Evaluation of the Drying Kinetics of Swirling Fluidized Bed Drying and Performance Assessment on the Nutritional Properties of Bentong Ginger

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Evaluation of the Drying Kinetics of Swirling Fluidized Bed Drying and Performance Assessment on the Nutritional Properties of Bentong Ginger

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Abstract

Bentong ginger (BG), grown in a high-altitude area of Bentong, Malaysia, has a similar scientific name to the common ginger species and has been patented by the Malaysian government. BG is known for its larger size and pungent taste and is nutritionally rich in antioxidants such as gingerols, which are responsible for a wide range of pharmacological and physiological effects in human health. This study presents the effect of swirling fluidized bed drying (SFBD) compared with oven drying (OD) and freeze-drying techniques (FD) on the drying kinetics, antioxidant potential, and 6-gingerol concentration of BG. The Midilli-Kucuk model showed the best fit at explaining the thin layer drying behavior of the BG for OD and SFBD, whereas the Page model showed the best fit for FD. The experimental results showed that SFBD reduces the total drying time (250 min) and energy consumption (160.4976 kWh/kg) with higher drying rate (0.1813 g/min) and moisture diffusivity (2.4317 × 10-10 m^2/s). In addition, the dried BG sample from the SFBD exhibited a slightly higher DPPH inhibition (89.2%) and the best option to preserve the 6-gingerol compound (2.626 mg/mL) in the Liquid Chromatography Quadrupole Time-of-Flight Mass Spectrometry (LC-QTOF/MS) analysis. Thus, the SFBD approach proved to be a feasible method for drying ginger.

Keywords: Bentong ginger; DPPH antioxidant; drying techniques; 6-gingerol, drying kinetics

Statements and Declarations

The authors declare that this contribution is original; it has never been published in any language that is currently being considered by another publication. The previously published article has been clearly referenced if the manuscript reports work that has been reported in a previously published paper. Permission to reproduce illustrations, tables, etc. from other publications been obtained. All of the named authors have seen and approved the work, and there are no other people who meet the authorship criteria but aren't included.

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1. INTRODUCTION

Ginger, scientifically known as *Zingiber officinale* Roscoe, is a member of the *Zingiberaceae* family that is consumed as a spice and condiment in food (An et al., 2020), popular for its unique pungent taste for traditional medicine, and used in health care products (Rupasinghe & Gunathilake, 2015). The presence of bioactive components in ginger, such as gingerols, phenolics, terpenes, and shogaols, is associated with health-promoting properties. In particular, 6-gingerol has a wide spectrum of biological activities such as antioxidant, antimicrobial, anti-cancer, anti-inflammatory, and analgesic effects (Majumder et al., 2021). Meanwhile, Bentong ginger (BG) is a ginger that is patented in Malaysia. Its name is adapted from a local plantation area in Bentong, Pahang. BG shares the same scientific name with the common ginger and is reported to have a high 6-gingerol content of up to 1.47 mg/g (Ghasemzadeh et al., 2016). It exhibits distinguishable traits such as a large size, a spicier and pungent taste, and a brownish color compared to the common ginger, as illustrated in Fig. 1 (Hosnan, 2019).

Fresh ginger contains 80–95% water, which makes the plant more susceptible to microbial growth and easier to rot and perish during postharvest storage. Meanwhile, dried ginger can be found widely in the local market, used as a spice, health supplement, and tea infusion. However, conventional drying limits its function due to the modification of the appearance, taste, and quality of the ginger. 6-gingerol, a vulnerable active compound associated with the pungent taste, is affected during drying due to its heat sensitive characteristics and the long drying process. Microorganism inhibition is effective when the moisture content of dried ginger is less than 10 wt %, whereas flavour and nutrition of foods can be preserved when the moisture content is less than 5 wt % (Geankoplis, 2014). Thus, a feasible drying technique that has an efficient water loss, is a low thermal approach, and minimizes the changes in the food nutrition is an important achievement not only from a food quality point of view but also economically.

Fig. 1 Image comparing common ginger (a) and Bentong ginger (b).

Several investigations on drying ginger have been undertaken using various dehydrating techniques such as microwave and hot air drying (An et al., 2016), convective drying (Ikechukwu et al., 2020; Izli & Polat, 2019), infrared drying (Osae et al., 2020), and freeze and vacuum drying (Ren et al., 2021). Hot air oven drying (HAOD) is the oldest dehydration technique and is widely used in the food industry; however, if the conditions of this technique are not controlled, such as high temperature and long processing time, it results in significant deterioration of quality attributes such as color, nutrient concentration, flavor, and texture. Freeze drying (FD) could potentially be a feasible alternative for producing high-quality dried ginger that has a good color and appearance and preserves its nutritional quality (Ren et al., 2021). However, this method is expensive and would not be cost effective for larger scale production (Melgar-Lalanne et al., 2017). To overcome the aforementioned challenges, the swirling fluidized bed drying (SFBD) is a new and simple design of the drying process that uses homogenous and quick drying, making it a great option for drying heat-sensitive compounds like gingerols. Our preliminary design of SFBD was developed by Abdul Halim et al., (2020). It was observed that the 67° swirling distributor had the best drying performance across all velocities without a negative impact on the stingless bee pot-pollen nutrients. Fluidized bed drying has a number of advantages, including ease of management, high dehumidification, minimal maintenance costs, and excellent thermal efficiency. Besides, the market price of BG is higher than that of common ginger due to its high pungent taste and high concentrations of bioactive compounds (Sharizan & Sahilah, 2021). However, because BG is a unique plant only produced in Malaysia, there has been no research reported on using the SFBD for BG; thus, this is the motivation for the current work.

