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Drying kinetics and mathematical modeling of spent coffee grounds drying using the spouted bed technique

Poomjai Sa-adchom*

Department of Mechanical Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna, Tak 63000, Thailand

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Abstract

The objective of this study was to investigate the drying kinetics of spent coffee grounds (SCGs) using spouted bed drying, with inlet air temperatures of 60, 75, and 90°C, and SCGs masses of 0.5 and 1 kg. The study also examined the specific energy consumption (SEC) and the color of the dried SCGs. To estimate the moisture ratio as a function of drying time, twelve mathematical drying models were used to fit the experimental data. In the experiments, the SCGs with an initial moisture content of approximately 52% w.b. were dried using the spouted bed technique until the final moisture content was less than 7% w.b. The experimental results found that as the inlet air temperature was increased, the moisture content of the SCGs and the SEC decreased. An increase in the mass of the SCGs resulted in a decrease in its moisture content but an increase in the SEC. Additionally, an increase in the inlet air temperature and the mass of the SCGs caused a decrease in the *L** value but an increase in the *a** and *b** values. Regression analysis revealed that, among the twelve models tested, the Midilli et al. model was the most suitable for describing the drying behavior of SCGs during spouted bed drying. The average values of coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2) of the Midilli et al. model under the spouted bed drying were 0.999602, 0.000468 and 0.00000201 for a mass of SCGs at 0.5 kg, and 0.999553, 0.000961 and 0.00000087 for a mass of SCGs at 1 kg, respectively.

Keywords: Drying kinetics, Mathematical modeling, Spent coffee grounds drying, Spouted bed technique

1. Introduction

Coffee is a widely consumed beverage worldwide, leading to the production of large quantities of spent coffee grounds (SCGs) on a daily basis [1]. Despite their high moisture content, SCGs have the potential to be a valuable and adaptable resource that can serve multiple purposes. Drying is a critical process in converting SCGs into valuable products such as biofuels, animal feed, and fertilizers [2]. This process prolongs the shelf life of SCGs, curbs microbial growth [3], and minimizes transportation costs by reducing the material's weight and volume [4].

Sun drying is a commonly used method for drying SCGs. Sun drying is a natural and inexpensive method that involves spreading the material on a flat surface and exposing it to sunlight. A research study conducted by Kang et al. [5] suggested that sun drying could reduce the moisture level of SCGs (11 mm thickness) from 65% w.b. to 15% w.b. in six days. However, sun drying is dependent on weather conditions and can be ineffective in humid or rainy conditions. Another method used to dry SCGs is convective drying, which involves exposing the material to hot air in a batch or continuous process. According to a study by Gómez-de la Cruz et al. [6], convective drying decreased the moisture content of SCGs (20 mm thickness) from 61.1% w.b. to 8.5% w.b. within 3 h, using a temperature of 100°C. However, convective drying can be energy-intensive and may cause thermal degradation and loss of volatile compounds.

Spouted bed drying is a widely used technique for drying various materials, including sawdust [7], shiitake mushrooms [8], tomato pomace [9], green bell pepper [10], and sorghum [11]. This technique involves using gas to fluidize solid particles in a bed, creating a spout or column of particles that rise to the top of the bed. As the gas flows through the bed, it causes the particles to move and mix, resulting in efficient heat and mass transfer. Spouted bed drying is also a technique employed in industrial systems that show promising economic viability. By utilizing a high-velocity gas stream to suspend and circulate solid particles, it enables rapid and efficient drying of various materials. This technique offers several economic advantages, such as reduced drying time, lower energy consumption, and increased production capacity [12, 13], making it a financially viable choice for industrial drying applications.

Although many studies have been conducted on drying using the spouted bed technique, no research has been conducted on drying SCGs using this technique. In this study, experiments were performed to investigate the effects of inlet air temperature (60, 75, and 90°C) and SCGs mass (0.5 and 1 kg) on drying kinetics, specific energy consumption, and the color of the dried SCGs. Additionally, twelve mathematical drying models were used to analyze drying kinetics and identify a suitable mathematical model for describing the drying behavior of SCGs. It should be noted that by utilizing multiple mathematical models, this study aimed to assess their applicability and compare their performance in fitting the experimental data. This approach allowed for a comprehensive analysis of the drying process and ensured a robust understanding of the underlying mechanisms. Additionally, it provided insights into the model's accuracy, sensitivity to input parameters, and suitability for further applications.

*Corresponding author.
Email address: poomjai.s@gmail.com
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2. Materials and methods

2.1 Experimental set-up

Figure 1 shows a schematic diagram of the closed-loop spouted bed dryer used in this study. It consisted of a forward-curved blade centrifugal fan (No.1) driven by a 0.4 kW electric motor (Chuan-fan, model CX-75SA, China), a 6 kW band heater (No.2), a PID temperature controller (Toho, model TTM-004-P-A, Japan) (No.3), a thermocouple type K (No.4), a 3-inch diameter throttle valve (No.5), a product entrance measuring 10x15 cm in height and width (No.6), a product exit measuring 6x4.5 cm in height and width (No.7), a spouted bed dryer column made of stainless steel with a diameter of 20 cm, a height of 125 cm, and a cone angle of 20° (No.8), an inlet air nozzle measuring 10 cm in diameter (No.9), a dust trap cyclone (No.10), a valve for the dust trap cyclone (No.11), an electric meter (Dai-ichi, model DD28, Thailand) (No.12), and a pipe system. In addition, a multifunction meter (Lutron, model PAM-9212SD, Taiwan) was connected to a pitot tube to determine the air velocity.

