimum fluidization velocity [11]. After determining the minimum fluidization velocity at room temperature, further investigations can explore the effect of different temperatures to optimize the drying process for black pepper.

Ambient Air was passed through the packed bed of black pepper and the pressure drop across the bed was measured. The air velocity was gradually increased, and the pressure drop values were recorded for a range of air velocities until the bed reached the fluidization state. Similarly, the air velocity, and pressure drop values were recorded for decreasing air velocity [12].

Drying experiments were carried out to study drying behavior and the drying time of black pepper. Drying time is defined as the time taken to dry black pepper from its initial moisture content to the desired final moisture content. First, a known weight of raw black pepper at room temperature, was fed into the drying chamber. Air at the desired temperature was passed through the bed. Samples were collected every 10 minutes to measure the moisture content of the black pepper particles at that time.

Bed pressure drops, and bed height were measured during the experiments. Drying experiments were carried out with varying drying air temperatures as 55 °C, 65 °C, and 75 °C at respective minimum fluidization velocities of the selected bed weights. Drying experiments were conducted until the black pepper particles reached around 12% moisture content. 12% moisture content was selected since it is within the optimal range for preserving black pepper.

The initial moisture content of raw pepper was around 325 % dry basis and it was determined according to the oven-drying method by drying a known weight of raw pepper in an electric oven (A Lab Tech LDO-060E) at 105 °C for 24 hours [13]. Drying experiments were carried out for three different bed weights; 0.75 kg, 1 kg, and 1.25 kg at a hot air temperature of 65 °C to determine the effect of bed height on drying of black pepper.



1- Air blower
2- Air heater with temperature control system
3- Thermo anemometer
4,7- Temperature indicators
5- Perforated plate
6- Fluidized bed
8- Cyclone separator

Fig 1. Fluidized bed drying experimental set-up.

3.3. Mathematical modelling of drying curves

Experimental data were fitted to thin-layer drying models in Table 1 to obtain drying curves.

Where;

k, k_1, h and g in the model equations in Table 1 are drying constants and a, b, c and n are the drying coefficients.

The moisture content of the material on dry basis is described as the mass of water available in the unit mas of material. Then the percentage of moisture content on dry basis, M is given by Equation 1.

$$\mathrm{M} = 100(\mathrm{W_b} - \mathrm{W_d})/\mathrm{W_d} \qquad (1)$$

Where W_b and W_d are the weight of the wet material and the weight of the dry material respectively.

The moisture ratio (MR) of drying of raw black pepper during thin layer drying can be expressed using Equation 2.

$$\mathrm{MR} = (\mathrm{M_t} - \mathrm{M_e})/(\mathrm{M_o} - \mathrm{M_e}) \qquad (2)$$

Where,
M_e - equilibrium moisture content (kg/kg dry basis)
M_t - moisture content at time t (kg/kg dry basis)
M_o - Initial moisture content (kg/kg dry basis)

The equilibrium moisture content value is relatively small compared to M_t and M_o. The equilibrium moisture content (M_e) is assumed to have a negligible effect on the moisture ratio in many drying models because it represents moisture that is not easily removed during drying. Once the material reaches equilibrium, moisture loss slows down significantly, and M_e has little impact on the overall moisture ratio. Therefore, moisture ratio can be expressed as in Equation 3.

$$\mathrm{MR} = \mathrm{M_t}/\mathrm{M_o} \qquad (3)$$

3.3.1 Error analysis

The validity of the model-predicted values was analysed and compared with experimental data through statistical parameters such as correlation coefficient (R^2), the reduced chi-square (χ^2), and the root mean square error (RMSE). The model is accurate when higher the R^2 and lower the χ^2 and RMSE [14]. Statistical parameters are defined using Equations 4, 5, and 6.