The drying technique is essential for preserving and extending the shelf life of BG. Lowering the moisture content delays the deterioration and extends the storage time, all of which improve the product quality. Aside from retaining the nutritional quality of BG, economic and environmental factors should be considered. The drying process is said to be efficient if it saves time, energy, and money. The rate of moisture removal indicates the effectiveness of the drying process time (Ahmad et al., 2017). There have been limited studies on the identification of bioactive compounds, particularly 6-gingerol, and the antioxidant abilities have not been investigated in relation to the dehydration of gingers using the SFBD drying process compared to conventional freeze and oven drying. Hence, this work evaluates the drying kinetics of different drying methods, including oven drying (OD), freeze drying (FD) and swirling fluidized bed drying (SFBD) in terms of moisture content, moisture ratio curves with the aid of mathematical models, drying rate curves, average drying rate, specific energy consumption, and effective moisture diffusivity. This work also studies the effect of all the drying techniques on the antioxidant activity of BG and its 6-gingerol concentration. To the best of the authors' knowledge, there have been no research studies on the use of thin-layer modelling for BG. As a result, this research reports, for the first time, on the application of thin-layer modelling to determine the drying characteristics of BG as a function of three different drying processes.

2. MATERIALS AND METHODS

2.1 Materials

Fresh Bentong ginger (BG) was procured from Pahang Agriculture Department, Malaysia. The samples were stored at -4 °C until further processing. All chemicals and reagent used in this study were of commercial grade. The chemicals used were ethanol (95% purity), methanol (99.4% purity), formic acid (HPLC grade), acetonitrile (HPLC grade), Folin-Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl free radical (DPPH•) solid, and sodium carbonate, which were purchased from Sigma-Aldrich (Gillingham, England).

2.2 Sample Preparation

The dirt and soil on the ginger rhizome were removed by thoroughly washing it in water and then drying it to remove excess water. The samples were then diced into uniform dimensions of 1 mm × 1 mm × 1 mm each prior to drying (Ghafoor et al., 2020).

2.3 Drying Techniques

2.3.1 Oven Drying

The oven drying method was performed by following the method of Ghafoor et al., (2020) with minor modifications. All samples (50 g each) were placed on a tray and dried in a conventional oven (Memmert UFB400, Germany) at 40 °C with the speed fan of 100%.

2.3.2 Freeze Drying

The freeze drying method reported in work of Ghafoor et al., (2020) was applied with minor modifications. Ginger samples (50 g each) were placed in a container and pre-frozen at -30 °C for 24 h and then dried in the freeze drier (Labconco, North Carolina) at -80 °C.

2.3.3 Swirling Fluidized Bed Drying

The swirling fluidized bed dryer was set up based on a previous study by Abdul Halim et al., (2020). Fig. 2 shows the swirling distributor design and setup of the SFBD. Ginger samples were placed inside the drying chamber, which was equipped with a 67° swirling distributor. A low-pressure blower (Venz, Thailand) supplied the superficial air velocity and was set at 2.0 m/s and at ambient conditions.

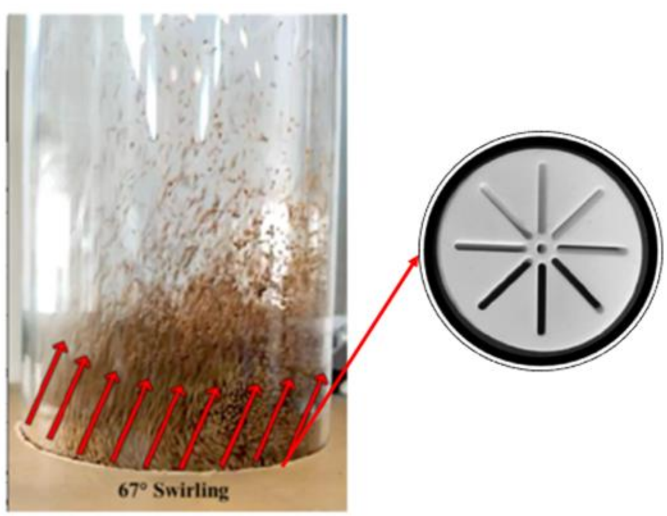


Fig. 2 Drying chamber of the fluidized bed dryer equipped with a 67° swirling distributor (Abdul Halim et al., 2020)

2.4 Sample Extraction

The dried samples were blended in a grinder to form a fine particle powder. Then, the powdered samples were mixed homogenously with an ethanol:water (70:30 v/v) solvent at a ratio of 1:20 according to the method of Cha et al., (2020) with slight modifications. The solutions were magnetically stirred at room temperature for 24 h, followed by separation by using a refrigerated centrifuge (Eppendorf 5810r, USA) at 4000×g for 30 min to obtain the liquid extract. The liquid extracts were then filtered using filter paper (Whatman Grade 41, 60 mm circle) to remove the excess solid.

2.5 Sample Analysis

2.5.1 Moisture Content

A thermogravimetric method was used to determine the moisture content of the dried ginger samples (Abdul Halim et al., 2020). The following equation was used to determine the moisture content:

$$Moisture\ Content, MC\ (\%) = \left(\frac{w_i - w_f}{w_i}\right) \times 100\ \% \tag{1}$$

where w_i and w_f are the initial and final weights (g), respectively.

2.5.2 Moisture Ratio

The moisture ratio (MR) of the ginger during the drying process was calculated using Equation 2.

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{2}$$

where M_t is the moisture content at t (kg H_2O kg^{-1} d.m.), t is the time (min), M_e is the equilibrium moisture content (kg H_2O kg^{-1} d.m.), and M_o is the initial moisture content at t (kg H_2O kg^{-1} d.m.) (Górnicki et al., 2020). The relative moisture content of the drying air is simplified into Equation 3 because the drying changed continually during the drying procedures (Tai et al., 2021).

$$MR = \frac{M_t}{M_o} \tag{3}$$

2.5.3 Drying Rate

The drying rate (DR) is defined as the quantity of moisture that has evaporated over time. The drying rates are calculated by using Equation 4

$$Drying\ rate, DR = \left(\frac{M_{t1} - M_{t2}}{t_2 - t_1}\right) \tag{4}$$

where M_{t1} and M_{t2} are the moisture content of the samples (kg water/kg dry solid) at time t_1 and t_2 (min), respectively (Kavak Akpinar & Toraman, 2016).