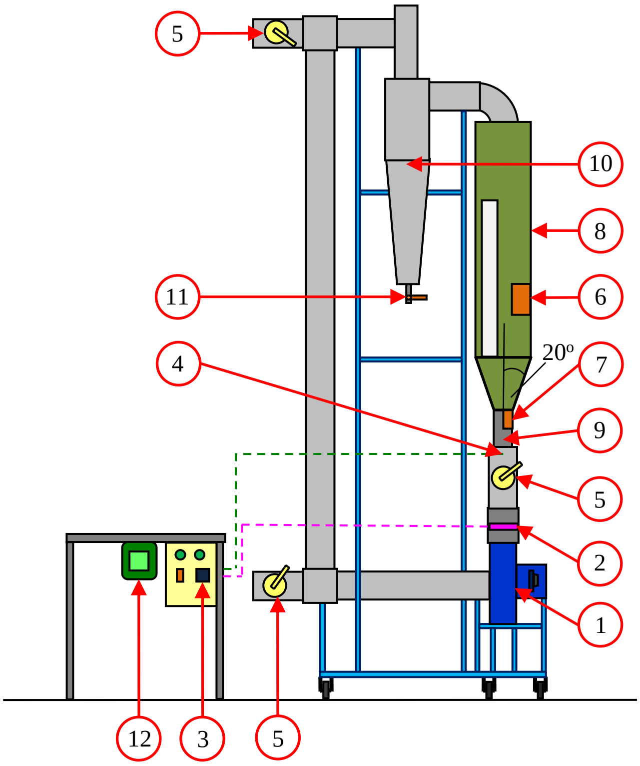


Figure 1 A schematic diagram of the closed-loop spouted bed dryer: (1) centrifugal fan, (2) band heater, (3) PID temperature controller, (4) thermocouple, (5) throttle valve, (6) product entrance, (7) product exit, (8) spouted bed dryer column, (9) inlet air nozzle, (10) dust trap cyclone, (11) valve for the dust trap cyclone, and (12) electric meter

This spouted bed dryer operated by using a centrifugal fan to force air through a band heater, producing hot air that was introduced into the spouted bed dryer column. The hot air was used to dry the material and was then directed to a dust trap cyclone. A portion of the hot air, approximately 20%, was released through a throttle valve to remove moisture from the system. The remaining 80% of the hot air was mixed with fresh incoming air and circulated back through the heating element for the next drying cycle. To minimize heat loss to the surroundings, the spouted bed dryer column and air ducts were insulated with polyethylene.

2.2 Sample preparation

Arabica spent coffee grounds (SCGs), not more than 2 days old, were purchased from a fresh coffee shop in Mueang District, Tak Province, Thailand. The SCGs were then stored in a plastic box in preparation for drying.

2.3. Methods

Spent coffee grounds (SCGs) with an initial moisture content of approximately 52% w.b., with a mass of 0.5 and 1 kg, were dried using the spouted bed technique at temperatures of 60, 75, and 90°C until the final moisture content was less than 7% w.b. [14]. To avoid exceeding the terminal fluidization velocity in the dryer, it is recommended to control the air velocity at a rate of approximately 1.5-10 times the minimum fluidization velocity [15]. In this study, the inlet air velocity in the spouted bed dryer column was set at 4.5 m/s, which corresponds to 2.81 and 1.55 times the minimum fluidization velocity for SCGs with masses of 0.5 and 1 kg, respectively.

The moisture content of SCG samples was measured using a moisture analyzer (Ohaus model MB23, Germany) with a readability of 0.01g at various drying times (5, 10, 15, 20, ..., 110 min). The experiments were conducted in triplicate, and the average values with their standard deviations were plotted.

2.4 Specific energy consumption

The specific energy consumption (SEC) for spouted bed drying was defined as the amount of energy required to remove a unit mass of water from a material during the spouted bed drying process. This parameter was crucial for evaluating the energy efficiency of spouted bed dryers and optimizing their operation. SEC could be calculated using Eq. (1) [16], as follows:

$$\mathrm{SEC} = \frac{3.6\mathrm{Q}}{\mathrm{m_W}} \tag{1}$$

where SEC was the specific energy consumption (MJ/kg_{water}), Q was the energy supplied in the drying process (kWh), m_w was the mass of water evaporated during drying (kg_{water}), and 3.6 was the conversion factor from kWh to MJ.

2.5 Color

A colorimeter (Konica Minolta, model CR-10 Plus, Japan) was used to measure the surface colors of both fresh and dried spent coffee grounds (SCGs). The illuminant used in our study was a standardized D65 light source, and the observer angle was set at 10°. The aperture size utilized in our measurements was 8 mm with a closed cone configuration. Additionally, the mass of the sample used in the color measurement was approximately 150 g. The colorimeter was set to the L^*, a^*, b^* system, where the L^* value indicates the degree of lightness, the a^* value indicates the presence of redness (+) or greenness (-), and the b^* value indicates the presence of yellowness (+) or blueness (-). The colorimeter was calibrated using a standard white tile before each color measurement was taken. The color difference (ΔE) of the dried product was calculated from the obtained data using the following equation [17]:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \tag{2}$$

where $\Delta L = L^* - L_0^*$, $\Delta a = a^* - a_0^*$, and $\Delta b = b^* - b_0^*$. L_0^*, a_0^*, and b_0^* were color parameters used to indicate the color of raw SCGs samples. The reference material was the raw SCGs samples, and a greater color change from this reference material was represented by a higher value of ΔE. Ten samples were collected from each experiment and measured on the surface. The mean color measurement value for each experiment was reported. It should be note that the mass of the sample used in our experiment was 150 g.

