

Drying of ginger slices—Evaluation of quality attributes, energy consumption, and kinetics study

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Abstract

Ginger slices were dried with Freeze drier (FD), relative humidity convective drier (RHCD), infrared drier (IR), and microwave drier (MD) at a temperature of 60°C. The influence of the drying techniques on total phenolic content (TPC), total flavonoid content (TFC), antioxidant activities, ABTS (2,2-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid), DPPH (1,1-diphenyl-2-picrylhydrazyl), FRAP (Ferric reducing antioxidant power capacity), and CUPRAC (Cupric ion reducing capacity), rehydration ratio (RR), color, enzyme inactivation (polyphenol oxidase, PPO and peroxidase, POD), energy consumption rate (ECR), microstructure, volatile compounds (aroma profile), and drying kinetics were assessed. The results showed that FD-ginger slices retained the highest antioxidant properties, ABTS (51.88 mgTE/g db), CUPRAC (95.51 mgTE/g db), DPPH (132.95 mgTE/g db), and FRAP (95.32 mgTE/g db), TPC (118.70 mg GAE/g db) and TFC (98.94 mg CE/g db), preserved microstructure and higher volatile compounds compared RHCD, IR, and MD. The RHCD-ginger slices attained the highest RR (3.6), lowest ECR (7.88 kWh/kg), lowest PPO (17%), and POD (22%) residual activity with preserved color properties than FD, IR, and MD. RHCD also enhanced the drying kinetics and lessened the drying time compared to FD, IR, and MD. Page model best fitted the experimental results of drying kinetics ($R^2 > 0.99$).

Practical application

One of the world's most consumed and used spices is ginger and due to its high moisture content, drying is normally used for its preservation. Therefore, to attain dried ginger of better quality, an effective, safe, efficient drier that can preserve product quality and reduce processing time, as well as energy consumption, is required for commercial purposes as a poor selection can have an adverse effect on the product quality. The outcome of the current investigation will offer a better understanding of various drying techniques and also provide more information on the selection of the best drying technique for drying ginger.

1 | INTRODUCTION

Ginger is one of the medicinal plant and spices of the world which is used as a raw material by the food and pharmaceutical industries in the production of wine and cosmetics, as well as for baking,

processing of meat, and medicinal products due to its high antioxidant properties (Osae et al., 2019). It is grown in various part of the world particularly in Asia and Africa. In Asia, it cultivated in India, China, Indonesia, Thailand, Japan, and Nepal. India is the major producer (6.55×10^5 tons) and consumer of ginger in the world. In Africa,

Nigeria, Ghana, Cameroun, Uganda, and Kenya are some of the producers and consumers of ginger (Wang et al., 2018).

Ginger is proven scientifically to contain a lot of pharmacological properties including anti-inflammatory, antioxidants, immunomodulatory, antimicrobial effects, and so forth (Srinivasan, 2017). The health benefits of these properties are due to the existence of gingerols, volatile oils, shogaols, and high antioxidant compounds (Jelled et al., 2015). However, fresh ginger (FG) contains a high amount of water (80–95%) at harvest and during postharvest storage and this encourages microbial deterioration which results in the reduction of shelf life and huge postharvest losses. One of the most common preservation techniques of ginger is drying. This technique has been established to extend the shelf life through the reduction of the moisture content to the minimum activity level to prevent microorganism degradation. It also eases the transportation of food and enables the availability and usability of the dried product regardless of the season (Deng et al., 2018; Karabacak, Suna, Tamer, & Çopur, 2018).

Most developing countries such as Ghana use natural open sun drying for dehydration of ginger and other agricultural crops. The long drying time of this technique (15 days and more) results in severe deterioration of the color and nutritional quality of the finished product. Food product dried by this technique is easily infected by rodents, insects, dust, and birds as a result of the long exposure to the outside environment. Furthermore, food samples dried by this technique are predisposed to the re-absorption of moisture at night enhancing the deterioration of the dried product (Yin et al., 2018). Therefore, to attain dried ginger of better quality, an effective, safe, efficient drier that can preserve product quality and reduce processing time is required.