2.5.4 Average Drying Rate

The average drying rate can then be determined based on the total reduction in the moisture content. The following equation describes the drying rates (Abdul Halim et al., 2020).

$$Average\ drying\ rate, \eta_D\ \ (\%/min) = \left(\frac{\Delta MC}{t}\right) \tag{5}$$

where ΔMC is the reduction in the moisture content in terms of percentage (%) and t is the total drying period (min).

2.5.5 Specific Energy Consumption

The total energy consumption by each drying method can be calculated as follows:

$$Total\ energy\ consumption, E_T\ (kWh) = P_{avg} \times T_D \tag{6}$$

where P_{avg} is the average amount of power used (W) and T_D is the total duration of drying (h).

The amount of Specific Energy Consumption, *SEC*, needed to dry the ginger for every drying method tested can then be calculated using the following equation:

$$SEC\ \left(\frac{kWh}{kg}\right) = \frac{E_T}{\Delta w} \tag{7}$$

where Δw is the change in the weight for each dried sample.

2.5.6 Effective Moisture Diffusivity

According to Ajayi et al., (2017), the effective moisture diffusivity of vegetables and fruits can be determined using Fick's second law of diffusion. By assuming a slab geometry for ginger, the value of the effective diffusivity (D_{eff}) can be obtained using Equation 8.

$$MR = \left(\frac{M - M_e}{M_0 - M_e}\right) = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4(L)^2}\right) \tag{8}$$

Equation 8 can further be simplified and expressed in logarithmic form, and a new linear equation is obtained, as shown in Equation 9. The value of D_{eff} can be obtained by plotting the experimental drying data in terms of ln MR versus drying time (t) in a linear graph. All calculations of D_{eff} are performed using Microsoft Excel.

$$\ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4(L)^2}\right) \tag{9}$$

where D_{eff} is effective moisture diffisuvity (m^2/s), L is the half thickness of ginger (m), t is the drying time (s), and π is a constant.

2.5.7 Mathematical Modelling

Several studies have suggested semi-theoretical and empirical models to describe the kinetic dynamics of the thin-layer drying process. The drying curves of the moisture ratio were fitted with seven thin-layer drying models in order to find the best model for characterizing the BG drying curve. The models are listed in Table 1. Nonlinear regression analysis was performed using the statistical software SPSS to analyze the parameters of the chosen model. The root means square error (RMSE), coefficient of determination (R^2), and chi-square (χ^2) were computed and used as major criteria for choosing the best equation to account for the variance in the drying curves of the dried samples. The best fit was determined by using the highest R^2 values and the lowest χ^2 and RMSE values. The following model equations I-VII can be used to calculate these statistical data (Tai et al., 2021).

Table 1 Selected thin layer drying models for describing the drying characteristics of Bentong ginger (Tai et al., 2021)

Model No.	Model Name	Model Equation
I	Lewis (Newton)	$MR = e^{(-kt)}$
II	Page	$MR = e^{(-k(t)^n)}$
III	Henderson and Pabis	$MR = ae^{(-kt)}$
IV	Logarithmic	$MR = ae^{(-kt)} + c$
V	Two-term exponential model	$MR = ae^{(-kt)} + (1-a)e^{(-kat)}$
VI	Wang and Singh	$MR = 1 + at + bt^2$
VII	Midilli-Kucuk	$MR = ae^{(-k(t)^n)} + bt$

2.5.8 DPPH Radical Scavenging Activity

Ginger sample extracts were analysed by using DPPH (2,2-diphenyl-1-picrylhydrazyl) following the method described by Ajayi et al., (2017) with minor modifications. To prepare 0.2 mM of the DPPH reagent, 0.0016 g of DPPH was added to 200 mL of methanol. Before being used, the reagent was kept in the dark for 24 h. Then, a cuvette was filled with 25 µL of sample and 975 µL of DPPH reagent and covered with parafilm. The solution was vigorously shaken for 10 s and then left at room temperature for 4 h. The absorbance was measured at 517 nm using a UV-vis spectrophotometer (Thermoscientific Genesys 50, Singapore). The following equation was used to calculate the antioxidant activity (DPPH radical scavenging):

$$DPPH\ Radical\ Scavenging\ (\%) = \frac{A_c - A_s}{A_c} \times 100\ \% \tag{10}$$

where A_c is the control absorbance of the DPPH reagent and A_s is the absorbance of the sample and the DPPH reagent mixture.

2.5.9 6-Gingerol Quantification

Liquid chromatography quadrupole time-of-flight mass spectrometry (LC-QTOF/MS) analysis was performed using the Vion IMS LCQTOF MS system to quantify the 6-gingerol content in the ginger extracts. The column used was ACQUITY CSH C_{18} (1.7 µm, 2.1 × 100 mm). The temperature of the column was kept at 40.0 °C. The injection volume was 1 µL, and the flow rate was 0.5 mL/min. For solvent A, the mobile phase was water with 0.1% formic acid, whereas for solvent B, it was acetonitrile with 0.1% formic acid. The gradient consisted of solvent B at the following concentrations: 2% to 30% over 7 min, 100% at 8 min, and hold until 10 min. The UV detection wavelength was set at 254 nm with a spectral channel resolution at 1.2 nm. A standard solution of 6-gingerol with purity ≥ 98% (HPLC grade) was purchased from Sigma Aldrich. By comparing the peak areas of the ginger extracts to those of the standard solution, the concentration of 6-gingerol in the extracts was estimated.

2.5.10 Statistical Analysis

The statistical analysis was performed using SPSS statistical software version 17.0 and one-way analysis of variance (ANOVA) (Chicago, IL, USA: SPSS Inc.). Significant differences at $p < 0.05$ were determined using Bonferroni's test. Each sample was measured in triplicate, with an average standard deviation of less than 5% for each.