2.6 Mathematical modeling of drying

The experimental drying data was used to calculate the moisture ratio (MR) using Eq. (3) as follows:

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \tag{3}$$

where M_t was the moisture content at any time of drying (kg_{water}/kg_{solid}), M_0 was the initial moisture content (kg_{water}/kg_{solid}), and M_e was equilibrium moisture content (kg_{water}/kg_{solid}). Due to the fact that the samples did not undergo uniform relative humidity and temperature conditions while being dried, the M_e values were significantly lower than M_t or M_0. As a result, the moisture ratio could be expressed as M_t/M_0 [18].

To identify the most suitable model for describing the drying process of spent coffee grounds, twelve mathematical drying models (listed in Table 1) were tested. The performance of each model was evaluated using three statistical measures: coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2), as calculated by Eq. (4)-(6) [19], as follows:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N} (\overline{MR}_{pre,i} - MR_{exp,i})^2} \right] \tag{4}$$

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

$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{N - z} \tag{6}$$

where N was the number of observations, z was the number of constants, $MR_{exp,i}$ and $MR_{pre,i}$ were experimental and predicted moisture ratio, respectively. The drying kinetics model that was considered the best had the highest average R^2 value and the lowest average values of both χ^2 and RMSE.

Table 1 Mathematical models tested for spouted bed drying of spent coffee grounds in this study

Model name	Expression of moisture ratio (MR)	Reference
Newton	MR = exp(-kt)	[20]
Page	MR = exp(-kt^n)	[21]
Modified Page	MR = exp[-$(kt)^n$]	[22]
Henderson and Pabis	MR = a exp(-kt)	[23]
Wang and Singh	MR = 1 + at + bt^2	[24]
Logarithmic	MR = a exp(-kt) + c	[25]
Two-term	MR = a exp(-kt) + b exp(-k_1t)	[26]
Weibull distribution	MR = (a-b) exp(-$(kt)^n$)	[27]
Midilli et al.	MR = a exp(-kt^n) + bt	[28]
Verma et al.	MR = a exp(-kt) + (1-a) exp(-gt)	[29]
Demir et al.	MR = a exp(-kt^n) + b	[30]
Diffusion approximation	MR = a exp(-kt) + (1-a) exp(-kbt)	[31]

2.7 Statistical analysis

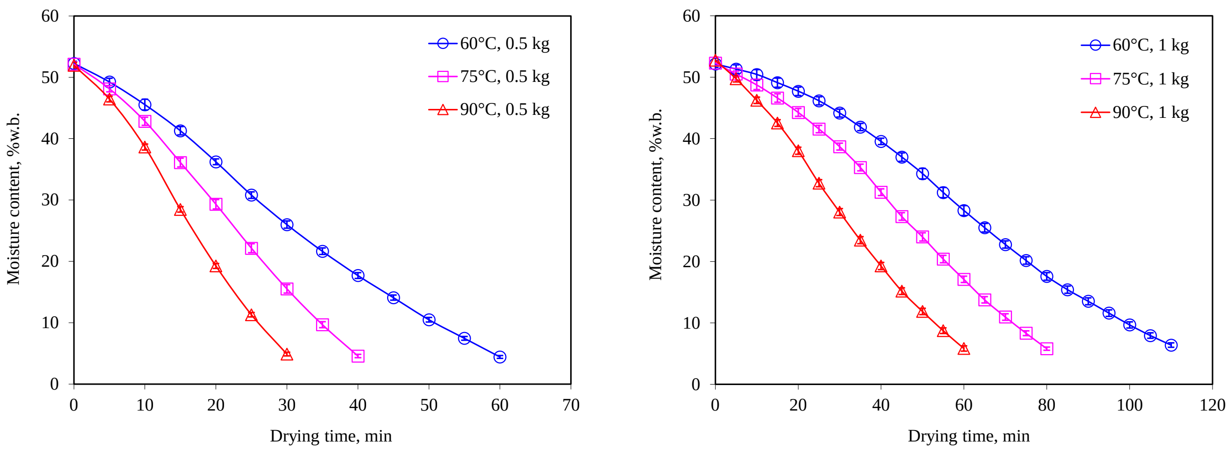
The data obtained from the experiments were subjected to statistical analysis using the software SPSS (Version 28) to perform a one-way analysis of variance (ANOVA), and the results were presented as means with standard deviations. To determine differences between the mean values, multiple comparisons were made using Duncan's multiple range test. The mean values were considered significantly different if the probability value (*P*-value) was less than 0.05. Additionally, the software SPSS was used for applying the models to experimental data via nonlinear regressions.

3. Results and discussion

3.1 Drying kinetics of spent coffee grounds

3.1.1 Effect of inlet air temperature on the drying kinetics

The drying curves of spent coffee grounds (SCGs) that were dried using inlet air temperatures of 60, 75, and 90°C are shown in Figure 2. It was found that increasing the inlet air temperature led to quicker reduction in moisture content of SCGs and shorter drying times. This was because the higher temperature of the inlet air increased the rate of evaporation and enhanced the moisture transfer from the material being dried to the air. The results of this research were consistent with those of Wachiraphansakul and Devahastin [32], who studied the drying kinetics of okara in a jet-spouted bed of sorbent particles. They found that using a drying air temperature of 130°C resulted in a shorter drying time than using 55°C by approximately 60-80 min. They also observed that using the highest level of drying air temperature (130°C) resulted in the highest drying rates of okara. Another study by Jayatunga and Amarasinghe [33] examined the drying kinetics of Sri Lankan black pepper in a spouted bed and found that the drying time decreased while the drying rate increased with an increase in air temperature. In addition, a study by Moradi et al. [10] investigated the drying kinetics of green bell pepper using an IR-assisted spouted bed dryer and found that a lower drying time was achieved while applying a higher drying temperature. They also noted that the drying rate increased as a result of an increase in the drying temperature.