$$\mathrm{R}^2 = 1 - \left\{\left(\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2\right) / \left(\sum_{i=1}^{N}\left(\mathrm{MR_{exp,i}} - \mathrm{MR_{exp,mean}}\right)^2\right)\right\} \qquad (4)$$

$$\chi^2 = \sum_{i=1}^{N}(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}})^2/(\mathrm{N} - \mathrm{z}) \qquad (5)$$

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{N}(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}})^2/\mathrm{N}} \qquad (6)$$

Where;
N - number of observations
z - number of constants in the drying model or number of parameters
$MR_{pre,i}$ - i^{th} predicted moisture ratio
$MR_{exp,i}$ - i^{th} experimental moisture ratio

4. Results and Discussion

4.1 Determination of minimum fluidization velocity

The minimum fluidization velocity of black pepper at selected bed weights was determined using the plot of pressure drop across the bed against the superficial air velocity. Pressure drop across the bed was calculated by subtracting the empty bed pressure drop from the pressure drop between the inlet and outlet of the fluidized bed with particles. Empty bed pressure drop refers to the pressure drop that occurred mainly due to perforated plate at respective air velocities.

Table 1

Thin layer drying models.

Model number	Model name	Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified page	$MR = \exp(-kt)^n$
4	Henderson and Pebis	$MR = a\exp(-kt)$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Two term	$MR = a\exp(-kt) + b\exp(k_1 t)$
7	Wang and Singh	$MR = 1 + at + bt^2$
8	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(kbt)$
9	Verma et. al	$MR = a\exp(-kt) + (1-a)\exp(gt)$
10	Modified Henderson and Pebis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
11	Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$
12	Midilli et. al	$MR = a\exp(-kt^n) + bt$

Pressure drops across the bed against the air velocity are plotted using logarithmic coordinates as shown in Figure 2. When the air velocity was increased, the pressure drop of the bed gradually increased up to a point where expansion of the bed started to take place. With the increment of airflow velocity, the pressure drop reached a maximum, subsequently the pressure drop became independent from the air flow and remained constant in its operating pressure drop. During the airflow descending process, the pressure drops across the bed initially remained constant at its operating pressure drop since particles inside the bed are in a fluidization state. Further reduction of air flow caused the bed to contract until it achieved the fixed bed state at point E. The air velocity corresponding to the point E is identified as the minimum fluidization velocity [15].

The minimum fluidization velocities were determined with respect to the bed weights and listed in Table 2. Results show that minimum fluidization velocity increases with increasing the bed weight. Theoretically, the minimum fluidization velocity is independent of the bed weight, however many researchers have investigated the effect of bed weight on fluidization and obtained similar results as observed in this study [11,16,17].

4.2 Effect of air temperature on drying of raw pepper

Drying experiments were carried out at three different hot air temperatures; 55 °C, 65 °C and 75 °C for raw black pepper at initial moisture content (M_{io}) of 325 % dry basis. During the drying process, the moisture content of black pepper was determined at 10 minutes time intervals. To obtain precise data for modeling the drying process, 10-minute intervals were selected Figure 3 shows the variation of moisture content of black pepper against drying time for three different drying temperatures of 0.75 kg of initial bed weight. Figure 3 shows that the drying time reduces with increasing air temperature which agrees with previous drying studies done on various agricultural products [5,18].

Gradients of the curves in Figure 3 were obtained by MATLAB to plot the rate of change of moisture content against the moisture content and shown in Figure 4. The results show that the drying of black pepper was achieved at a falling rate period. Similar drying behaviour at a falling rate period has been observed by other researchers for black pepper and many agricultural products such as apples and paddy [5].