3. RESULTS AND DISCUSSION

3.1 Moisture Content (MC)

The moisture level of food is used to estimate its stability and susceptibility to microbial contamination. Moisture content is set below 10 wt% as a target to inhibit the microbial growth, resulting in a reduced shelf life and large postharvest losses. The microorganism activity becomes inactive when the moisture content is below 10 % (Geankoplis, 2014). The moisture content of BG removed by OD, FD, and SFBD drying procedures was 90.40%, 90.64%, and 90.64%, respectively. The moisture content value of BG affected by the three different drying methods is considered to be comparable to the previous findings. According to Cherrat et al., (2019), the moisture loss using oven drying at 40 °C was 89.42%. The moisture content of BG dried under the standard drying method at 105 °C for 3 h using an oven reported previously by Sharizan & Sahilah, (2021) and Lim, (2019) was 88.57% and 78.8%, respectively. Overall, all drying techniques used in this study successfully removed up to 90% of the moisture content while leaving 10% moisture in the dried BG.

3.2 Moisture Ratio

The moisture ratios of the ginger samples at 40 °C during the drying process, oven drying (OD), swirling fluidized bed drying (SFBD), and -80 °C for freeze drying (FD) are depicted as drying curves in Fig. 3. The moisture content was measured every 10 min for OD and SFBD and every 4 h for FD during the drying process until a consistent weight was achieved. As presented in Fig. 3, the moisture ratio dropped as the drying time increased for all the drying techniques. A comparison of the three results reveals that the SFBD approach was shorter, taking only around 250 min (4.17 h), whereas OD and FD took 300 min (5 h) and 2160 min (36 h), respectively. In comparison to previous findings, the time taken for OD in our findings was less than that reported by Cherrat et al., (2019), where the constant weight of ginger was achieved at 710 min (11.83 h) at 40 °C, while the time taken for FD in our findings was higher than that reported by Ren et al., (2021), where the constant weight of ginger was achieved at 1110 min (18.5 h) at -80 °C.

It is apparent that the moisture ratio curve for the SFBD ginger decreased significantly at the initial stage compared to the OD and FD ginger. This can be explained by the fact that in SFBD, heat travels through a floating state, allowing the full surface of the product to be exposed to air, and the bed temperature remains consistent during the drying period, resulting in fast drying. However, in OD, the heat passes through the surface of the food material, which requires more time for heat to be transferred to the inner parts of the food (Sivakumar et al., 2016). Also, due to the poor heat transfer rate as the sublimation front goes from the exterior to the interior of the frozen ginger being dried, FD takes longer than OD and SFBD (Sivakumar et al., 2016). The study reported by Chupawa et al., (2021), stated that the hydrodynamics of gas-solid phases are directly linked to the heat transfer phenomena, and turbulence can improve the flow homogeneity and mixing efficiency.

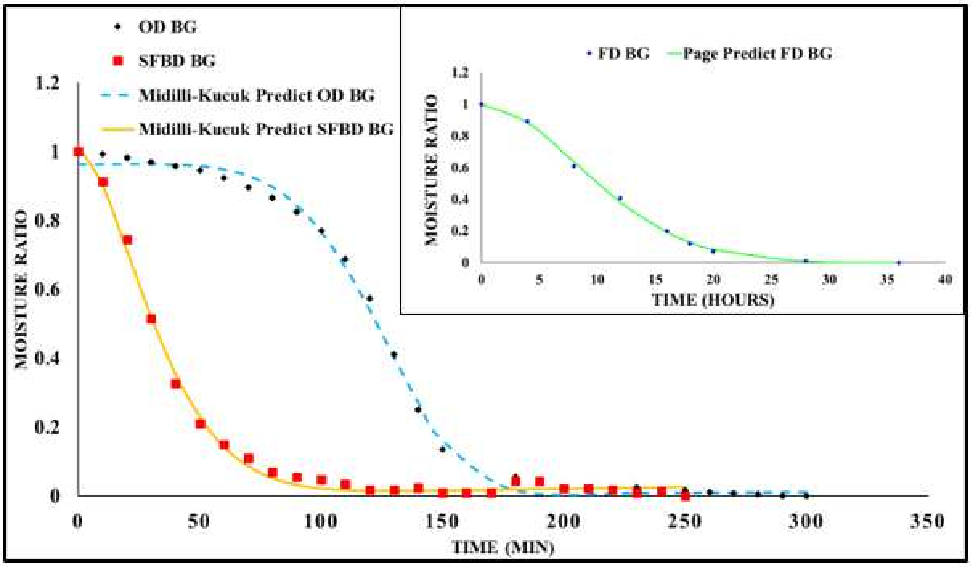


Fig. 3 Drying curves of the predicted and experimental moisture ratio against time

3.3 Drying Rates and Average Drying Rates

Fig. 4 shows that SFBD has the highest drying rate, followed by OD and FD. Furthermore, a comparison of the average drying rates also shows that SFBD has a higher average drying rate than OD and FD, as shown in Table 2. This suggests that the swirling condition of the fluidized bed increases the moisture removal and driving effective potential for heat and mass transfer (Chuwattanakul & Eiamsa-Ard, 2019), which is consistent with the results discussed previously by Abdul Halim et al., (2020), who discovered that the drying rate of bees pot-pollen using SFBD was faster than that of standard FBD and OD. Besides, the swirling motion of bed particles produces cyclone-like features that contribute to the low elutriation (Haron et al., 2017).

