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Effect of drying temperature in a fluidized-bed dryer on germinated azuki red beans

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ABSTRACT

Understanding the drying kinetics of sprouted azuki red beans in a fluidized-bed dryer is essential for balancing energy efficiency with preservation of their nutritional and health benefits. This study investigated the effects of the fluidized-bed dryer temperature on sprouted azuki red beans using shade drying as a baseline. The fluidized-bed dryer reduced the moisture content to 11–13% (wet basis) within 35 min, compared with 4,200 min for shade drying. Although the fluidized-bed dryer produced a darker product, it yielded superior bioactive properties, including total phenolic and flavonoid contents, radical scavenging capacity, and ferric ion-reducing antioxidant power. The most favorable bioactive properties and the lowest specific energy consumption were achieved at 150 °C because of the rapid drying rate. Among tested models, the logarithmic model provided the best fit to the observed drying behavior. These results highlight the efficiency of fluidized-bed dryers and will help food processing companies improve the energy efficiency of their drying processes while maintaining the product quality and antioxidant properties of sprouted azuki red beans.

Keywords: antioxidants; conservation of energy resources; empirical model; flavonoids; food handling

1. INTRODUCTION

Azuki red beans (*Vigna angularis*) have been revered for centuries in Asian cultures for their distinct flavor and nutritional richness, and they have recently captured attention for their potential health benefits and the culinary versatility of their sprouts. Li et al. (2011) reported that germinated azuki red beans are abundant in essential vitamins and bioactive compounds such as free amino acids, polyunsaturated fatty acids, and γ-aminobutyric acid, which are vital to overall health.

In the food processing industry, drying processes are critical to improving the shelf life and storage stability of food products such as germinated azuki red beans. Fluidized-bed dryers (FBDs) offer advantages including an efficient heat transfer, gentle process, and fast drying time, which can improve the product quality while reducing the processing time. However, their high energy consumption means that the process parameters need to be optimized for efficiency. One key process parameter is the drying temperature, which is critical to the specific energy consumption (SEC) of the FBD (Khoshtaghaza et al., 2015; Chayjan et al., 2013). The relationship between the drying temperature and SEC is not always linear: Khanali et al. (2016) used an FBD to dry paddy rice and reported that the SEC increased as the drying temperature was increased from 50 °C to 60 °C but decreased when the drying temperature was further increased from 60 °C to 70 °C. Khoshtaghaza et al. (2015) used an FBD to dry soybean kernels and reported that increasing the drying

temperature from 80 °C to 140 °C increased the SEC from 50.94 × 10^3 to 338.76 × 10^3 kJ/kg. However, Chayjan et al. (2013) reported that increasing the temperature for drying squash seeds from 50 °C to 80 °C decreased the SEC from 2.303 × 10^6 to 0.783 × 10^6 kJ/kg.

The drying temperature can also affect the nutritional content, texture, and color of the food product. Siddhuraju (2006) and Dueñas et al. (2005) reported that heating antioxidants such as phenolic compounds and flavonoids may form Maillard reaction products like hydroxymethylfurfuraldehyde (HMF) that also exhibit high antioxidant activity. Conversely, Houshmand-Dalir et al. (2022) reported that increasing the drying temperature may decrease the total phenolic content (TPC) of food products. The effects of the drying temperature on antioxidants are governed by the interplay between the thermal degradation and enhanced extraction of bound phenolic compounds as well as structural modifications within the matrix of the food product (Akther et al., 2022; Li et al., 2024). Consequently, optimizing the drying temperature to improve energy efficiency must be balanced with the need to preserve or enhance the functional properties of the food product.

Mathematical models play a crucial role in characterizing the drying behavior or kinetics of food products, which becomes particularly complex in FBDs because of the dynamic nature of heat and mass transfer. Empirical regression models are instrumental for describing drying kinetics by establishing correlations between the drying time and moisture content based on experimental observations. Many models have been developed for the drying kinetics of various food products including shrimp (Nanan et al., 2023), paddy rice (Sitorus et al., 2021), broad beans (Hashemi et al., 2009), and chopped coconut (Madhiyanon et al., 2009). However, few studies have focused on modeling the drying kinetics of germinated azuki red beans in an FBD.

The objective of this study was to examine the influence of the drying temperature of an FBD on the drying kinetics of germinated azuki red beans. A comparative analysis was also carried out with shade drying regarding color differences and the presence of antioxidants. Determining the optimal drying temperature in terms of energy efficiency and functional properties is essential to facilitating the production of germinated azuki red beans.

2. MATERIALS AND METHODS

2.1 Germination of azuki red beans

Azuki red beans were cleaned, and any defective beans were separated and removed. The azuki red beans had an initial bulk density of 633.33 kg/m^3 and moisture content (wet basis unless stated otherwise) of 7.53%. Therefore, the azuki red beans were soaked in room-temperature water until the moisture content reached a steady-state of about 58%, which typically took around 21 h. The moisture content was measured hourly to determine the water uptake. Subsequently, the azuki red beans were germinated in air until their root length reached 0.5–1.0 mm. The azuki red beans had a germination rate of 70–85%, and the final moisture content of the germinated azuki red beans was 58%.