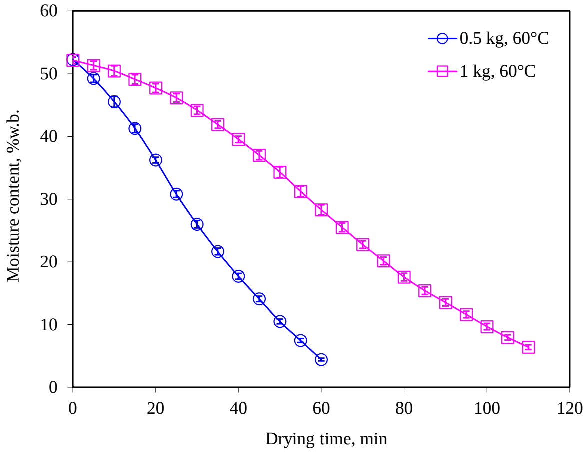


(a) a spent coffee grounds mass of 0.5 kg (b) a spent coffee grounds mass of 1 kg

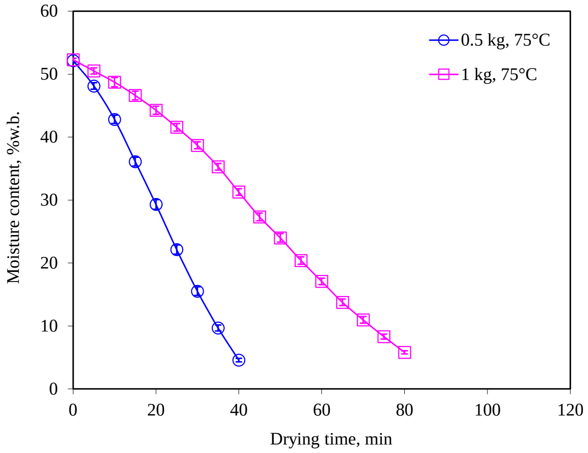
Figure 2 Drying curves of spent coffee grounds dried using inlet air temperatures of 60, 75, and 90°C

3.1.2 Effect of mass of the spent coffee grounds on the drying kinetics

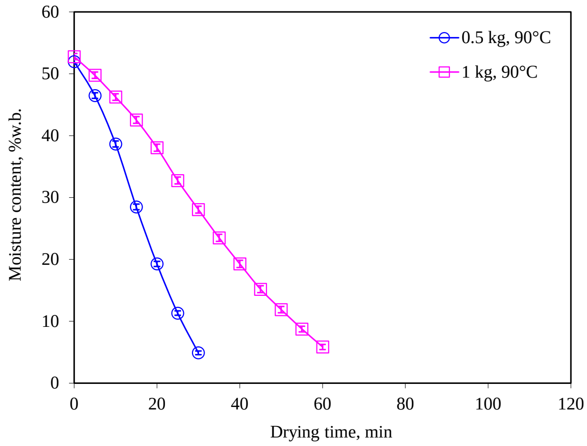
The drying curves of spent coffee grounds (SCGs) with masses of 0.5 and 1 kg, which were dried using the spouted bed technique, are shown in Figure 3. It was observed that an increase in the mass of the SCGs resulted in a slower reduction of moisture content of SCGs and a longer drying time. This was because the moisture content of a material is typically expressed as a percentage of the material's dry weight. Therefore, if a material had a higher mass, it contained more water and took longer to dry out than a smaller mass of the same material. In addition, the mass of the material could also affect the fluidization behavior of the bed. As the mass of the material increased, it became more difficult to fluidize and maintain a spout, leading to longer drying times. The findings were in agreement with earlier studies conducted by Rajashekhara and Murthy [34]. They examined the drying of agricultural grains, such as ragi, wheat, and barley, in a multiple porous draft tube spouted bed and found that as the bed mass increased, the drying rates decreased and the drying time increased. In addition, San Jose et al. [35] analyzed the drying kinetics of sawdust in conical spouted beds and determined that an increase in sawdust mass resulted in lower drying rates and longer drying times.



(a) An inlet air temperature of 60°C



(b) An inlet air temperature of 75°C



(c) An inlet air temperature of 90°C

Figure 3 Drying curves of SCGs with masses of 0.5 and 1 kg, dried using the spouted bed technique

3.2 Specific energy consumption of spent coffee grounds drying

3.2.1 Effect of inlet air temperature on the specific energy consumption

The specific energy consumption (SEC) of spent coffee grounds (SCGs) drying is shown in Table 2. It was observed that at the same mass of SCGs, the SEC significantly decreased with an increase in the inlet air temperature due to the faster drying rate at higher temperatures, which led to a reduction in the time required for drying and thus the amount of energy required. The results of this study agreed with de Brito et al. [11], who investigated the SEC of sorghum drying using spouted bed dryers and found that higher temperatures resulted in a decrease in SEC. Similarly, the findings of Moradi et al. [10], which examined the SEC of green bell pepper drying with an IR-assisted spouted bed dryer, showed that higher drying temperatures resulted in less SEC.

3.2.2 Effect of mass of the spent coffee grounds on specific energy consumption

In Table 2, it is observed that at the same inlet air temperature, increasing the mass of spent coffee grounds results in a significant increase in SEC. This was because as the mass of the material increased, the total amount of moisture that needed to be removed also increased, which meant that more energy was required to achieve the same level of drying. Furthermore, the mass of the material could have affected the airflow and heat transfer within the drying system, making it more difficult for the heated air to come into contact with the material and remove the moisture. These factors resulted in longer drying times and higher energy consumption. The findings of this study were consistent with those of Wachiraphansakul and Devahastin [32], who investigated the SEC of okara drying in a jet-spouted bed dryer and found that an increase in the mass ratio of sorbent particles to okara (SR) from 0.2 to 0.3 resulted in an increase in SEC value.