According to Makarichian et al., (2021), the initial, constant rate, and falling rate are the three stages of the standard drying process. Fig. 4 illustrates the variation in the drying rate versus moisture content during the drying processes. The results reveal that the drying rate increased with a rapid spike at high moisture content levels for all the drying procedures and then steadily dropped thereafter except for SFBD. During the initial stage, water is removed from the bigger capillaries, while water is removed from the smaller capillaries during the falling stage, making water dehydration more complicated and the drying rate decrease as the drying period passes (Altay et al., 2019). In the OD procedure, all of the drying stages were observed, whereas in the FD and SFBD procedures, only the initial and falling rate stages were observed. The absence of the constant rate stage is quite frequent when drying agro products. At the constant rate stage, surface moisture is known to be the most effective factor (Makarichian et al., 2021). Hence, it can be concluded that the presence of the constant rate stage in OD was due to the presence of surface moisture. Besides, it is possible that the constant rate stage in FD was not observed because of the long measurement interval (4 h). Furthermore, failure to detect the constant rate stage in SFBD could be attributed to drying mechanisms that accelerated the removal of the surface moisture and increased the outflow of moisture.

Table 2. Comparison of the drying potential of OD, FD, and SFBD

Drying Method	OD	FD	SFBD
Average drying rate (g/min)	0.1507	0.0210	0.1813
Specific energy consumption (kWh/kg)	221.1900	1469.5499	160.4976
Effective moisture diffusivity (D_{eff}) m²/s	2.0264×10^{-10}	1.8643×10^{-11}	2.4317×10^{-10}

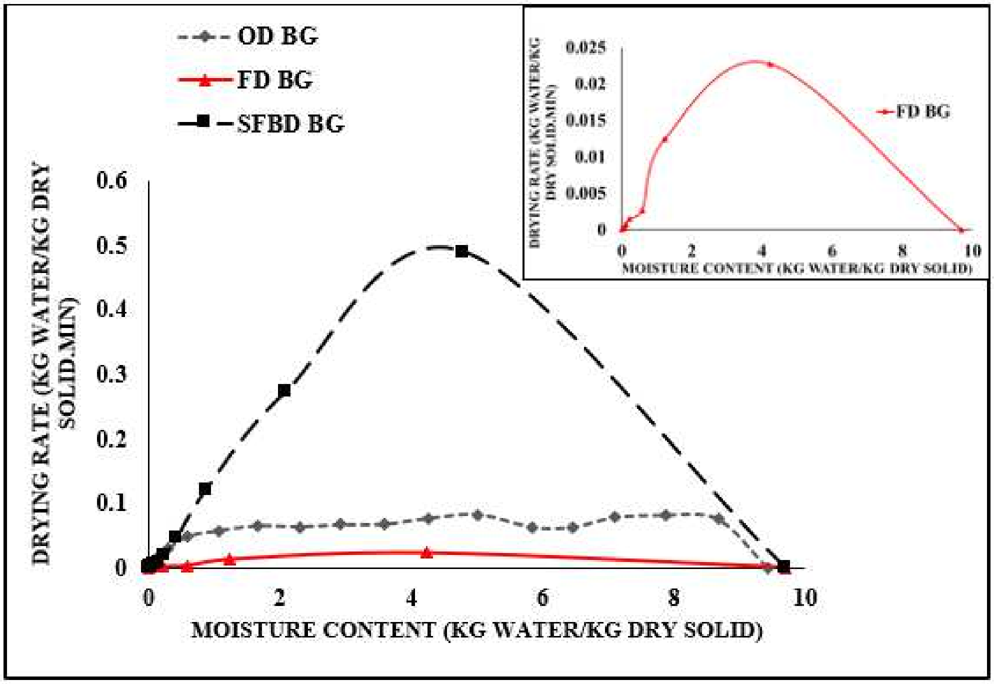


Fig. 4 Variation in the drying rate versus moisture content

3.4 Specific Energy Consumption (SEC)

Dehydrating is the most energy-intensive drying procedure used in agricultural and food-processing operations, accounting for 20–30% of the total energy consumption (Ye et al., 2021). Moreover, higher energy consumptions translate into higher costs. Thus, estimating the amount of energy consumed during a sample drying process could greatly benefit industries by allowing them to choose the technique that uses the least amount of energy and thus save money (Mouhoubi et al., 2022). From Table 2, SFBD has the lowest energy consumption of 160.50 kWh/kg compared to 221.19 kWh/kg and 1469.55 kWh/kg for OD and FD, respectively. The high energy usage from the oven drying is due to its heating element to maintain the hot temperature. On the other hand, freeze drying relies on a compressor and vacuum pump, which require high energy. Additionally, Rabha et al., (2017) claimed that the specific energy consumptions depend on the drying time. Our data support the claim because the drying times for OD and FD are longer than for SFBD, which results in a higher specific energy consumption. In conclusion, SFBD is preferable in terms of energy consumption compared to oven drying and freeze drying.

3.5 Effective Moisture Diffusivity

Effective moisture diffusivity is a crucial indicator in choosing the most appropriate drying techniques that could improve the lifespan of the product. It is defined as the moisture movement and is strongly related to the drying rate. It is widely accepted that Fick's second law can be applied during the falling rate period of drying because drying is primarily controlled by diffusion (Suherman et al., 2021). The obtained result revealed that the value of D_{eff} for SFBD was slightly higher compared to OD and higher than FD, as presented in Table 2. Previous studies reported that the value of D_{eff} for ginger dried at 40 °C ranged from 2.57×10^{-10} m^2/s to 5.49×10^{-10} m^2/s using an ARS-0680 environmental chamber (Ikechukwu et al., 2020), hybrid solar dryer (Ghafoor et al., 2020), cyclone type convective dryer (Onwude et al., 2016), and convection-desiccant dryer (Hasibuan & Bairuni, 2018). No studies have reported the value of D_{eff} for FD ginger. The value of D_{eff} for ginger dried using FD and SFBD is reported for the first time in this work. D_{eff} of BG was comparable to other spices, such as basil leaves, mango ginger, mint leaves, and parsley, which have effective diffusivity values ranging from 4.53×10^{-12} to 2.65×10^{-10} m^2/s (Onwude et al., 2016). The study reported by Onu Chijioke et al., (2017), mentioned that for agricultural and food products, the effective moisture diffusivity varies from 10^{-11} to 10^{-9} m^2/s, which includes the values obtained in this study. Ahmad et al., (2017) mentioned that a higher effective moisture diffusivity value indicates that the moisture removal process to the environment has been sped up and the drying time has been reduced, promoting an efficient drying technique in terms of time and energy consumption. This is consistent with our findings that SFBD consumes less specific energy than OD and FD.