2.2 Fluidized-bed dryer

Figure 1 shows the FBD used in this study, which comprised a cylindrical chamber, 9-kW electrical air heater, 1.5-kW backward curve blade centrifugal blower, and cyclone system equipped with a data acquisition system. The drying chamber was constructed from stainless steel and had an internal diameter of 0.15 m and height of 0.9 m. The airflow rate was adjusted by a damper (labeled D in the figure) and was measured by a differential pressure measuring instrument (Testo 510, Testo SE & Co. KGaA, Germany) with an accuracy of ±0.05 hPa. The temperature of the airflow (i.e., drying temperature) was controlled by a proportional–integral–derivative (PID) controller with an accuracy of ±1 °C at the inlet of the drying chamber.

To dry the germinated azuki red beans in the FBD, the drying chamber was first preheated to a specific temperature: 110 °C, 130 °C, or 150 °C. Then, 1.12 kg of germinated azuki red beans were loaded into the drying chamber to form a bed with a height of approximately 10 cm. The airflow rate was kept constant at a superficial air velocity of about 2.2 m/s. During the drying period, samples were collected from the outlet (labeled "4" in the figure) every 5 min to measure the moisture content until a final moisture content of 10–13% was achieved. To minimize experimental variation, tests were repeated a minimum of three times at each temperature.

2.3 Shade drying

For shade drying, germinated azuki red beans were spread evenly in a basket lined with thin white cloth. The basket was then placed in a shaded area with good air circulation at the ambient temperature. The moisture content of the beans was measured every 10 h until it reached 10%.

2.4 Moisture content determination

To determine the moisture content at a specific sampling time, 10 g of germinated azuki red beans was distributed in three separate containers and dried in a convection oven set to 103 °C for 72 h. The moisture content was calculated by using a mass balance (BSA Series, Sartorius, Germany) with a weighing accuracy of 0.0002 g. The average of the triplicate samples was calculated to determine the moisture content for a specific sampling time.

The moisture ratio (MR) was calculated using Equation (1):

$$MR = \frac{M_t - M_{eq}}{M_0 - M_{eq}} \quad (1)$$

where M_t is the moisture content for a specific sampling time (g water/g dry matter), M_0 is the initial moisture content, and M_{eq} is the equilibrium moisture content. Analysis of the MR showed that M_{eq} was quite small relative to M_t or M_0 (Doymaz & Sahin, 2016). Therefore, a simplified Equation (2) is given:

$$MR = \frac{M_t}{M_0} \quad (2)$$

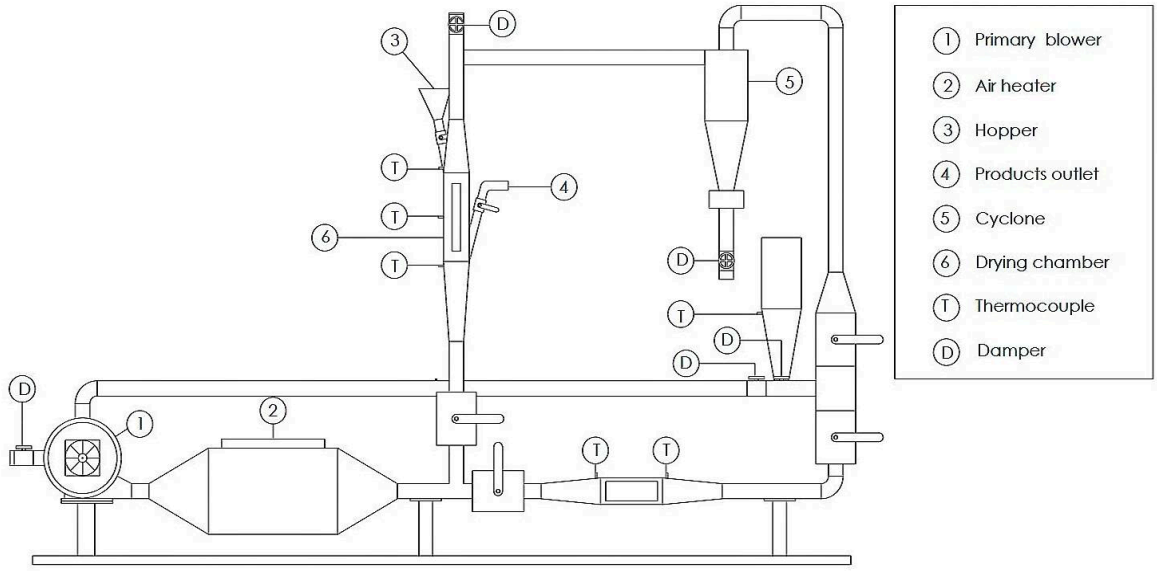


Figure 1. Schematic diagram of a fluidized-bed dryer

2.5 Total color difference

The color difference of the germinated azuki red beans was evaluated by using a colorimeter (NH300, 3NH, China). The color was measured in the L*a*b* color space, where L^* is the lightness, and a^* and b^* are chromatic components; a^* ranges from green to red while b^* ranges from blue to yellow. The total color difference (ΔE) was quantified as seen in Equation (3):

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

where ΔL^*, Δa^*, and Δb^* are the differences in the lightness and chromatic components between the initial and final states. A higher ΔE^* value indicates a more substantial color difference. In this study, L_0^*, a_0^*, and b_0^* were set to the initial color values of the germinated azuki red beans before drying.