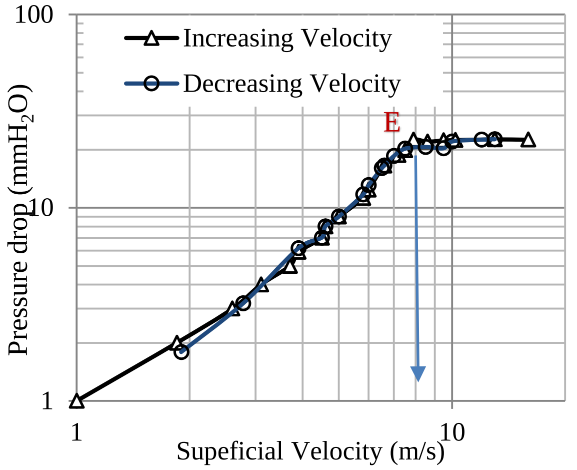


Fig 2. Log-Log plot of Pressure drop (mm H_2O) vs. superficial velocity (m/s) for 0.75 kg of bed weight of black pepper at ambient temperature.

Table 2

Minimum fluidization velocity of black pepper with respect to bed weight**.**

Bed weight (kg)	**Minimum fluidization velocity, U_{mf} (m/s)**
0.75	8.0
1.00	9.5
1.25	11.0

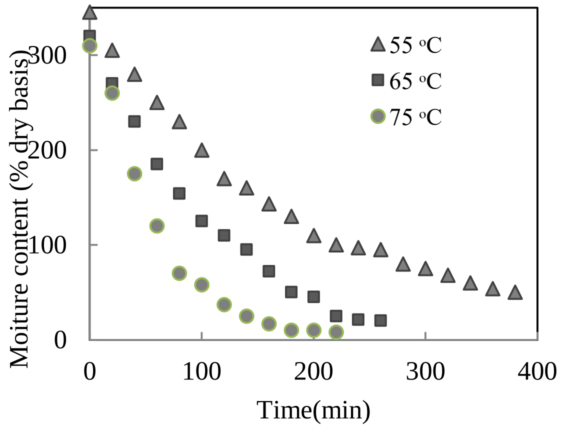


Fig 3. Moisture content (% dry basis) vs drying time of black pepper when dried in a fluidized bed dryer at different drying temperatures; Experimental conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

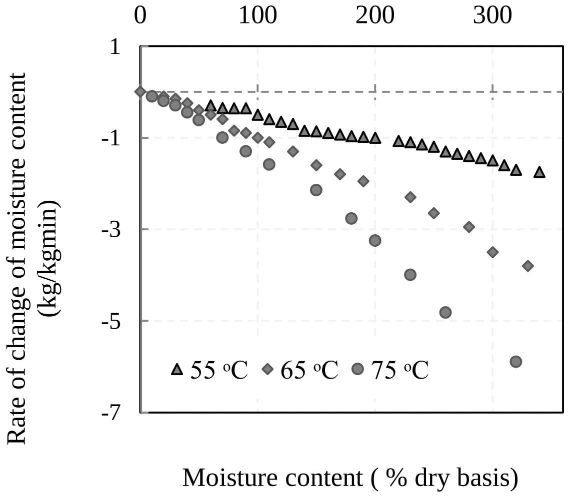


Fig 4. Rate of change of moisture content (dM/dt) vs moisture content (% dry basis) of black pepper when dried in a fluidized bed dryer at different drying temperatures; Experiment conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

Higher drying rates were observed at high air temperatures due to high moisture diffusivity, however, it is important to obtain the optimum drying temperature which preserves the product quality. Jayatunga and Amarasinghe have found that 65°C is the best temperature for black pepper drying in the spouted bed dryer [10].

4.3 Effect of bed weight on drying of raw pepper

Figures 5 and 6 show the effect of bed weight on drying kinetics. According to Figure 5, drying time was increased with the increase of bed weights. For 0.75 kg of bed weight, the time taken to reach moisture content to 15 % dry basis was 240 minutes while more than 240 minutes were required for 1.25 kg weighted bed to reach 15% moisture content. The rate of change of moisture content of black pepper was lower for heavy beds than light beds for a specific moisture content which proves that heavy beds need more time to dry than light beds. This result agrees with the findings of a previous research study for spouted bed drying of black pepper [19]. According to Figure 6, the drying rate was increased with decreasing bed weights, which was the same as the results observed in many investigations [21,22].