3.6 Mathematical Modelling

The moisture content of BG was computed as a moisture ratio and fitted to seven thin-layer drying models using experimental data from three different drying processes. Table 3 shows the obtained results as well as the model's statistical analysis, which included the coefficient of correlation (R^2), the root mean square error (RMSE), and Chi-square (χ^2). If a thin-layer model has a higher R^2 value (near one), as well as a lower RMSE and χ^2 value, it is considered acceptable for the experimental data (Suherman et al., 2021). As shown in Table 3, the values of the R^2, RMSE, and χ^2 for seven drying models and all drying techniques ranged from 0.7961–0.9985, 0.0143–0.1886, and 0.0003–0.0370, respectively. The coefficient of correlation value, $R^2 > 0.95$, indicates a satisfactory fit. In comparison to others, the Midilli-Kucuk model was the best fit for OD and SFBD, while the Page model was the best fit for FD. Although the Page model was chosen for FD, the Midilli-Kucuk model also best fits the experimental data, as it shows only a slight difference in terms of the RMSE value when compared to the Page model. The Midilli-Kucuk model was found in several studies to be able to fit drying curves of food products dried using an oven, such as sweet potato slices (Gasa et al., 2022), Chinese saffron (*Crocus sativus* L) (Yao et al., 2019), pomegranate fruit peel (Mphahlele et al., 2019), and *Plectranthus amboinicus* leaves (Nurafifah et al., 2018). Similarly, for freeze-dried products such as purple shallots (Thuy et al., 2020), tomato (Lopez-Quiroga et al., 2019), red pepper (Koc, 2020), and water chestnut (Yang et al., 2019), the Page model was determined to be the best fit model. The Page model and two-term exponential model also fit well because the parameter values only differ slightly in comparison to the Midilli- Kucuk model for OD and SFBD, respectively.

According to previous research studies, the Page model and two-term exponential model were determined to be the best thin-layer model to represent the behavior of ginger for some other drying methods, namely, hybrid solar drying (Suherman et al., 2021), an integrated solar drying (Borah et al., 2017), convective drying (Hasibuan & Bairuni, 2018; Ikechukwu et al., 2020; Izli & Polat, 2019), vacuum drying (Thorat et al., 2012) and microwave drying (Izli & Polat, 2019). Fig. 3 represents the drying curves of predicted and experimental moisture ratio data for all drying methods, and Fig. 5 a), b), and c) reveal that all of the data for all drying procedures are close to the straight line, indicating that the experimental and predicted moisture values based on the Midilli Kucuk model for OD and SFBD and the Page model for FD are in agreement. The moisture ratio of the ginger for three different drying methods can be predicted using the following equations:

For **OD**: $\mathrm{MR} = 0.9625\mathrm{e}^{\left(-1.5217\times10^{-11}(\mathrm{t})^{5.0910}\right)} + 3.5012\times10^{-5}\mathrm{t}$, $R^2 = 0.9975$, $\chi^2 = 0.0005$, RMSE = 0.0209

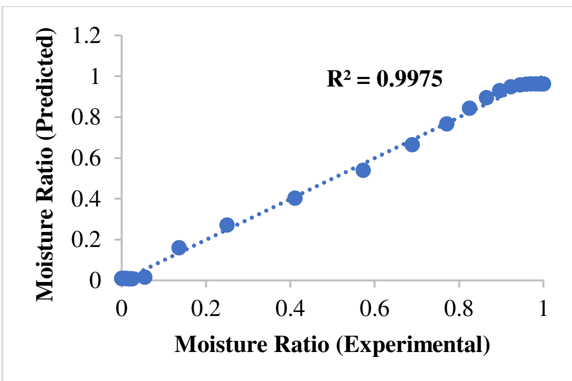
For **FD**: $\mathrm{MR} = \mathrm{e}^{\left(-4.7396\times10^{-6}(\mathrm{t})^{1.8576}\right)}$, $R^2 = 0.9985$, $\chi^2 = 0.0003$, RMSE = 0.0141

For **SFBD**: $\mathrm{MR} = 1.0162\mathrm{e}^{\left(-0.0032(\mathrm{t})^{1.5709}\right)} + 0.0001\mathrm{t}$, $R^2 = 0.9965$, $\chi^2 = 0.0003$, RMSE = 0.0168

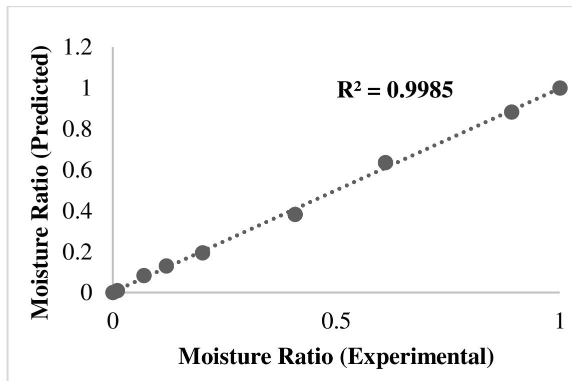
Table 3 Thin-layer models applied to the drying curves for BG affected by different drying techniques

Model	Drying techniques	Model constants	R^2	χ^2	RMSE
Lewis	OD	k = 0.0066	0.7961	0.0370	0.1886
	FD	k = 0.001443	0.9324	0.0099	0.0940
	SFBD	k = 0.0262	0.9678	0.0027	0.0510
Page	OD	k = 3.5180E-10; n = 4.4527	0.9954	0.0009	0.0282
	FD	k = 4.7396E-06; n = 1.8576	0.9985	0.0003	0.0141
	SFBD	k = 0.0032; n = 1.5642	0.9935	0.0006	0.0229
Henderson-Pabis	OD	a = 1.2514; k = 0.0083	0.8534	0.0278	0.1599
	FD	a = 1.1052; k = 0.0016	0.9453	0.0092	0.0846
	SFBD	a = 1.1061; k = 0.0287	0.9763	0.0021	0.0438