Table 2 Specific energy consumption (SEC) of spent coffee grounds drying

Inlet air temperature (ºC)	Mass of spent coffee grounds (kg)	Drying time (min)	SEC (MJ/kg_{water})
60	0.5	60	7.82±0.36^{d}
	1	110	15.42±0.25^{a}
75	0.5	40	6.66±0.22^{e}
	1	80	13.32±0.25^{b}
90	0.5	30	5.86±0.08^{f}
	1	60	11.82±0.13^{c}

Mean ± standard deviation with different small letter (a–f) superscripts on the same column are significantly different, at $P < 0.05$ according to Duncan's multiple range test.

3.3 Colors of dried spent coffee grounds

3.3.1 Effect of inlet air temperature on the colors of dried spent coffee grounds

The colors of dried spent coffee grounds (SCGs) are shown in Table 3. It was found that at the same mass of SCGs, SCGs dried at higher inlet air temperatures had significantly lower lightness (L* value) but higher redness (a* value) than those dried at lower inlet air temperatures. However, SCGs dried at the inlet air temperature of 90°C had significantly higher yellowness (b* value) and color difference (ΔE value) than those dried at 60°C, while the b* and ΔE values of SCGs dried at the inlet air temperature of 75°C were not significantly different from those of 60 and 90°C. This phenomenon can be explained by the Maillard reaction, which is a non-enzymatic browning reaction that occurs between amino acids and reducing sugars under high temperature and low moisture conditions [36, 37]. The results of this study were in agreement with Tun et al. [4], who dried SCGs in a hot air oven at drying temperatures of 40 and 105°C. They found that increasing the drying temperature decreased the L* value but increased the a* and b* values of the SCGs.

Table 3 Colors of dried spent coffee grounds

Inlet air temperature (ºC)	Mass of spent coffee grounds (kg)	Drying time (min)	Colors			
			L*	***a****	***b****	**Δ*E***
60	0.5	60	3.96±0.07^{a}	0.89±0.05^{e}	5.41±0.25^{d}	3.90±0.14^{c}
	1	110	3.63±0.10^{bc}	1.22±0.03^{c}	5.63±0.29^{cd}	3.92±0.28^{c}
75	0.5	40	3.73±0.08^{b}	1.10±0.04^{d}	5.87±0.31^{bcd}	4.15±0.26^{bc}
	1	80	3.41±0.12^{d}	1.57±0.03^{b}	6.11±0.23^{abc}	4.30±0.22^{abc}
90	0.5	30	3.50±0.11^{cd}	1.24±0.03^{c}	6.30±0.21^{ab}	4.42±0.21^{ab}
	1	60	3.22±0.09^{e}	1.81±0.04^{a}	6.60±0.32^{a}	4.71±0.25^{a}

Mean ± standard deviation with different small letter (a–e) superscripts on the same column are significantly different, at $P < 0.05$ according to Duncan's multiple range test.

3.3.2 Effect of mass of the spent coffee grounds on the colors of dried spent coffee grounds

In Table 3, it was found that at the same inlet air temperature, 0.5 kg of dried spent coffee grounds (SCGs) had a significantly higher lightness (L* value) but a significantly lower redness (a* value) compared to 1 kg of dried SCGs. Additionally, 0.5 and 1 kg of dried SCGs were not significantly different in yellowness (b* value) and color difference (ΔE value). This was because a larger mass of material required more time to dry, which prolonged the exposure of reducing sugars and amino acids to each other, thereby increasing the Maillard reaction [38, 39]. However, the effect of the mass of the SCGs on the colors of dried SCGs has not been previously reviewed in the literature.

3.4 Evaluation of the drying models

The moisture content data collected under different drying conditions were transformed into moisture ratio expressions and used regression analysis to fit curves with drying time using 12 drying models listed in Table 1. The drying coefficients (k, n, a, b, and c) obtained from these models, along with statistical analyses evaluating the models' performance under various drying conditions, such as the coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2), are presented in Tables 4 and 5 for 0.5 kg and 1 kg masses of spent coffee grounds, respectively.

Table 4 Prediction of model coefficients for a spent coffee grounds mass of 0.5 kg