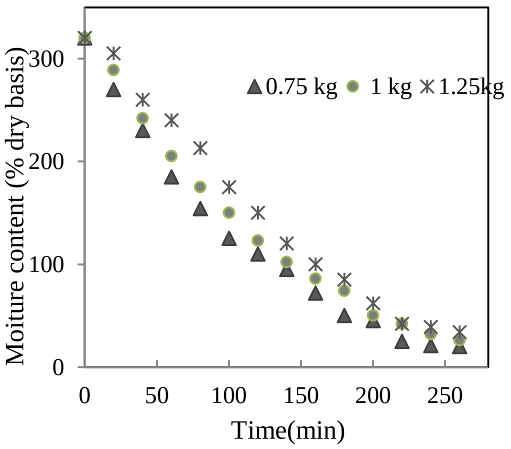


Fig 5. Moisture content (% dry basis) versus time at three different bed weights of black pepper when dried in fluidized bed dryer; Experiment conditions: M_{io} = 325 %, T = 65 0C, U_{mf} = 8 m/s, 9.5 m/s and 11 m/s for bed weights 0.75 kg, 1 kg and 1.25 kg respectively.

4.4 Modelling of drying curves

Drying experiments were carried out for black pepper with an initial moisture content of around 325 % dry basis and continued for around 3 hours until they achieved a moisture content of around 15 % dry basis. Experimentally determined moisture content values were converted to moisture ratio values and plotted against time as shown in Figure 7. The moisture ratio gradually decreases with time. Furthermore, it can be described as, the higher the hot air temperature, the higher the driving force for heat transfer and the rate of heat transfer, and hence higher the rate of moisture removal from the material.

Calculated moisture ratio values were fitted to twelve thin-layer drying models shown in Table 1. Excel solver was used to determine the model parameters which were summarized in Table 3. Results show that all twelve models were given good fits.

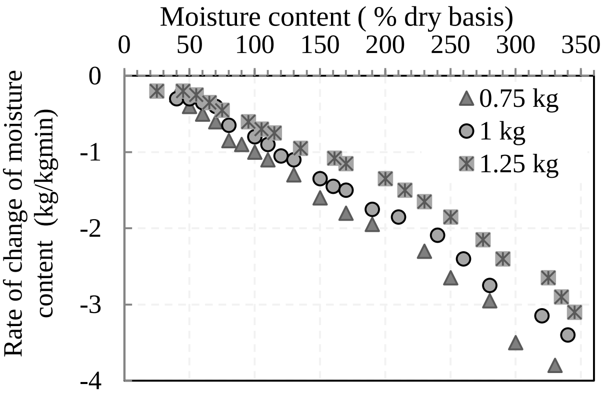


Fig 6. Rate of change of moisture content (dM/dt) versus moisture content (% dry basis) at three different bed weights of black pepper when dried in fluidized bed dryer; Experiment conditions: M_{io} = 325 %, T = 65 ºC, U_{mf} = 8 m/s, 9.5 m/s and 11 m/s for bed weights 0.75 kg, 1 kg and 1.25 kg respectively

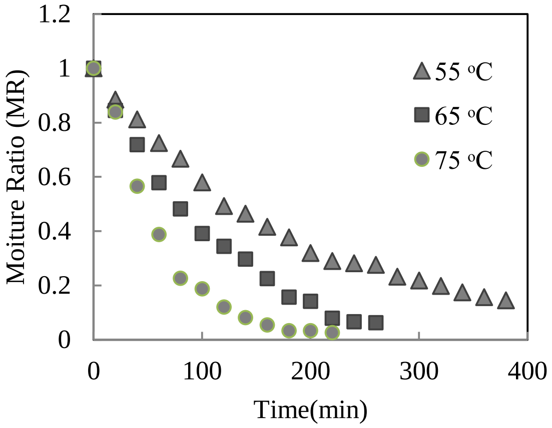


Fig 7. Moisture ratio versus time at different temperatures for black pepper when dried in fluidized bed dryer at different drying temperatures; Experiment conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