Recently, infrared drying (IR) has been reported to improve drying rate (DR), lessen processing time, save energy, and enhance the final product quality. IR-drying has been used in drying various agricultural crops including carrot (Wang, Xu, Wei, & Zeng, 2018), strawberry (Adak, Heybeli, & Ertekin, 2017), garlic (Feng et al., 2018), and paddy (Zare, Naderi, & Ranjbaran, 2015). It has also been established to preserve the sensory and nutritional attributes of the finished product. However, the main disadvantage with the use of IR-drying is the non-uniformity of the finished dried product especially when the food product varies in size and shape (Riadh, Ahmad, Marhaban, & Soh, 2015). Freeze drying (FD) has gained a lot of attention as a dehydration technique for retaining the overall quality of the final product as well as preserving the sensory and the physicochemical properties (Ren, Perussello, Zhang, Kerry, & Tiwari, 2018; Valadez-Carmona et al., 2017). Chen et al. (2017) and Krzykowski et al. (2018) established that the application of FD improved the nutritional, antioxidant, physicochemical, sensory, and textural properties as well as drying kinetics of dried black mulberry and pepper. However, the operation of FD is very expensive with comparatively low drying efficiency (Duan et al., 2016).

Another alternative drying technique is microwave drying (MD). This drying technique has some merits over the conventional drying methods which include enhanced process control, advanced DR, reduction of processing time, and preservation of food quality (Valadez-Carmona et al., 2017). MD has been used in the drying of

several crops such as garlic (Demiray & Tulek, 2014), celery slices (Karabacak et al., 2018), and cacao pod husks (Valadez-Carmona et al., 2017). The main drawback of MD drying involves fast energy dissipation which moves through the food medium during drying (Demiray, Seker, & Tulek, 2017).

Relative humidity convective drying (RHCD) is also receiving much attention as a potential drying method for dehydration of various agricultural products due to its efficiency in preserving antioxidant properties and enhancement of drying kinetics. Sarpong et al. (2018) and Osaie et al. (2019) revealed that the use of RHCD reduced the processing time, improved the DR, and retained the antioxidant properties of dried carrot and ginger. It is also used in the dehydration (drying) of sensitive products like spices and medicinal plants.

Deciding on an appropriate drying technique for the dehydration and processing of agricultural products is of prime importance for the cosmetics, food, pharmaceutical, and beverage industries as a bad choice can affect the quality of the final products. Hence, the aim of this present study are: (a) to evaluate the influence of four drying techniques (FD, RHCD, IR, and MD) on ginger in respect of its antioxidant activity (ABTS, CUPRAC, DPPH, and FRAP), bioactive compounds (TPC and TFC), rehydration ratio (RR), color, enzyme activity (PPO and POD), microstructure, and energy consumption rate (ECR) of the techniques; (b) to examine the effect of different models on the drying kinetics of ginger under various drying methods.

2 | MATERIALS AND METHODS

2.1 | Plant material

Freshly harvested ginger rhizomes were bought from local producers at Jema, Kintampo South District, Bono East Region, Ghana (7.9017° N, 1.7696° W) in March 2019. They were authenticated as true samples of *Zingiber officinale* Roscoe at the State Key Laboratory of Natural Medicines, China Pharmaceutical University based on their macroscopic, organoleptic, microscopic, phytochemical characteristics, and voucher samples deposited. They were washed thoroughly, cleaned, and then sliced into a uniform dimension of 3–4 mm using an industrial slicing machine (SS-250, SEP Machinery Company Ltd., Guangzhou, China). The average initial moisture content of the FG was $81.55 \pm 1.25\%$ (wet basis) and was determined according to the AOAC method (AOAC, 2000).