2.6 Model fitting

To identify the most suitable empirical equation for predicting drying behavior, five thin-layer models were evaluated as detailed in Table 1. Nonlinear regression analysis was employed to evaluate the models' ability to predict the drying kinetics using the determination coefficient (R^2), root mean square error (RMSE), and chi-square statistic (X^2). These are defined in Equations (4)–(6).

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

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

$$X^2 = \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N-P} \quad (6)$$

where $MR_{exp,i}$ is the MR obtained from experiments, $MR_{pre,i}$ is the MR predicted by a model, N is the number of data points in the experiment, and P is the number of parameters in a model. The model that yielded the highest R^2 value and lowest RMSE and X^2 values was determined to be most appropriate for predicting the drying kinetics.

2.7 Activation energy

The activation energy (Ea) represents the amount of energy required to break the bonds holding water molecules during the drying process and can be modeled by one of the following Arrhenius-type equations in Equations (7) and (8):

$$D_{eff} = D_0 \, exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad (7)$$

or

$$\text{In } D_{eff} = -\frac{E_a}{R(T+273.15)} + In\ D_0 \quad (8)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), D_0 is the diffusion coefficient (m^2/s), Ea is the activation energy (kJ/mol), T is the drying temperature (°C), and R is the gas constant (8.314 kJ/mol K).

Table 1. Mathematical models given by various authors for the drying data

No.	Names	Model	References
1	Newton/Lewis	$MR = \exp(-kt)$	Aktaş et al. (2009)
2	Henderson and Pabis	$MR = a\exp(-kt)$	Kaleta and Górnicki (2010)
3	Wang and Singh	$MR = 1+at+bt^2$	Wang and Singh (1978)
4	Logarithmic	$MR = a\exp(-kt)+c$	Kingsly et al. (2007)
5	Diffusion approach	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	Kassem (1996)

Note: a, b, and c are parameters of the empirical model, k is the drying rate constant, t is the drying time in minutes

2.8 Specific energy consumption

In this study, Equation (9) was used to define the SEC as the energy consumed by the drying process to remove one kilogram of moisture from the germinated azuki red beans (MJ/kg):

$$SEC\ (MJ/kg - water) = -\frac{3.6\ P_e}{m_i - m_f} \quad (9)$$

where m_i is the mass of germinated azuki red beans before drying (kg), m_f is the mass of germinated azuki red beans after drying (kg), and P_e is the amount of electrical consumption by the drying process (kWh), which was primarily from the blower and air heater.

2.9 Antioxidant agent determination

Samples collected during the drying process were used to determine four antioxidant agents: TPC, 2,2-diphenyl-1-picrylhydrazyl (DPPH), total flavonoid content (TFC), and ferric ion–reducing antioxidant power (FRAP). TPC and FRAP were obtained by the Folin–Ciocalteu method and were expressed by using gallic acid as the calibration standard (mg gallic acid equivalents (GAE)/g dry weight (DW)). TFC was expressed by using catechin as the calibration standard (mg catechin equivalents (CE)/g DW). The DPPH radical scavenging activity was expressed as the percentage inhibition (%), so no external standard was used for its quantification.

TPC and DPPH were measured by following the procedure described by Surayot and Seekhaw (2018). TFC was quantified by spectrophotometry following the methodology described by Herald et al. (2012). FRAP was measured by a modified version of the method presented by de la Torre et al. (2015). The DPPH radical scavenging activity was calculated as per Equation (10):

$$DPPH\ radical\ scavenging\ activity\ (\%\ Inhibition) = \frac{A_1 - A_2}{A_1} \times 100 \quad (10)$$

where A_1 is the control absorbance and A_2 is the sample absorbance.

3. RESULTS AND DISCUSSION

3.1 Drying kinetics

Despite the relatively high initial moisture content of 58%, the FBD achieved stable fluidization under the experimental conditions. This is because the superficial air velocity of about 2.2 m/s exceeded the minimum fluidization velocity and generated adequate drag force to overcome interparticle cohesion. In addition, the relatively small germinated azuki red beans facilitated particle movement. Rapid evaporation of the surface moisture at elevated temperatures further reduced stickiness, which improved particle separation and maintained stable fluidization during the drying process.

Figures 2a and 2b depict the moisture content and MR, respectively, of the germinated azuki red beans during the drying process in the FBD. At all drying temperatures, the moisture content gradually declined over time until it reached an equilibrium point. The moisture content had low standard deviations of 0.21–1.65% at 110 °C, 0.12–0.89% at 130 °C, and 0.03–1.40% at 150 °C, which indicate good repeatability of the experimental data and confirm the reliability of the observed drying behavior.

At all drying temperatures, the moisture content initially decreased at a constant rate, which indicated that moisture removal was dominated by surface evaporation. At a drying temperature of 150 °C, the moisture content reduced rapidly from approximately 58% to 43% within the first 5 min. A similar but less pronounced trend was observed at 130 °C, where the constant moisture removal rate was lower but also lasted for 10 min owing to the lower drying intensity. In contrast, the constant moisture removal rate was low and lasted for a very short time at 110 °C as the drying process quickly transitioned to the next stage.