The thin layer drying model which had the highest R^2 (close to one) and lowest χ^2 and RMSE values was considered as the best model to explain the drying behaviour. R^2 values ranged between 0.9905 and 0.9995. The highest R^2 was obtained from *Midilli et.al*, *Page*, Modified page, Logarithmic, Verma et. al and Modified *Henderson and Pabi's* models while *Wang and Singh* model shows a significant deviation at high temperatures. Two term and Newton models show more stability at high temperatures than at low temperatures.

Data fitting to 12 thin layer drying models at three different temperatures 55 °C, 65 °C and 75 °C, show that, model suggested by *Midilli et.al* has given best combination of R^2, reduced χ^2 and RMSE. Therefore, *Midilli et. al* model was selected as the best model to explain the drying behaviour of Sri Lankan black pepper under fluidizing conditions. Experimental and model predicted results are compared in Figure 8 and showings that good relationship between the experimental moisture ratio with modelled moisture ratio from *Midilli et al* model of black pepper in a fluidized bed dryer at different drying temperatures.

According to the model fitted results in Table 3, drying rate constants (k) at 55 °C ranged from 0.003-0.081 min^{-1}. It was between 0.007 and 1.106 min^{-1} at 65 °C and finally drying rate constant can be observed ranging between 0.01 and 1.85 min^{-1} at 75 °C. These value ranges agree with the value ranges observed from previous studies by Amarasinghe et. al and Darvish et. al [3, 22] for their studies on the effect of microwave power on drying. 'n' value observed for *Page* and *Modified Page* model are almost equal to 1 and that implies both models behave same, and this can be compared with the *Newton* model which has no 'n' term and *Henderson and Pebis model* where a term is nearly equal to one. So, the plots given by these models showed a similar behavior as *Midilli et. al* model which gave 'n' term nearly equal to 1 with a very low value for the term 'b'. According to the results observed, the model proposed by *Midilli et. al* has given a similar trend as the above-mentioned models with more accuracy.

4.5 Effective diffusion coefficient

Moisture distribution within solid particles can be described using Fick's diffusion equation. To understand the diffusion of moisture from a solid surface, this model is used in the present study with the following assumptions: (i) all particles are identical and spherical in shape (ii) moisture diffuses from the particle core to the outer surface and then evaporates (iii) drying conditions are uniform inside the fluidized bed [14,19,4].

Fick's diffusion equation for spherical particles is shown in Equation 7 [5, 23].

$$\delta M/\delta t = D_{eff}[\delta M/\delta r^2 - 2\delta M/r\delta r] \qquad (7)$$

An analytical solution was obtained for Equation 7 under initial and boundary conditions to obtain Equation 8 [24 , 25].

$$MR = 6/\pi^2 \sum_{n-1}^{\infty}[1/n^2 \exp\left(-n^2\pi^2 D_{eff} t/r_s^2\right)] \qquad (8)$$

where,
D_{eff} – effective moisture diffusivity (m^2/s)
n = 1,2, 3…. number of terms taken into consideration.
r – particle radius (m),
t – time (s).
Equation 8 can be simplified to Equation 9 by considering one term of the series.

$$\ln(MR) = \ln\left(6/\pi^2\right) - \pi^2 D_{eff} t/r^2 \qquad (9)$$

Drying curves of moisture ratio against time at different temperatures show that black pepper drying was predominant at the falling rate period, where mass diffusion was the process involved in moisture removal.