Model	Drying temp. (ºC)	Constants				R^2	RMSE	χ^2
Newton [20]		k						
	60	0.025823				0.968098	0.017517	0.00081386
	75	0.035580				0.948319	0.028630	0.00182030
	90	0.048315				0.947412	0.041107	0.00268010
		Average				0.954610	0.029084	0.00177142
Page [21]		k	n					
	60	0.002957	1.609920			0.998326	0.005347	0.00002123
	75	0.002797	1.794460			0.996641	0.009365	0.00005054
	90	0.004652	1.802440			0.998175	0.009340	0.00000012
		Average				0.997714	0.008017	0.00002396
Modified Page [22]		k	n					
	60	0.026855	1.609920			0.998326	0.005347	0.00002124
	75	0.037767	1.794460			0.996641	0.009365	0.00005054
	90	0.050814	1.802440			0.998175	0.009340	0.00000012
		Average				0.997714	0.008018	0.00002397
Henderson and Pabis [23]		a	k					
	60	1.103020	0.029004			0.959123	0.003353	0.00019173
	75	1.100150	0.039919			0.937752	0.007274	0.00098966
	90	1.089060	0.053364			0.938166	0.022728	0.00220287
		Average				0.945014	0.011118	0.00112809
Wang and Singh [24]		a	b					
	60	-0.016733	0.000018			0.995986	0.007001	0.00012279
	75	-0.020043	-0.000085			0.996484	0.008417	0.00013034
	90	-0.027795	-0.000108			0.994459	0.013542	0.00021009
		Average				0.995643	0.009653	0.00015441
Logarithmic [25]		a	k	c				
	60	3.48516	0.005402	-2.45315		0.996649	0.000805	0.00005074
	75	7701.13	0.000003	-7700.11		0.996546	0.003154	0.00003444
	90	13499.4	0.000002	-13498.4		0.994865	0.015625	0.00036149
		Average				0.996020	0.006528	0.00014889
Two-term [26]		a	k	b	k_1			
	60	29.8412	0.014267	-28.8319	0.013941	0.980191	0.012760	0.00067159
	75	37.1562	0.029836	-36.1472	0.029710	0.951895	0.024457	0.00226379
	90	31.4005	0.025976	-30.3918	0.025381	0.964104	0.033217	0.00372249
		Average				0.965396	0.023478	0.00221929
Weibull distribution [27]		a	b	k	n			
	60	291720175	291720174	0.026121	1.735250	0.998304	0.008085	0.00014396
	75	70426547	70426546	0.036276	2.050040	0.996036	0.015777	0.00074752
	90	247338866	247338865	0.048905	2.028390	0.996925	0.018906	0.00074966
		Average				0.997088	0.014256	0.00054705
Midilli et al. [28]		a	k	n	b			
	60	0.991236	0.003428	1.511050	-0.001622	0.999761	0.000879	0.00000003
	75	0.981122	0.002660	1.702600	-0.003730	0.999705	0.000019	0.00000008
	90	0.973397	0.003851	1.797180	-0.002517	0.999341	0.000505	0.00000593
		Average				0.999602	0.000468	0.00000201
Verma et al. [29]		a	k	g				
	60	48.607500	0.052423	0.053262		0.989373	0.005353	0.00019195
	75	48.974400	0.076882	0.078228		0.980959	0.007691	0.00061057
	90	52.612700	0.107347	0.109219		0.985229	0.010723	0.00139268
		Average				0.985187	0.007922	0.00073173
Demir et al. [30]		a	k	n	b			
	60	1.151880	0.003679	1.470950	-0.162416	0.999733	0.000859	0.00000003
	75	1.244880	0.003195	1.617890	-0.269473	0.999508	0.000042	0.00000004
	90	1.086400	0.004208	1.752560	-0.116850	0.999154	0.000494	0.00000591
		Average				0.999465	0.000465	0.00000199
Diffusion approximation [31]		a	k	b				
	60	-1697.67	0.001132	1.008110		0.995920	0.006981	0.00013406
	75	-607010	0.000000	2.464300		0.996547	0.012205	0.00039503
	90	-5485.22	0.117581	0.999791		0.992080	0.013539	0.00009038
		Average				0.994849	0.010908	0.00020649

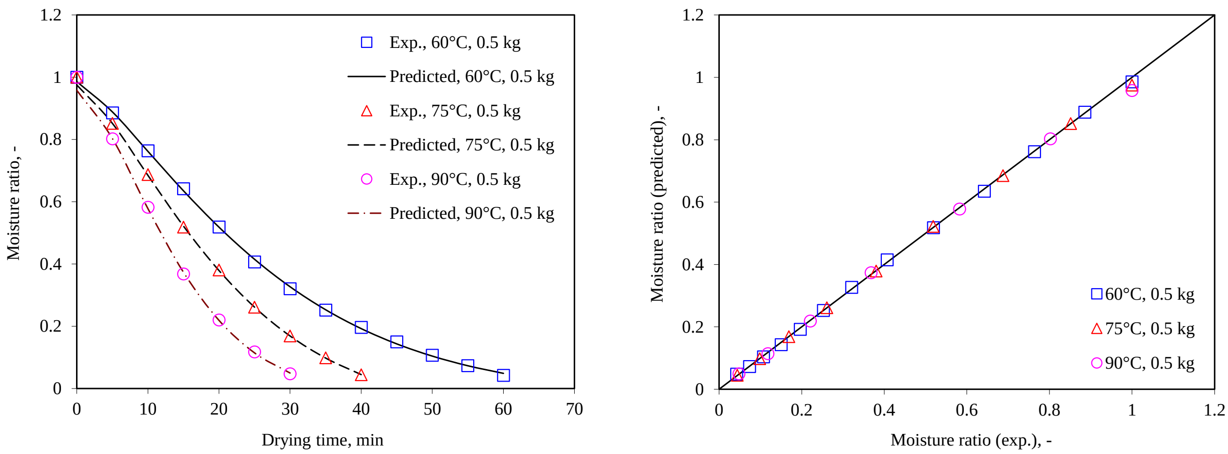
Table 5 Prediction of model coefficients for a spent coffee grounds mass of 1 kg