For all drying temperatures, the next stage of the drying process was predominantly governed by a falling moisture removal rate, where the internal diffusion of moisture became the controlling mechanism and the moisture content decreased nonlinearly over time. This is because the outer surfaces of the beans began to dry, and internal moisture slowly diffused to the exterior. The rate of moisture removal decreased as the remaining moisture had to traverse from deeper within the beans to the surface. To achieve the final moisture content of 10.63–12.96%, the drying temperatures of 110 °C, 130 °C, and 150 °C required drying times of 35, 25, and 15 min, respectively.

With shade drying, the germinated azuki red beans took 70 h to reach a moisture content of 12.8% and 100 h to attain an equilibrium moisture content of about 10%. The long drying time was attributed to the absence of external heating and forced convection, which combined with the high initial moisture content resulted in a low drying rate under ambient conditions.

3.2 Effect of drying conditions on total color change

Table 2 presents the observed ΔE for both the FBD at different drying temperatures and shade drying at ambient temperature. Increasing the drying temperature greatly increased ΔE, which indicates a greater color deviation. This effect was especially pronounced when compared to shade drying. These results suggest that increasing the drying temperature may increase color degradation due to thermal effects such as browning from the Maillard reaction or pigment breakdown.

With shade drying, the germinated azuki red beans took 70 h to reach a moisture content of 12.8% and 100 h to attain an equilibrium moisture content of about 10%. The long drying time was attributed to the absence of external heating and forced convection, which combined with the high initial moisture content resulted in a low drying rate under ambient conditions.

3.3 Effective moisture diffusivity

Figure 3a shows the D_{eff} values at each drying temperature while Figure 3b depicts ln D_{eff} versus $1/T$. D_{eff} increased with the drying temperature, which corresponds with the moisture removal rate. The D_{eff} values ranged from 63.8×10^{-11} to 218.0×10^{-11} m^2/s, which falls within the range reported by Khoshtaghaza et al. (2015) for soybean kernels dried by microwaves in an FBD ($6.25–42.14 \times 10^{-10}$ m^2/s) and the broader ranges reported by Arumuganathan et al. (2009) and Zogzas et al. (1996) for drying various types of food products ($10^{-6}–10^{-11}$ m^2/s).

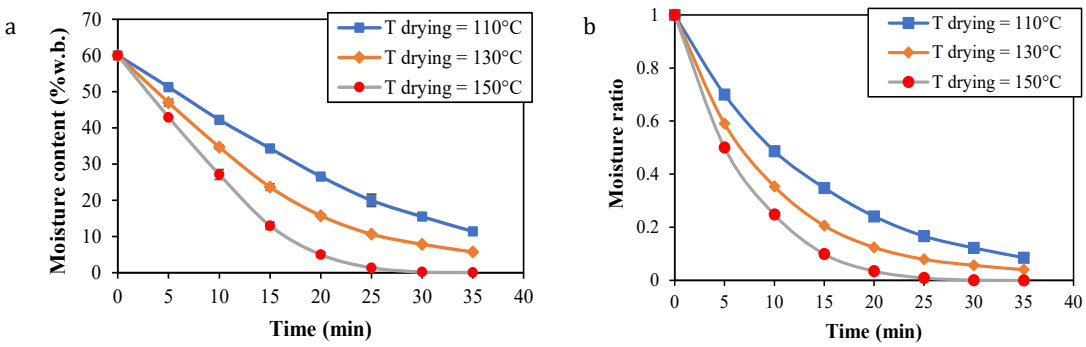


Figure 2. Moisture ratio for drying of germinated azuki red beans in a fluidized-bed dryer at various drying temperature

Table 2. Drying performance, final moisture content, and total color difference of sprouted azuki red beans under different drying conditions

Drying temperature (°C)	Drying time (min)	Final moisture content (% w.b.)	Total color difference (ΔE)
Fluidized-bed dryer			
110	35	11.39	16.63
130	25	10.63	16.70
150	15	12.96	17.01
Shade drying			
Ambient temperature	4200	12.81	10.78

3.4 Activation energy

E_a was calculated based on the slope of ln D_{eff} versus $1/T$ (Figure 3b). In this study, E_a was 41.01 kJ/mol, and D_0 was 2.34×10^{-4} m²/s (R^2 = 0.90). Other studies have reported a wide range of E_a values for food products dried in FBDs. Madhiyanon et al. (2009) reported E_a = 25.94 kJ/mol for chopped coconut at drying temperatures of 60–120 °C. Chayjan et al. (2013) reported E_a = 31.94–34.94 kJ/mol for squash seeds at drying temperatures of 50–80 °C, and E_a = 44.31–36.59 kJ/mol for rough rice at drying temperatures of 50–70 °C. Hashemi et al. (2009) reported E_a = 17.10–27.71 kJ/mol for broad beans dried at temperatures of 35–65 °C in an FBD assisted by dielectric heating.