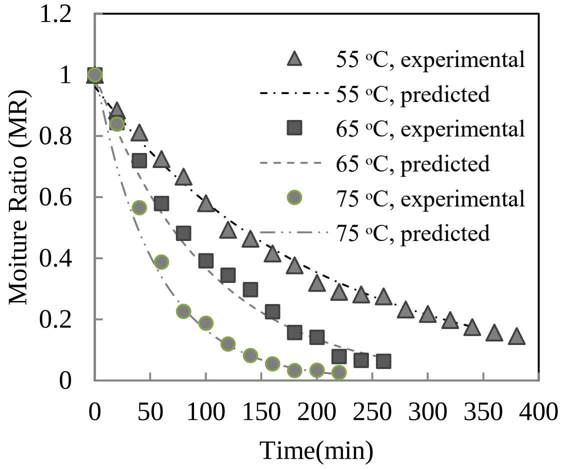


Fig 8. Experimental moisture ratio vs time and predicted moisture ratio by *Midilli et. al* model vs time for black pepper dried in a fluidized bed dryer at different drying temperatures; Experiment conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

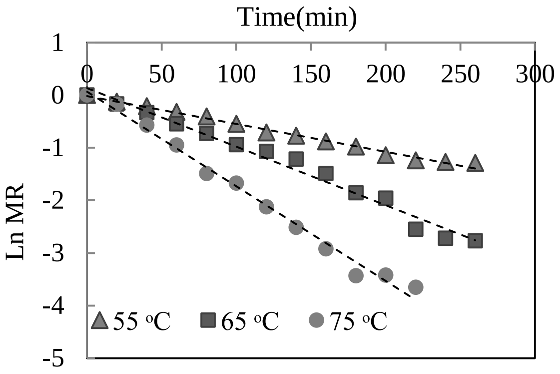


Fig 9. Ln (MR) vs time at different temperatures for black pepper dried in a fluidized bed dryer at different drying temperatures.; Experiment conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

D_{eff} was determined from the gradient of ln (MR) versus time plots shown in Figure 9. Fick's law solution gave the value for D_{eff} at temperatures 55 °C, 65 °C and 75 °C respectively as indicated in Table 4.

The effective moisture diffusivity (D_{eff}) is increased with increasing drying temperature. Previous research studies carried out at a temperature range of 35-120 °C for agricultural products resulted in D_{eff} within the range of 10^{-11}-10^{-9} m^2/s [22, 23]. This study shows that for black pepper D_{eff} values fall within the same range. Amarasinghe et. al observed D_{eff} within the range 2.43×10^{-10}- 1.42×10^{-9} m^2/s for pepper drying at microwave dryer while Jayatunga observed 8.11×10^{-11} - 2.03×10^{-10} m^2/s range for black pepper drying in spouted bed at same temperature range used in their study [19, 22]. Fluidized beds can cause rapid heat and mass transfer between the product and heating medium which results in higher D_{eff} values and similar results have been observed for green peas, banana, and pumpkin drying [5]. D_{eff} values resulting from this study are acceptable as they are within the same ranges observed by various research studies carried out for agricultural products.

4.5.1 Activation energy for moisture diffusion

Temperature and effective moisture diffusivity relationship can be given by Arrhenius type equation as given in Equation 10 [27].

$$D_{eff} = D_{0eff} \exp[-E/R(T + 273.15)] \qquad (10)$$

Equation (10) can be simplified to its linear logarithmic form by substituting T_{abs} =T+273.15 as in Equation (11).

$$\ln(D_{eff}) = \ln(D_{0eff}) - (E/RT_{abs}) \qquad (11)$$

Where,
D_{0eff} -pre-exponential factor of the Arrhenius constant (m^2/s)
E - activation energy for moisture diffusion (kJ/mol)
R - universal gas constant (kJ/mol K)
T_{abs} - is the absolute temperature (K)