Model	Drying temp. (°C)	Constants				R^2	RMSE	χ^2
Newton [20]		k						
	60	0.011565				0.945768	0.008390	0.00026546
	75	0.016119				0.943315	0.010481	0.00040627
	90	0.024149				0.964860	0.015673	0.00068699
		Average				0.951315	0.011515	0.00045291
Page [21]		k	n					
	60	0.000213	1.947660			0.999471	0.002309	0.00000950
	75	0.000498	1.890200			0.997364	0.005781	0.00006119
	90	0.002482	1.635920			0.998442	0.006458	0.00004389
		Average				0.998426	0.004849	0.00003819
Modified Page [22]		k	n					
	60	0.013012	1.947660			0.999471	0.002309	0.00000950
	75	0.017897	1.890200			0.997365	0.005781	0.00006120
	90	0.025557	1.635920			0.998442	0.006458	0.00004389
		Average				0.998426	0.004849	0.00003820
Henderson and Pabis [23]		a	k					
	60	1.149300	0.013902			0.930350	0.018365	0.00005163
	75	1.126870	0.018858			0.929644	0.014477	0.00000014
	90	1.101280	0.027204			0.955778	0.005118	0.00012630
		Average				0.938591	0.012654	0.00005935
Wang and Singh [24]		a	b					
	60	-0.005745	-0.000025			0.990081	0.002795	0.00003515
	75	-0.008228	-0.000042			0.994767	0.001936	0.00002228
	90	-0.015246	-0.000001			0.995682	0.005277	0.00007548
		Average				0.993510	0.003336	0.00004430
Logarithmic [25]		a	k	c				
	60	4303	0.000002	-4301.97		0.990339	0.001893	0.00000599
	75	3524.77	0.000003	-3523.75		0.992674	0.001120	0.00000857
	90	5.95062	0.002870	-4.92176		0.996344	0.000361	0.00002485
		Average				0.993119	0.001125	0.00001314
Two-term [26]		a	k	b	k_1			
	60	23.5645	0.002576	-22.5564	0.002286	0.980411	0.004408	0.00012401
	75	26.1577	0.005287	-25.1503	0.004966	0.973371	0.005820	0.00021530
	90	13.1131	0.001085	-12.1048	-0.000082	0.996088	0.002876	0.00004170
		Average				0.983290	0.004368	0.00012700
Weibull distribution [27]		a	b	k	n			
	60	-122411872	-122411873	0.012858	2.039040	0.999691	0.002552	0.00001639
	75	-46607066	-46607067	0.017419	2.104420	0.998185	0.006878	0.00014411
	90	286636554	286636553	0.024792	1.792500	0.998440	0.009377	0.00022432
		Average				0.998772	0.006269	0.00012827
Midilli et al. [28]		a	k	n	b			
	60	0.983237	0.000157	2.004490	-0.000151	0.999767	0.001135	0.00000005
	75	0.972382	0.000329	1.934450	-0.001111	0.999405	0.001487	0.00000043
	90	0.974635	0.002019	1.645520	-0.001079	0.999486	0.000261	0.00000212
		Average				0.999553	0.000961	0.00000087
Verma et al. [29]		a	k	g				
	60	8.504530	0.003983	0.003686		0.976729	0.003071	0.00003852
	75	10.338800	0.011339	0.011135		0.957048	0.007259	0.00022422
	90	12.199600	0.014630	0.014172		0.978438	0.010304	0.00032185
		Average				0.970738	0.006878	0.00019486
Demir et al. [30]		a	k	n	b			
	60	1.004840	0.000164	1.992940	-0.022579	0.999748	0.001220	0.00000005
	75	1.114940	0.000423	1.859930	-0.146822	0.999237	0.001704	0.00000058
	90	1.076690	0.002189	1.610940	-0.103885	0.999419	0.000282	0.00000223
		Average				0.999468	0.001068	0.00000096
Diffusion Approximation [31]		a	k	b				
	60	-2176480	2.2002×10^{-9}	2.64162		0.990341	0.004871	0.00010499
	75	2.22242	5.6954×10^{-11}	-124038000		0.994393	0.002360	0.00003220
	90	-6607.36	5.6020×10^{-2}	0.999844		0.994805	0.008642	0.00006086
		Average				0.993180	0.005291	0.00006602

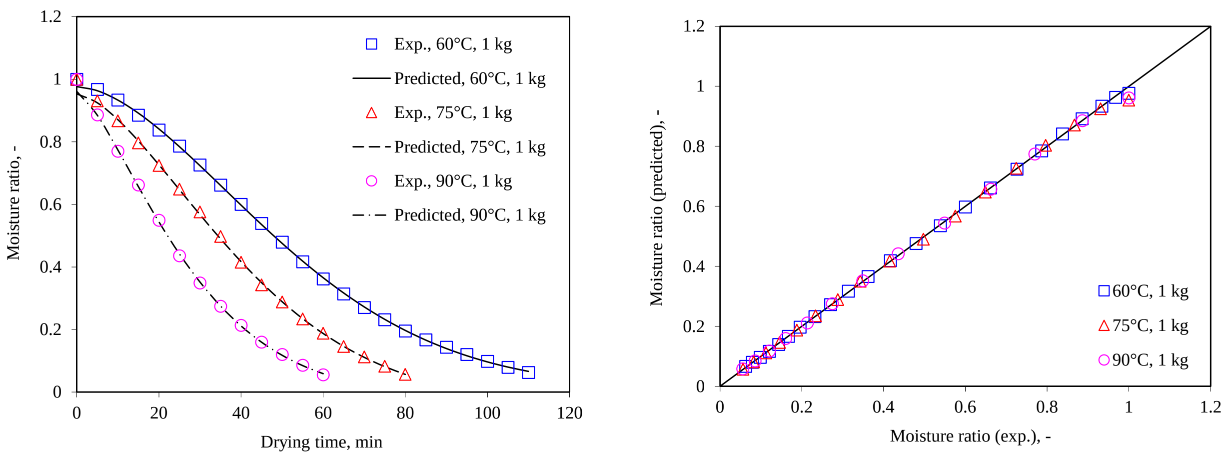
In Tables 4 and 5, the statistical analysis was conducted on several models, which yielded varying values of coefficient of determination (R^2), root mean square error (RMSE), and reduced chi-square (χ^2). The decision criteria for selecting the best model involved a comprehensive analysis of these statistical indicators. A high value of R^2 indicated a good fit to the experimental data, while the low values of RMSE and χ^2 provided information about the magnitude of the residuals and the goodness of fit, respectively.