3.5 Empirical model

Table 3 compares the evaluation metrics of the selected models. The predictions of the five models generally showed good agreement with the experimental data with average values of R^2 = 0.99 and RMSE = 0.01. The exception was the Wang and Singh model, which achieved slightly lower accuracy with average values of R^2 = 0.98 and RMSE = 0.05.

3.6 Specific energy consumption

In an FBD, the SEC depends on both the fluidization velocity and drying temperature. According to Khoshtaghaza et al. (2015), the SEC for drying soybean kernels increased with the drying temperature at all fluidization velocities. However, Khanali et al. (2016) reported the opposite tendency for the drying of rough rice. This may be explained by the extremely different ranges of drying temperatures used by the two studies: 50–70 °C for the soybean kernels and 80–140 °C for the rough rice drying. In this study, the drying velocity was fixed at approximately 2.2 m/s. Table 4 presents the effects of the drying temperature on the SEC, which decreased with an increasing drying temperature. This can be attributed to the shorter drying time to reach the final moisture content and matches the observations of Khanali et al. (2016), who applied a fluidization velocity of 4.5 m/s.

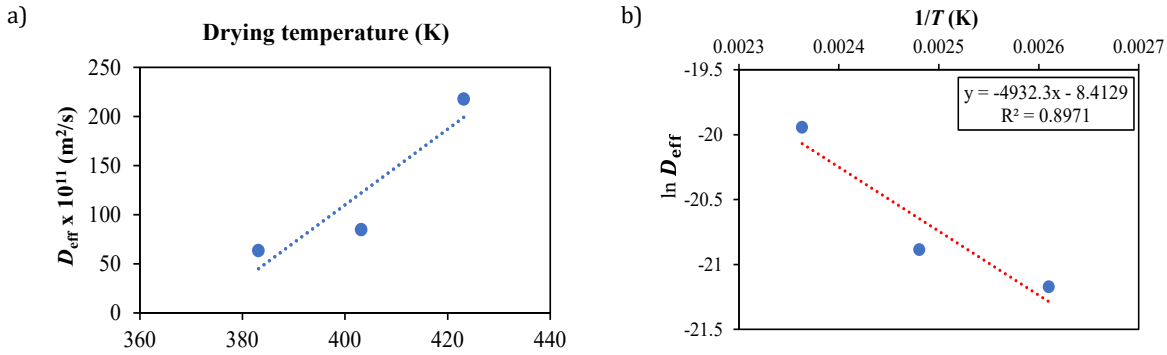


Figure 3. (a) D_{eff} versus drying air temperature and (b) ln D_{eff} against $1/T$ at for drying of germinated azuki red beans in a fluidized-bed dryer

Table 3. Statistical comparison for the prediction of drying germinated azuki red beans under various operating conditions

Names	Model	T_{drying}	Parameter				R^2	*RMSE*	$X \times 10^{-3}$
		(°C)	k	a	b	c			
Newton/Lewis	$MR = \exp(-kt)$	110	0.071034				0.9999	0.0027	0.0086
		130	0.103663				0.9995	0.0071	0.0579
		150	0.144596				0.9982	0.0139	0.2205
Henderson and Pabis	$MR = a.\exp(-kt)$	110	0.070953	0.998897			0.9999	0.0027	0.0098
		130	0.103378	0.997094			0.9995	0.0070	0.0660
		150	0.145351	1.006415			0.9983	0.0137	0.2499
Wang and Singh	$MR = 1+at+bt^2$	110		-0.056915	0.000902		0.9935	0.0241	0.7740
		130		-0.072054	0.001320		0.9765	0.0482	3.0997
		150		-0.083721	0.001637		0.9571	0.0685	6.2535
Logarithmic	$MR = a.\exp(-kt)+c$	110	0.071804	0.995112		0.004830	0.9999	0.0025	0.0096
		130	0.108229	0.985561		0.015500	0.9999	0.0030	0.0144
		150	0.137094	1.022546		-0.019904	0.9994	0.0082	0.1070
Diffusion approach	$MR = a.\exp(-kt)+(1-a)\exp(-kbt)$	110	0.072367	0.982301	0.355106		0.9999	0.0025	0.0097
		130	0.105490	0.998844	-0.723819		0.9965	0.0190	0.5764
		150	0.105342	3.426437	0.885166		0.9997	0.0052	0.0440

Table 4. Drying characteristics and specific energy consumption of sprouted azuki red beans at different temperatures

Drying temperature (°C)	Drying time (min)	Final moisture content (% w.b.)	Specific energy consumption (MJ/kg)
110	35	11.39	26.59
130	25	10.63	24.93
150	15	12.96	17.31