Table 3 Thin layer drying models and model parameter

Model	Temperature ^{0}C	R^2	RMSE	χ^2	Model Parameters
Newton	55	0.9970	0.0159	0.000264	k= 0.0043
	65	0.9986	0.0144	0.000217	k= 0.0098
	75	0.9985	0.0159	0.000263	k= 0.0161
Page	55	0.9973	0.0146	0.000231	k= 0.0033; n=1.0519
	65	0.9986	0.0142	0.000219	k= 0.0090; n=1.0160
	75	0.9985	0.0159	0.000274	k= 0.0158; n=1.0040
Modified page	55	0.9973	0.0146	0.000231	k= 0.0044; n=1.0519
	65	0.9986	0.0142	0.000219	k= 0.0097; n=1.0160
	75	0.9985	0.0159	0.000274	k= 0.0161; n=1.0040
Henderson and Pabis	55	0.9969	0.0157	0.000267	k= 0.0044; a=1.0066
	65	0.9986	0.0144	0.000226	k= 0.0098; a=1.0018
	75	0.9987	0.0155	0.000260	k= 0.0159; a= 0.9874
Logarithmic	55	0.9978	0.0131	0.000195	k= 0.0030; a=1.2695; c=-0.2784
	65	0.9987	0.0135	0.000206	k= 0.0091; a=1.0128; c= -0.0283
	75	0.9993	0.0104	0.000122	k= 0.0144; a=1.0034; c= -0.0310
Two term	55	0.9969	0.0156	0.000289	k= 0.0044; a= 1.0086; k_1= 7.2340; b = -0.0087
	65	0.9986	0.0139	0.000230	k= 0.0113; a= 1.9237; k_1= 0.0134; b = -0.9302
	75	0.9988	0.0151	0.000271	k= 0.0157; a= 0.9766; k_1= 1.3916; b = -0.0233
Wang and Singh	55	0.9977	0.0140	0.000214	a= -0.0038; b = 4.6294
	65	0.9965	0.0257	0.000719	a = -0.0079; b = 1.7766
	75	0.9914	0.0512	0.002852	a= -0.0108; b=2.9186
Approximation of diffusion	55	0.9970	0.0163	0.000301	k= 0.0812; a= 0.0044; b= 0.0536
	65	0.9986	0.0144	0.000236	k= 1.1062; a=-0.0019; b= 0.0088
	75	0.9987	0.0152	0.000261	k= 0.8679; a= 0.0158; b= 0.0182
Verma et al.	55	0.9976	0.0139	0.000221	k= 0.0069; a= -2.9914; g= 0.0061
	65	0.9986	0.0144	0.000236	k= 1.1057; a= -0.0028; g= 0.0098
	75	0.9988	0.0151	0.000258	k= 1.8534; a= 0.0233; g= 0.0157
Modified Henderson and Pabis	55	0.9978	0.0133	0.000232	k= 0.0061; a= 2.1009; c= -1.1203; b= 0.0193; g= 7.2340; h= 0.0084
	65	0.9987	0.0134	0.000237	k= 0.0140; a= 4.9062; c= 3.2124; b= -7.1177; g= 0.0176; h= 0.0207
	75	0.9994	0.0097	0.000125	k = 0.0217; a= 5.8623; c= -4.9544; b= 0.0920; g=1.3694; h= 0.0237
Two-term exponential	55	0.9975	0.0139	0.000212	k= 0.0055; a=1.5252
	65	0.9985	0.0144	0.000226	k= 0.0098; a= 0.9862
	75	0.9988	0.0151	0.000247	k= 0.6787; a= 0.0232
Midilli et. al	55	0.9979	0.0127	0.000175	k= 0.0055; n=0.8730; a=1.0020; b= -0.0007
	65	0.9988	0.0132	0.000190	k= 0.0109; n= 0.9652; a=1.0006; b= -0.0001
	75	0.9995	0.0089	0.000086	k=0.0197; n= 0.9362; a= 0.9902; b= -0.0001

Natural logarithm values of effective diffusivity values were plotted against the reciprocal of absolute temperature as in Figure 10 and activation energy (E) was calculated from the slope and pre-exponential factor (D_{0eff}) was derived from the interception of plot in Figure 10 and stated in Table 4. When comparing previous research studies done by *Jayathunga et. al* for black pepper drying in spouted bed, values for D_{0eff} and E were 1.25×10^{-4} m^2/s and 38.59 kJ/mol respectively [20]. Perea-Flores has derived D_{0eff} and E as 1.12×10^{-3} m^2/s and 41.41 kJ/mol from their studies on castor oil seeds drying in a fluidized bed dryer [27]. Therefore, according to this comparison, it can be concluded that D_{0eff} and activation energy values derived from this study are within acceptable range.