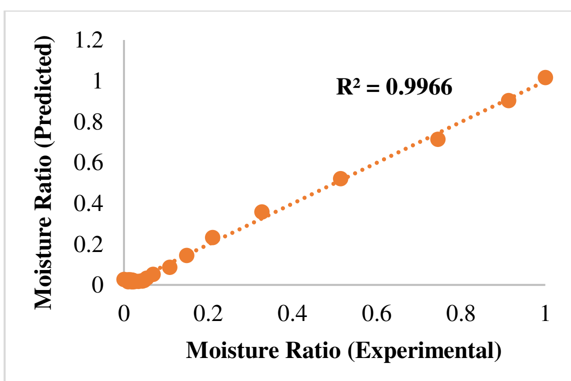
Logarithmic	OD	a = -1998.9134; k = -2.0620E-06; c = 1999.9834	0.9070	0.0184	0.1273
	FD	a =1.2632; k = 0.0011; c = -0.1808	0.9653	0.0068	0.0673
	SFBD	a = 1.1065; k = 0.0286; c = -0.0007	0.9763	0.0022	0.0438
Two-term exponential	OD	a = 2.3976; k = 0.0128	0.9358	0.0122	0.1058
	FD	a = 2.2427; k = 0.0025	0.9940	0.0010	0.0280
	SFBD	a = 2.1257; k = 0.0433	0.9958	0.0004	0.0183
Wang and Singh	OD	a = -0.0039; b = 4.8824E-07	0.8981	0.0193	0.1333
	FD	a = -0.0010; b = 2.7502E-07	0.9758	0.0041	0.0562
	SFBD	a = -0.0134; b = 4.0588E-05	0.8408	0.0139	0.1134
Midilli-Kucuk	OD	a = 0.9625; k = 1.5217E-11; n = 5.0910; b = 3.5012E-05	0.9975	0.0005	0.0209
	FD	a = 1.0013; k = 5.0594E-06; n = 1.8472; b = 1.8147E-06	0.9985	0.0003	0.0146
	SFBD	a = 1.0162; k = 0.0032; n = 1.5709; b = 0.0001	0.9965	0.0003	0.0168



a) OD



b) FD



c) SFBD

Fig. 5 Plot of experimental moisture against predicted ratio by the best fit thin-layer model of (a) OD, (b) FD, and (c) SFBD

3.7 DPPH Inhibition

Ginger contains antioxidant agents including β-carotene, terpenoids, polyphenols, and rutin, as well as numerous polyphenol compounds that have antioxidant, antibacterial, and anticancer properties (Ghafoor et al., 2020). Fig. 6 displays the percentage of DPPH free radical scavenging activity of fresh and dried BG affected by different drying methods. The DPPH scavenging activity values shown in Fig. 6 revealed that there was no significant difference between the drying methods. BG undergoing SFBD experienced higher antioxidant activities compared to fresh, OD, and FD. The study by Ghafoor et al., (2020) stated that the inactivation of the polyphenol oxidase enzyme, reduction in the moisture content level, and increase in the dry matter content during the drying process caused the dried samples to have higher antioxidant properties than fresh BG. Evidently, the results for the moisture content removed by all drying methods show that there is only a slight difference, which clarifies the phenomenon of the DPPH inhibition activity because there is no significant variation in the results.

The percentage of DPPH inhibition of BG for OD, FD, and SFBD was 78.40%, 86.69%, and 89.20%, respectively, whereas for fresh BG (control), it was 18.85%. The reported data by Ghasemzadeh et al., (2018) showed that conventional oven dried ginger exhibited higher inhibition activity around 96.2 % than the synthetic antioxidant butylated hydroxytoluene (BHT). This demonstrates that our OD BG result was lower than previously reported. However, the results for FD were higher than the value reported by Ghasemzadeh et al., (2016) for BG dried using the freeze dryer, ranging from 14.7% to 41.0%. According to Menon et al., (2021), the bioactive constituents of ginger will differ from one plant to the next, and this variation is due to two factors. The first factor is the degree of freshness or dryness of the rhizomes and the second is the plant's origin. The nutrient content of ginger varies according to the growing conditions, agronomic application, varieties, preserving methods, extraction methods, and storage conditions (Sharif et al., 2018). Therefore, the variation in the antioxidant activity of dried gingers may be attributed to the following factors.

The key phytochemicals responsible for the antioxidant activity in herbs and spices are phenolic compounds (phenolic acids, flavonoids, terpenes, etc). Gingerols, paradols, shogaols, and zingerone, as well as beta-carotene, ascorbic acid, terpenoids, and alkaloids are some of the non-volatile pungent principles of ginger that were found to have antioxidant properties in the DPPH assay (Ali et al., 2018). On the other hand, 6-gingerol, a lipid-based natural bioactive phtyochemical from ginger, has a significant response to the DPPH antioxidant activity assay and is widely known for its therapeutic effect (Alsahli et al., 2021). From the result above, it can be concluded that SFBD is favourable due to the response of their antioxidant activities in the DPPH assay. However, further analysis will be done to quantify the content of 6-gingerol through LC-QTOF/MS analysis to evaluate its effect on the antioxidant activity of ginger.