2.2 | Chemicals and reagents

The following chemicals and reagent were used for the experiment: 1,1-diphenyl-2-picrylhydrazyl (DPPH), 2,2-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), sodium hydroxide (NaOH), neocuproine, copper (II) chloride, ammonium acetate, Folin Ciocalteu reagent, sodium carbonate (Na_2CO_3), catechol (o-diphenol), catechin, and gallic acid were from procured from Sigma-Aldrich (St. Louis, MO). Ammonium persulfate, sodium nitrate (NaNO_3), hydrogen

peroxide (H_2O_2), and potassium persulfate were bought from National Pharmaceutical Corporation (Beijing, China).

2.3 | Sample preparation

The ginger sample was prepared following a previous outlined procedure (Osae et al., 2019). Respectively, they contained $81.55 \pm 1.25\%$ (wet basis) moisture content, as determined by the AOAC method (AOAC, 2000).

2.4 | Drying techniques

2.4.1 | Infrared drying

The IR-drying was conducted by following the method previously reported by Wang, Xu, et al., 2018 with minor modification. The ginger slices (0.9 kg) were dried at the following conditions; temperature (60°C) at the wind speed of 2 m/s. Drying was deemed complete when the sample reached a constant moisture content.

2.4.2 | Relative humidity convective drying

The ginger slices (0.9 kg) were dried in a relative humidity convective drier (lab-scale hot-air drier equipped) which works with a temperature range from 30 to 75°C , relative humidity (10–40%), air velocity (2 ms^{-1}) and power of 1.2 kw as previously described in detail by Osae, Zhou, Alolga, et al. (2019). The ginger slices were dried under the following conditions: Temperature (60°C), relative humidity (20%), and air velocity (2 ms^{-1}). Drying lasted until the sample reached constant dry weight.

2.4.3 | Microwave drying

The MD was conducted by following the method previously reported by Sattar et al. (2019) with little adjustment. The ginger slices (0.9 kg) were dried in a microwave oven (model NJO7-3, Jiequan Apparatus co. Ltd Nanjing, China) at a temperature of 60°C , 50 Hz frequency, and 850 W power. Drying lasted until the sample reached constant dry weight.

2.4.4 | Freeze-drying

FD of the ginger samples (0.9 kg) was carried out by following the method previously reported by Krzykowski et al. (2018) with minor adjustment. A laboratory Freeze drier (model ALPHA 1–4 freeze drier) was used. Prior to drying, the ginger slices were frozen in a freezer (model, GTL 4905, Liebherr, Germany) at -25°C for 48 hr. The frozen ginger slices were then dried at a constant pressure of 63 Pa and a

temperature of 60°C . Drying lasted until the sample reached constant dry weight (equilibrium moisture). The dried ginger slices were ground into powder, sieved, and stored in a dry place for further assessment after the drying process.

2.5 | For total phenolic and flavonoid content as well as antioxidant activity measurement

About 1 g amount of each powdered ginger sample was weighed and 20 ml aliquot of 80% methanol added. This mixture was ultrasonicated for 10 min (using Trans-O-Sonic/D150-IM, Mumbai) and centrifuged at $10,000 \times g$ for 30 min at 4°C using Hanil, Supra 22K, Korea. The supernatants were then used for phytochemical tests.

2.6 | Analysis of antioxidant properties

The antioxidant activity (ABTS, FRAP, CUPRAC, and DPPH) were assessed following the method previously described by Osae, Zhou, Tchabo, et al. (2019) and Tchabo et al. (2018) with minor modification. The antioxidant activities such as ABTS (2,2-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid), CUPRAC (Cupric ion reducing capacity), DPPH (1,1-diphenyl-2-picrylhydrazyl), and FRAP (Ferric reducing antioxidant power capacity) assays were measured spectrophotometrically with a spectrophotometer, model UV-1600 (Rayleigh Analytical Instrument), Beijing, China. The antioxidant activities were expressed as mg of Trolox equivalent per gram of sample on a dry basis (mgTE/g db).

2.7 | Analysis of TPC and TFC

TPC and TFC of the dried ginger samples and the FG were assessed by following the established protocol of Jelled et al. (2015) and Tchabo et al. (2017). The results of TPC and TFC were expressed as mg GAE/g db and mg CE/g db of the sample, respectively.