3.7 Antioxidant agents

TPC is a key indicator of how drying conditions affect the nutritional and functional properties of food products. After the drying process, the germinated azuki red beans had TPC values of 4.32–10.55 mg GAE/g DW. As shown in Figure 4a, the drying temperatures of 110 °C, 130 °C, and 150 °C had standard deviations of 0.01–0.05, 0.01–0.05, and 0.01–0.04 mg GAE/g DW, respectively, which confirm the reliability of the experimental measurements. Compared with the control sample (germinated azuki red beans before drying), drying at temperatures of 110 °C and 130 °C for durations of 0, 5, and 15 min had minimal effects on TPC. At a drying temperature of 150 °C, however, increasing the drying time resulted in a slight increase in TPC, which can be attributed to several mechanisms. Higher temperatures induce the thermal breakdown of cellular structures, which enhances the release of bound phenolic compounds. In addition, the Maillard reaction can form products with antioxidant activity that contribute to TPC. These effects are less pronounced at lower temperatures, which is why the changes in TPC were minimal. Overall, the germination and drying processes only slightly influenced TPC. In contrast, Moongngarm and Saetung (2010) reported a notable increase in TPC, which they primarily attributed to germination. The present study focused on the combined effects of germination and drying; while germination contributed to the baseline TPC, the subsequent drying process only slightly modified TPC depending on the drying temperature. The lower TPC values compared to Umar et al. (2022) (5.4±0.01 mg GAE/g DW) may be attributed to differences in the bean variety, germination conditions, and analytical procedure.

Figure 4b shows the DPPH radical scavenging activity of the germinated azuki red beans after the drying process. The DPPH radical scavenging activity ranged from 18.77% to 43.20% with standard deviations of 0.0%–0.08%, 0.0%–0.05%, and 0.0%–0.02% for drying temperatures of 110 °C, 130 °C, and 150 °C, respectively. These low standard deviations indicate the high repeatability and precision of the measurements across all experimental conditions. The germination and drying processes were found to influence the DPPH radical scavenging activity, which correlates with the TPC results. Umar et al. (2022) reported a DPPH radical scavenging activity of 67.49% for germinated red beans, which is greater than the results in this study. Umar et al. (2022) also reported a DPPH radical scavenging activity of 20.80% for azuki red beans, which matches this study's findings. However, Dueñas et al. (2005) suggested no significant divergence ($p < 0.05$) between raw and fermented samples although the DPPH radical scavenging activity increased after the drying process.

As shown in Figure 4c, the germinated azuki red beans had TFC values of 18.10–58.19 mg GAE/g DW after the drying process. The standard deviations were 0.0–0.03, 0.0–0.05, and 0.0–0.09 mg GAE/g DW for drying temperatures of 110 °C, 130 °C, and 150 °C, respectively, which indicate good repeatability of the measurements and confirm that the observed changes in TFC can be attributed to the effects of the drying temperature rather than experimental uncertainty. According to Siddhuraju (2006) and Dueñas et al. (2005), the resilience of phenolics and flavonoids during heating may be due to the formation of Maillard reaction products such as HMF, which have high antioxidant activity.

As shown in Figure 4d, the germinated azuki red beans had FRAP values of 0.64–2.52 mg GAE/g DW after the drying process with standard deviations of 0.01–0.02, 0.01–0.03, and 0.01–0.04 mg GAE/g DW for drying temperatures of 110 °C, 130 °C, and 150 °C, respectively. The small standard deviations indicate the good

repeatability of the measurements and confirm that the observed changes in FRAP can mainly be attributed to the effects of the germination and drying processes rather than experimental uncertainty. The FRAP values were influenced by the germination and drying processes, which supports the TPC and DPPH radical scavenging activity results. Boateng et al. (2008) reported that the FRAP values of kidney beans and pinto beans increased with drying. The processes of soaking and drying beans have also been found to decrease the levels of certain antinutritional factors including trypsin inhibitors and phytic acid and enhance the concentrations of beneficial compounds such as tannins, catechins, and other polyphenols. Although TPC tends to decrease following soaking, it generally increases after toasting. The soaking step softens the structure of the cell walls, which promotes the release of bound polyphenols that may diffuse into the soaking water (Boateng et al., 2008).

4. CONCLUSION

This study examined the effects of the drying temperature of an FBD on the drying kinetics and antioxidant activity of germinated azuki red beans. Increasing the drying temperature decreased the SEC. The effective moisture diffusivity had a range of 63.8–218.0 × 10^{-11} m^2/s, and the activation energy was 41,007.14 kJ/mol. The logarithmic model most accurately described the drying behavior. Antioxidant activity improved notably at higher drying temperatures, especially at 150 °C.