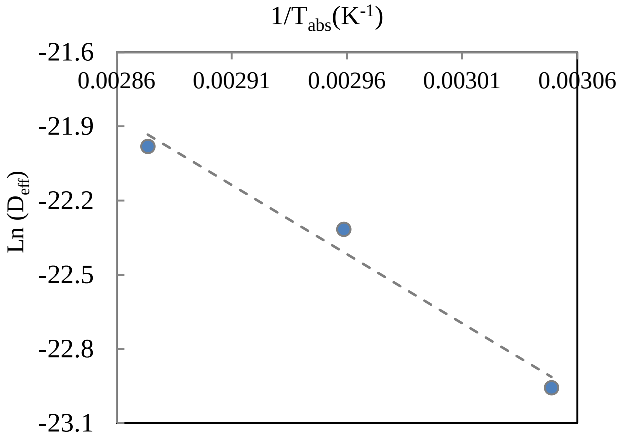


Fig 10. Ln (D_{eff}) vs $1/T_{abs}$ for black pepper dried in a fluidized bed dryer. Experiment conditions: U_{mf} = 8 m/s, M_{io} = 325 %, bed weight =0.75 kg

Table 4

Drying process and moisture transfer parameters at different temperatures

Temperature (°C)	**D_{eff} (m^2/s)**	**D_{0eff} (m^2/s)**	**E kJ/mol**
55	$1.071x10^{-10}$	2.844×10^{-3}	46.518
65	$2.032\ x10^{-10}$		
75	$2.844\ x10^{-10}$		

This study contributes to the advancement of efficient drying techniques for Sri Lankan black pepper by utilizing a fluidized bed dryer, which enhances product quality and processing efficiency. The analysis of thin-layer drying models aids in forecasting drying time, providing a scientific basis for process optimization. Further mathematical modeling, correlating key operating parameters such as air temperature, velocity, and bed weight with moisture content over time, will enable operators to accurately predict drying duration. This research lays the foundation for improving drying control strategies and enhancing the overall efficiency of black pepper drying processes.

5. Conclusion

The fluidization behaviour of black pepper showed that minimum fluidizing velocity increases with bed weight. Drying experiments showed that the fluidized bed drying of pepper lies in the falling rate of drying. Drying time and drying rate strongly depend on drying air temperature and bed weight. *Midili et. al* model was the best-fitted thin layer model for the experimental data. Results show that an increase in temperature causes an increase in drying rate constant in the models owing to an increase in the efficiency of the moisture transfer from the black pepper particle surface.

The effective diffusion coefficient and activation energy for moisture diffusion were calculated within the temperature range of 55-75 °C. Effective moisture diffusivity values were in the range of 1.071×10^{-10} - 2.844×10^{-10} m^2/s and the activation energy for moisture diffusion was 46.518 kJ/mol. The drying rate constants and the effective diffusivity values were in the same order of magnitude as the values obtained by other workers for similar products.

For future work, the authors plan to conduct Computational Fluid Dynamics (CFD) modeling to further analyze the drying process. The data obtained from the *Midilli et al.* model and the effective diffusivity in this study will be utilized to enhance the understanding and optimization of fluidized bed drying. Additionally, future research will focus on determining the optimum drying temperature to preserve quality and evaluating the properties of black pepper dried in a fluidized bed. The aim is to correlate the *Midilli et al.* model with operational parameters such as drying temperature and bed weight, which will provide valuable insights into the dynamic relationship between drying conditions and product quality.

Conflicts of Interest

The authors have no conflicts of interest.

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