2.8 | Rehydration ratio

The rehydration assessment was conducted following the method previously described by Wang, Xu, et al. (2018) with little modification. Briefly, the dried ginger samples were dipped in a distilled water bath at 25°C for 6 hr. The rehydrated samples were removed after the process, blotted with tissues paper and weighed with an electronic balance (SP402 model, Ohaus Co., Ltd., Parsippany, NJ). The process was replicated three times and the RR was calculated using Equation (1).

$$RR = \frac{W_1}{W_2} \quad (1)$$

Where W_1 and W_2 are the weights of the samples before and after rehydration, respectively.

2.9 | Color analysis

The color assessment of dried and fresh samples was measured according to the method previously reported by Osae, Zhou, Aloga, et al. (2019). The overall color difference (ΔE) of the dried ginger samples was estimated by the Equation (2):

$$\Delta E = \sqrt{(L_0 - L^*)^2 + (a_0 - a^*)^2 + (b_0 - b^*)^2} \quad (2)$$

2.10 | Enzyme inactivation

The PPO and POD enzyme extraction and measurement of the enzyme activity were conducted according to the method previously reported by Osae, Zhou, Tchabo, et al. (2019).

2.11 | Mathematical modeling of drying curves (drying curves and kinetics modeling)

Four drying models were employed for the assessment of the outstanding model that best fitted the drying curves of dried ginger samples (Table 1). The moisture ratio (MR) and DR of ginger slices dried under the four drying methods (FD, RHCD, IR, and MD) were evaluated with the equations as follows (Osae et al., 2019a);

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (3)$$

Where M_0 is the initial moisture content, M_t is the moisture content at the drying time t , M_e is the equilibrium moisture contents, and MR is the moisture ratio.

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \quad (4)$$

Where t_1 and t_2 are the drying times in minutes at different times during drying, respectively. However, the M_{t_1} and M_{t_2} are the moisture content of pretreated ginger samples at different drying times (t_1 and t_2) and are expressed on a dry weight basis.

To evaluate the quality fitness of the experimental results, reduced chi-square (χ^2), the coefficient determination (R^2), and

TABLE 1 Selected models applied for the drying kinetics of ginger under drying methods

Model number	Model name	Model equations	References
1.	Newton	$MR = \exp(-kt)$	Deshmukh et al. (2013)
2.	First-order model	$MR = M \exp(-k_0 t)$	Osae, Zhou, Aloga, et al. (2019)
3.	Weibull	$MR = \exp\left[-\left(\frac{t}{\beta}\right)^\alpha\right]$	Wang, Xu, et al. (2018)
4.	Page	$MR = \exp(-kt^n)$	IZli & POLat (2019)

reduced sum of square (RSS) parameter were used. Lower RMSE and Chi-square (χ^2) values with higher coefficient determination (R^2) values were employed to measure the appropriateness of the model to the FD, RHCD, MD, and IR drying curves of ginger slices. These parameters were calculated by the expression of the Equations (5)–(7) (Dai et al., 2015; Wang, Xu, et al., 2018):

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{\text{exp},i} - MR_{\text{pre},i})^2}{N-z} \quad (5)$$

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

$$R^2 = \frac{\sum_{i=1}^N (MR_{\text{pre},i} - MR_{\text{exp},i})^2}{\sum_{i=1}^N (MR_{\text{pre}} - MR_{\text{exp},i})^2} \quad (7)$$

Where z is the number of constants and N is the number of experiences. $MR_{\text{exp},i}$ is the experimental dimensionless MR and $MR_{\text{pre},i}$ are the computed dimensionless MR.

2.12 | Energy consumption rate

The ECR was estimated during the dehydration process by following the previous established methods of Shewale, Rajoriya, and Hebbar (2019) with the Equation (8):

$$\text{Energy Consumption Rate} = \frac{\text{CEV}}{W_0} \quad (8)$$

where CEV is the consumed energy value (kWh) and W_0 is the amount of moisture removed during drying (kg).