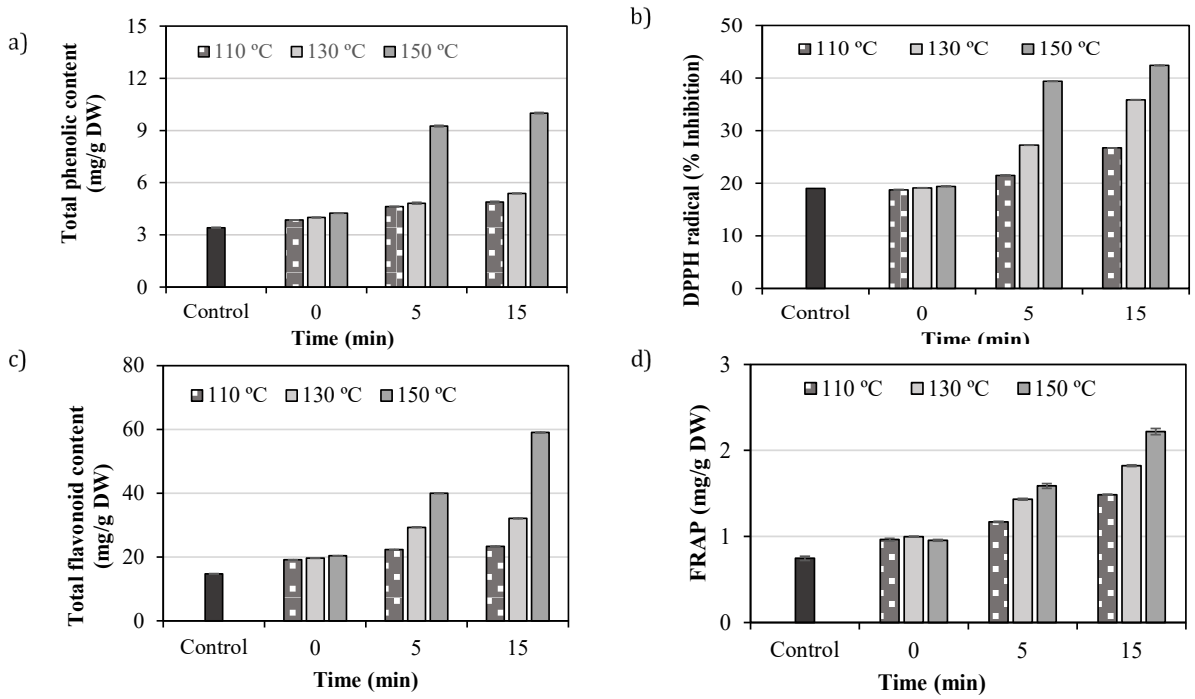


Figure 4. Amount of (a) total phenolic content (TPC), (b) 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical, (c) total flavonoid content (TFC), and (d) ferric ion reducing antioxidant power (FRAP) for drying of germinated azuki red beans in a fluidized-bed dryer at various drying times and temperatures

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AUTHOR CONTRIBUTIONS

K.S. carried out conceptualization, methodology, investigation, moisture-content analysis, drying-kinetics modelling, color measurement and analysis, specific energy consumption analysis, data interpretation, visualization, and writing—original draft. C.T. designed and responded for methodology, investigation, antioxidant activity analysis, total phenolic content analysis, data interpretation, and writing—review and editing. Both authors discussed the results, reviewed the manuscript, and approved the final version.

REFERENCES

Aktaş, M., Ceylan, İ., & Yilmaz, S. (2009). Determination of drying characteristics of apples in a heat pump and solar dryer. *Desalination*, *239*(1–3), 266–275. https://doi.org/10.1016/j.desal.2008.03.023

Akther, S., Jothi, J. S., Badsha, M. R., Rahman, M. M., Das, G. B., & Alim, M. A. (2022). Drying methods effect on bioactive compounds, phenolic profile, and antioxidant

capacity of mango powder. *Journal of King Saud University* – Science, *35*, Article 102370. https://doi.org/10.1016/j.jksus.2022.102370

Arumuganathan, T., Manikantan, M. R., Rai, R. D., Anandakumar, S., & Khare, V. (2009). Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. *International Agrophysics*, *23*(1), 1–7.

Boateng, J., Verghese, M., Walker, L. T., & Ogutu, S. (2008). Effect of processing on antioxidant contents in selected dry beans (*Phaseolus* spp. L.). *LWT - Food Science and Technology*, *41*(9), 1541–1547. https://doi.org/10.1016/j.lwt.2007.11.025

Chayjan, R. A., Salari, K., Abedi, Q., & Sabziparvar, A. A. (2013). Modeling moisture diffusivity, activation energy and specific energy consumption of squash seeds in a semi fluidized and fluidized bed drying. *Journal of Food Science and Technology*, *50*(4), 667–677. https://doi.org/10.1007/s13197-011-0399-8

de la Torre, A. A. S. B., Henderson, T., Nigam, P. S., & Owusu-Apenten, R. K. (2015). A universally calibrated microplate ferric reducing antioxidant power (FRAP) assay for foods and applications to Manuka honey. *Food Chemistry*, *174*, 119–123. https://doi.org/10.1016/j.foodchem.2014.11.009

Doymaz, İ., & Sahin, M. (2016). Effect of temperature and pre-treatment on drying and rehydration characteristics of broccoli slices. *Journal of Food Measurement and Characterization*, *10*(2), 364–373. https://doi.org/10.1007/s11694-016-9315-2

Dueñas, M., Fernández, D., Hernández, T., Estrella, I., & Muñoz, R. (2005). Bioactive phenolic compounds of cowpeas (*Vigna sinensis L*). Modifications by fermentation with natural microflora and with *Lactobacillus plantarum* ATCC 14917. *Journal of the Science of Food and Agriculture*, *85*(2), 297–304. https://doi.org/10.1002/jsfa.1924

Hashemi, G., Mowla, D., & Kazemeini, M. (2009). Moisture diffusivity and shrinkage of broad beans during bulk drying in an inert medium fluidized bed dryer assisted by dielectric heating. *Journal of Food Engineering*, *92*(3), 331–338. https://doi.org/10.1016/j.jfoodeng.2008.12.004