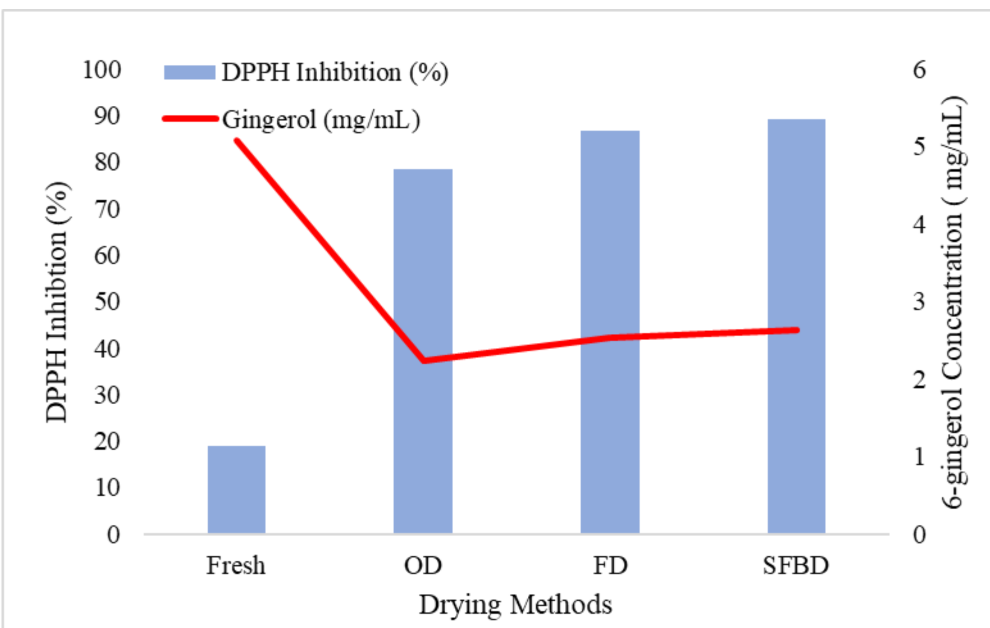


Fig. 6 Effect of the drying methods on the percentage of DPPH free radical scavenging activity and 6-gingerol concentration

3.8 6-Gingerol Content

The quality of ginger is determined by its pungency and spicy flavour. Gingerol and its derivatives are the biomarker compounds that give ginger its quality. 6-gingerol is a non-volatile pungent compound that can be found in fresh ginger compared to its other derivatives. Several studies revealed the biological activities of 6-gingerol, including antioxidant, anticancer, anti-inflammatory, antimicrobial, antiapoptotic, and many more. The study by Pawar et al., (2016) revealed that there is a strong and significant correlation between 6-gingerol and free radical scavenging activities. Thus, LC-QTOF/MS analysis was performed to quantify the concentration of 6-gingerols in three types of ginger extracts affected by different drying methods and fresh ginger extracts.

Based on Fig. 6, it can be observed that the 6-gingerol content is higher in the fresh ginger extract compared to the dried ginger extracts for all the drying methods. Besides, there is no significant difference in the 6-gingerol content between the drying methods, which is consistent with the DPPH inhibition result. Li, (2017) stated that gingerols are the main polyphenol that can be found in fresh ginger compared to dried ginger, as gingerols consist of the β-hydroxyl keto-functional group, which is thermally liable and prone to dehydrate. The level of gingerols varies significantly according to the processing methods, storage time (Ghasemzadeh et al., 2016), and ginger species (Li, 2017). Our findings agreed with Ghasemzadeh et al., (2016), as the gingerol content of BG was differ according to the dehydration techniques and was observed to be lower than the fresh BG.

Furthermore, the 6-gingerol content decreases in dried ginger extracts as decomposition takes place and 6-gingerol transforms to some other compounds such as 6-shogaol and zingerone (Guo et al., 2019). Hence, it can be assumed that the 6-gingerol content of dried BG degrades to other active compounds, as stated by Guo et al., (2019). Apart from that, the drying method stimulated the release of bound phenolic compounds from the food matrix as well as the development of new compounds with improved antioxidant characteristics (Mustafa et al., 2019). This explained the phenomena where dried BG exhibits a higher antioxidant activity through the DPPH scavenging activity than fresh ginger. Therefore, it can be inferred that the antioxidant activity of ginger not only depends on the gingerol compound but also other active compounds.

4. CONCLUSION

In this research, the effect of three different drying methods on the drying kinetics and nutritional quality was evaluated. The highest and lowest drying times to obtain the equilibrium moisture content were achieved by using FD and SFBD, respectively. The application of SFBD resulted in the lowest specific energy consumption at 160.4976 kWh/kg as well as high drying rates and effective moisture diffusivity at 0.1813 g/min and 2.4317×10^{-10} m^2/s, respectively. A higher effective moisture diffusivity value would help accelerate the moisture removal in ginger samples, making it easier to achieve the equilibrium moisture content. Furthermore, the SFBD technique is the most effective at preserving the 6-gingerol compound of BG, resulting in the higher DPPH inhibition. Hence, drying using SFBD can be employed as a new drying technology for ginger because it saves time and energy as well as promotes its nutritional values. Aside from that, this work fills another gap by fitting the experimental moisture ratio data of BG affected by three different drying methods to seven thin-layer drying models and comparing the results using statistical criteria. Among the tested models, the Midilli-Kucuk model was the best fit for OD and SFBD, while the Page model was the best fit for FD to describe the drying kinetics of BG. The moisture ratios calculated experimentally and predicted by the chosen model are in close agreement and fit to a straight line smoothly. The model has the highest value of R^2, the lowest value of χ^2, and RMSE, respectively. It is recommended that future work could focus on optimizing the SFBD process parameters to achieve the best drying for ginger samples.

Declarations

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Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

Data Availability Statement
All data generated or analyzed during this study are included in this published article.

Authors' Contribution Statements
Sarmilaah Dewi Subramaniam: Investigation, Writing- original draft
Nurul Aini Binti Mohd Azman: Review and editing, Supervision
Siti Kholijah Binti Abdul Mudalip: Data Validation
Luqman Abdul Halim: Data curation, Analyzed and Interpreted the data
Firdaus Basrawi: Formal analysis

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