2.13 | Microstructure analysis

The microstructure analysis was conducted by following the methods as reported by Wang, Bai, et al. (2018) and Oladejo, Ma, Qu, Zhou, and Wu (2017) Scanning electron microscope (SEM) were employed for the microstructural analysis of ginger samples dried by the different techniques. The SEM images were obtained by removing a small part of the dried ginger from the surface and the inner part at a dimension of $5 \times 5 \times 5 \text{ mm}^3$. The pieces of the dried ginger were then fastened on the metal stub. A thin layer of gold was used to coat each specimen and the sample structural changes were assessed by placing them under high vacuum.

2.14 | Determination of volatile compounds

The determination of the volatile (flavor) compounds of the dried ginger samples were conducted by following the previously established protocol of Bonah et al. (2019) with minor modifications. Briefly, to measure characteristic flavor and aroma responses, the dried ginger

slices were ground into powder (placed in a 50 ml glass tube and sealed) and a PEN3 electronic nose (E-nose; AIRSENSE Analytics GmbH, Schwerin, Germany) were used to detect the various volatile compounds. The electronic nose composed of the sensor array, gas collecting system, intelligent recognition system, and sensor detection curve. The sensor array system comprises of 10 various sensors as presented in Table 2. The graphical abstract of the experiment is shown in Figure 1.

2.15 | Statistical analysis

All experiments were performed in triplicate. The experimental data obtained were presented as the means values \pm standard deviation. The data were analyzed by one-way analysis of variance, Tukey test for comparison of the means were assessed using Minitab version 17 (Minitab Inc., Philadelphia, PA). Values of $p < .05$, were respectively considered statistically significant. Drying kinetics analysis was performed using OriginPro software 2018.

3 | RESULTS AND DISCUSSION

3.1 | The effect of different drying techniques on the antioxidant properties of dried ginger slices

The ABTS, CUPRAC, DPPH, and FRAP methods were used to assess the potential source of antioxidant properties in the fresh and dried ginger

TABLE 2 Sensor sensitives of the sensor array in PEN 3 E-nose (Winmuster, Version 1.6.2, Airsense Analytics GmbH, Schwerin, Germany)

No.	Sensors	Sensing species
S1.	W1C	Aromatic organic compounds
S2.	W5S	Very sensitive, broad range sensitivity, reacts to nitrogen oxides, very sensitive with a negative signal
S3.	W3C	Ammonia, also used as a sensor for aromatic compounds
S4.	W6S	Detect mainly hydrogen gas
S5.	W5C	Alkanes, aromatic compounds, and nonpolar organic compounds
S6.	W1S	Sensitive to methane. A broad range of organic compounds detected
S7.	W1W	Detects inorganic sulfur compounds, for example, H ₂ S. Also sensitive to many terpenes and sulfur-containing organic compounds
S8.	W2S	Detects alcohol, partially sensitive to aromatic compounds, broad range
S9.	W2W	Aromatic compounds, inorganic sulfur, and organic compounds
S10.	W3S	Reacts to high concentrations (>100 mg kg ⁻¹) of methane and aliphatic organic compounds.

samples. The antioxidant properties of the FG and the dried ginger slices as evaluated by ABTS, CUPRAC, DPPH, and FRAP are presented in Table 3.