As a decision criterion for model selection, the Midilli et al. and Demir et al. models demonstrated high average values of R^2, along with low average values of RMSE and χ^2. In Table 4 (for a mass of SCGs at 0.5 kg), the Midilli et al. model yielded the highest average value of R^2 (0.999602) and provided the average values of RMSE (0.000468) and χ^2 (0.00000201). In comparison, the Demir et al. model showed average values of R^2 (0.999465) and yielded the lowest average values of RMSE (0.000465) and χ^2 (0.00000199). It was observed that the average values of RMSE and χ^2 for the Midilli et al. and Demir et al. models were quite similar. However, in Table 5 (for a mass of SCGs at 1 kg), the Midilli et al. model yielded the highest average value of R^2 (0.999553) and the lowest average values of RMSE (0.000961) and χ^2 (0.00000087). Comparatively, the Demir et al. model showed average values of R^2 (0.999468), RMSE (0.001068), and χ^2 (0.00000096). Therefore, taking all these factors into consideration, the Midilli et al. model was selected to describe the drying characteristics of SCGs under the spouted bed drying technique. The result was consistent with prior research on the drying process of SCGs, as reported by Gómez-de la Cruz et al. [40]. They investigated a mathematical model for describing the drying behavior of SCGs and found that the Midilli et al. model was in good agreement with the experimental results (R^2 = 0.999842 and RMSE = 0.003369).

The selected model's validity was verified by comparing the predicted moisture ratio to the experimental moisture ratio under various drying conditions. Figure 4 displays comparisons between the experimental and predicted moisture ratios against drying time, demonstrating that the Midilli et al. model aligns well with the experimental outcomes. In addition, the plot of predicted moisture ratio versus experimental moisture ratio, as shown in Figure 4, appeared as a straight line, indicating that the Midilli et al. model accurately described the drying behavior of the SCGs.



(a) a spent coffee grounds mass of 0.5 kg



(b) a spent coffee grounds mass of 1 kg

Figure 4 Comparisons between experimental data and best fit of Midilli et al. model at temperatures of 60, 75 and 90°C

Based on the above analysis, in order to use the Midilli et al. model to calculate the moisture ratio of SCGs within the ranges of the inlet air temperatures (60, 75 and 90°C) and the masses of SCGs (0.5 and 1 kg) in this study, it was necessary to consider the constant values of a, k, n, and b in the Midilli et al. model as a linear equation in terms of the inlet air temperature (T) and the mass of SCGs (m). This linear equation was expressed as [41].

$$a = x_0 + x_1T + x_2m \quad (7)$$

$$k = x_3 + x_4T + x_5m \quad (8)$$

$$n = x_6 + x_7T + x_8m \quad (9)$$

$$b = x_9 + x_{10}T + x_{11}m \quad (10)$$

where a, k, n, b, x_0 to x_{11} were constant values, T is the inlet air temperature (°C), and m was the mass of SCGs (kg). Therefore, the Midilli et al. model could be expressed in the form of Eq. (11), as shown below:

$$MR = (x_0 + x_1T + x_2m)\exp(-(x_3 + x_4T + x_5m)t^{(x6 + x7T + x8m)}) + (x_9 + x_{10}T + x_{11}m)t \quad (11)$$

where MR was the moisture ratio (-), and t was the drying time (min). Eq. (11) was analyzed using regression analysis to determine the constant values of the equation. The results of the analysis were presented in Eq. (12), which could be used to explain the drying behavior of SCGs at temperatures of 60, 75, and 90°C and with masses of 0.5 and 1 kg.

$$MR = a\exp(-kt^n) + bt \quad (12)$$

where a = 1.02014 - 0.000440683T - 0.010334m, k = 0.00293434 + 3.80944x10^{-5}T - 0.0049565m, n = 1.57012 - 0.001214T + 0.38242m, and b = -0.00218738 - 3.03861x10^{-5}T + 0.00368577m. The analysis of the Midilli et al. model in Eq. (12) resulted in an R^2 value of 0.994824, an RMSE of 0.001944, and a χ^2 value of 0.000135. These outcomes indicated that the model was suitable for describing the drying behavior of SCGs.

4. Conclusions

Investigations were carried out to study the drying kinetics of spent coffee grounds (SCGs) using spouted bed drying at inlet air temperatures of 60, 75, and 90°C, and SCGs masses of 0.5 and 1 kg. The study also examined the specific energy consumption (SEC) and the color of the SCGs after drying. In addition, twelve mathematical drying models were used to fit the experimental data obtained to estimate the moisture ratio as a function of drying time. Based on the experimental results, it was found that increasing the inlet air temperature caused the moisture content of the SCGs and the SEC to decrease. An increase in the mass of the SCGs could lead to a decrease in its moisture content but an increase in the SEC. An increase in the inlet air temperature and the mass of the SCGs could cause a decrease in the *L** value but an increase in the *a** and *b** values, making the SCGs appear darker. Based on the regression analysis results, it was concluded that among twelve mathematical drying models, the Midilli et al. model was the most suitable for describing the drying behavior of SCGs at inlet air temperatures of 60, 75, and 90°C, and SCGs masses of 0.5 and 1 kg. Furthermore, this study can help optimize the drying process parameters, such as the inlet air temperature and mass of SCGs. This optimization can lead to improved product quality, reduced processing time, and increased overall efficiency for drying SCGs using the spouted bed technique.

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