Herald, T. J., Gadgil, P., & Tilley, M. (2012). High-throughput micro plate assays for screening flavonoid content and DPPH-scavenging activity in sorghum bran and flour. *Journal of the Science of Food and Agriculture*, *92*(11), 2326–2331. https://doi.org/10.1002/jsfa.5633

Houshmand-Dalir, M., Tavakolipour, H., Chaji, H., Kalbasi-Ashtari, A., & Sharayei, P. (2022). The impacts of fluidized and static bed drying methods on bio-active compounds and antioxidant properties of saffron petal [Special issue]. *Journal of Medicinal Plants and By-products*, *11*, 117–125. https://doi.org/10.22092/jmpb.2020.128832.1166

Kaleta, A., & Górnicki, K. (2010). Some remarks on evaluation of drying models of red beet particles. *Energy Conversion and Management*, *51*(12), 2967–2978. https://doi.org/10.1016/j.enconman.2010.06.040

Kassem, A. S. (1996). Comparative studies on thin-layer drying models for wheat. *Proceedings of the 13th International Congress on Agricultural Engineering*, *6*, 2–6.

Khanali, M., Banisharif, A., & Rafiee, S. (2016). Modeling of moisture diffusivity, activation energy and energy consumption in fluidized bed drying of rough rice. *Heat and Mass Transfer*, *52*(11), 2541–2549. https://doi.org/10.1007/s00231-016-1763-z

Khoshtaghaza, M. H., Darvishi, H., & Minaei, S. (2015). Effects of microwave-fluidized bed drying on quality, energy consumption and drying kinetics of soybean kernels. *Journal of Food Science and Technology*, *52*(8), 4749–4760. https://doi.org/10.1007/s13197-014-1557-6

Kingsly, R. P., Goyal, R. K., Manikantan, M. R., & Ilyas, S. M. (2007). Effects of pretreatments and drying air temperature on drying behavior of peach slice. *International Journal of Food Science and Technology*, *42*(1), 65–69. https://doi.org/10.1111/j.1365-2621.2006.01210.x

Li, L., Liu, B., & Zheng, X. (2011). Bioactive ingredients in adzuki bean sprouts. *Journal of Medicinal Plants Research*, *5*(24), 5894–5898.

Li, Q., Wang, S., Wang, R., Shen, D., Mo, R., Tang, F., & Liu, Y. (2024). Comparative investigation on the phenolic compounds and antioxidant capacity of walnut kernel from different drying methods. *Food Production, Processing and Nutrition*, *6*(1), Article 41. https://doi.org/10.1186/s43014-023-00216-2

Madhiyanon, T., Phila, A., & Soponronnarit, S. (2009). Models of fluidized bed drying for thin-layer chopped coconut. *Applied Thermal Engineering*, *29*(14–15), 2849–2854. https://doi.org/10.1016/j.applthermaleng.2009.02.003

Moongngarm, A., & Saetung, N. (2010). Comparison of chemical compositions and bioactive compounds of germinated rough rice and brown rice. *Food Chemistry*, *122*(3), 782–788. https://doi.org/10.1016/j.foodchem.2010.03.053

Nanan, K., Eiamsa-ard, S., Chokphoemphun, S., Kumar, M., Pimsarn, M., & Chuwattanakul, V. (2023). Influence of bed height and drying temperature on shrimp drying characteristics using a fluidized-bed dryer. *Case Studies in Thermal Engineering*, *48*, Article 103144. https://doi.org/10.1016/j.csite.2023.103144

Siddhuraju, P. (2006). The antioxidant activity and free radical-scavenging capacity of phenolics of raw and dry heated moth bean (*Vigna aconitifolia*) (Jacq.) Marechal seed extracts. *Food Chemistry*, *99*(1), 149–157. https://doi.org/10.1016/j.foodchem.2005.07.029

Sitorus, A., Novrinaldi, N., Putra, S. A., Cebro, I. S., & Bulan, R. (2021). Modelling drying kinetics of paddy in a swirling fluidized bed dryer. *Case Studies in Thermal Engineering*, *28*, Article 101572. https://doi.org/10.1016/j.csite.2021.101572

Surayot, P., & Seekhaw, P. (2018). Phytochemical screening, determination of total phenolic and flavonoid contents and antioxidant activities from *Crateva Magna* (LOUR.) DC. *Rajabhat Journal of Sciences, Humanities & Social Sciences*, *19*(2), 297–305. https://ph01.tci-thaijo.org/index.php/psru/article/view/137091

Umar, A., Khan, M. T., Bukhari, S., Sardar, R., Naheed, K., Younas, H., Hussain, S., Gillani R. A., & Kiani, R. K. (2022). *Antioxidant activity and total phenolic contents of dried and germinated legumes*. Research Square. https://doi.org/10.21203/rs.3.rs-1239490/v1

Wang, C., & Singh, R. P. (1978). Use of variable equilibrium moisture content in modeling rice drying. *Transactions of American Society of Agricultural Engineers*, *11*(6), 668–672.

Zogzas, N. P., Maroulis, Z. B., & Marinos-Kouris, D. (1996). Moisture diffusivity data compilation in foodstuffs. *Drying Technology*, *14*(10), 2225–2253. https://doi.org/10.1080/07373939608917205