The ABTS antioxidant activity of ginger slices dried by the various drying methods (FD, RHCD, IR, and MD) ranged from 23.24 to 70.2 mgTE/g db. The FD-ginger slices exhibited the ($p < .05$) maximum antioxidant activity of 70.2 mgTE/g db, the RHCD (37 mgTE/g db), MD (33.01 mgTE/g db), and IR-dried ginger slices (23.24 mgTE/g db) were recorded for the second, third, and fourth, respectively. The highest CUPRAC antioxidant activity was obtained by the FD-ginger slices (95.51 mgTE/g db). The RHCD- and IR-dried ginger slices were 82.03 and 71.63 mgTE/g db, respectively, while the MD-ginger slices recorded the least antioxidant activity of 57.44 mgTE/g db. The outcome from the DPPH antioxidant activity demonstrated that the FD-ginger slices retained the highest antioxidant activity of 132.95 mgTE/g db followed by RHCD-ginger slices (121.91 mgTE/g db), and IR-dried ginger slices (106.55 mgTE/g db) with MD-ginger slices (94.86 mgTE/g db) obtaining the lowest. A similar trend was reported for the FRAP antioxidant activity with the following values 95.32, 71.22, 56.30, and 48.40 mgTE/g db for FD, RHCD, IR, and MD-ginger slices, respectively. From the above antioxidant activity data, it could be deduced that the dried ginger slices under different drying techniques indicated a particular trend: FD-ginger slices > RHCD-ginger slices > IR-dried ginger slices > MD-ginger slices.

The maximum ABTS, CUPRAC, DPPH, and FRAP antioxidant activity reported for the FD-sample may be ascribed to the highest color change (Table 4) observed after the drying process. According to Osaie, Zhou, Alolga, et al. (2019), most agricultural product after drying often has some Maillard reaction due to a kind of chain-breaking mechanism which yields greater antioxidant activity. This assertion is in agreement with Dalla Nora et al. (2014) who reported that high antioxidant activity is usually associated with the dried product with Maillard reaction. The creation of browning compounds due to intermediate oxidation of polyphenol during drying also results in high antioxidant properties in dried products (Michalska, Wojdyło, Lech, Łysiak, & Figiel, 2016). Remarkably, our results further established that there was an affirmative relationship between the TPC and antioxidant activity. This shows that the increase in the TPC may generally be ascribed to a greater amount of antioxidant activity. This outcome is in agreement with the findings of Karabacak et al. (2018). The greater amount of antioxidant activity preserved by the RHCD-ginger slices may be ascribed to the combined influence of relative humidity (RH) and temperature which resulted in the preservation of greater percentage of the antioxidant activity (Sarpong et al., 2018). These results are in line with the previous findings of Osaie, Zhou, Xu, et al. (2019a) who reported higher retention of antioxidant activity of RHCD-ginger slices. Similarly, shorter drying time (Figure 4) observed by the RHCD also retained a higher amount of antioxidant activity.

According to Feng et al. (2018), maximum antioxidant properties were preserved during the IR-drying of garlic slices and this outcome is in agreement with the results of a previous study (Nalawade, Sinha, & Hebbar, 2018). An et al. (2016), who explored the influence of IR-drying on the antioxidant properties of Chinese ginger, revealed that the IR-drying method enhanced the retention of the antioxidant properties and other bioactive compounds of the dried Chinese ginger. Wanyo, Siriamornpun, and Meeso (2011) reported a similar outcome during the

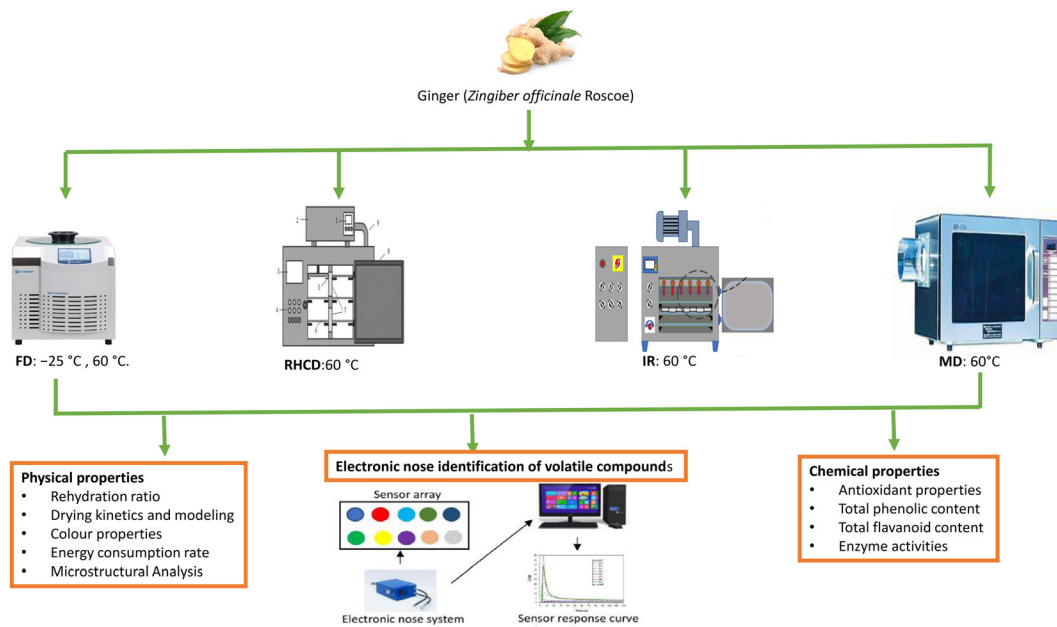


FIGURE 1 The graphical abstract of the experiment

TABLE 3 Results of antioxidant activities, total phenolic, and total flavonoid content of ginger samples under different drying methods

Drying methods	Antioxidant activities (mgTE/g db)				Total phenolic (mg GAE/gdw) and flavonoid content(mg CE/gdw)	
	ABTS	CUPRAC	DPPH	FRAP	TPC	TFC
FG	70.2 ± 1.18 ^a	121.90 ± 4.50 ^a	162.26 ± 4.74 ^a	114.19 ± 3.14 ^a	135.21 ± 1.24 ^a	105.73 ± 1.07 ^a
FD	51.88 ± 3.82 ^b	95.51 ± 0.34 ^b	132.95 ± 0.16 ^b	95.32 ± 2.95 ^b	118.70 ± 2.5 ^b	98.94 ± 0.32 ^b
RHCD	37 ± 2.0 ^c	82.03 ± 4.09 ^c	121.91 ± 1.22 ^c	71.22 ± 3.66 ^c	101.21 ± 1.85 ^c	79.13 ± 0.54 ^c
IR	23.24 ± 0.23 ^e	71.63 ± 0.30 ^d	106.55 ± 0.24 ^d	56.30 ± 1.96 ^d	94.09 ± 1.63 ^d	66.08 ± 0.18 ^d
MC	33.01 ± 2.87 ^d	57.44 ± 1.28 ^e	94.86 ± 0.65 ^e	48.40 ± 1.43 ^e	83.41 ± 6.20 ^e	51.47 ± 0.10 ^e

Note: Difference values followed by the different letters (a–f) in the column are significantly different ($p < .05$) according to Tukey test.

Abbreviations: FD, freeze drier; FG, fresh ginger; IR, infrared drier; MC, Microwave drier; PVD, Pulsed vacuum drier; RHCD, relative humidity convective drier.

	FG	FD	RH	IR	MD
<i>L</i>	64.18 ± 1.40 ^a	58.16 ± 3.10 ^c	61.56 ± 2.86 ^b	59.50 ± 3.40 ^c	59.73 ± 2.48 ^c
<i>a</i>	1.62 ± 0.10 ^b	1.72 ± 0.07 ^a	1.69 ± 0.15 ^b	1.74 ± 0.09 ^a	1.79 ± 0.19 ^a
<i>b</i>	36.80 ± 0.40 ^a	32.45 ± 1.07 ^d	34.13 ± 1.49 ^c	33.55 ± 2.92 ^b	31.95 ± 3.32 ^d
ΔE		7.43 ^d	3.71 ^a	5.70 ^b	6.58 ^c

Note: Difference values followed by the different letters (a–f) in the column are significantly different ($p < .05$) according to turkey test.

Abbreviations: FD, freeze drier; FG, fresh ginger; IR, infrared drier; MD, microwave drier; RHCD, relative humidity convective drier.

TABLE 4 Total color change of ginger samples dried under different drying methods

IR-drying of mulberry leaves. As observed in Table 3, the MD technique also preserved some amount of antioxidant properties. Our results are in agreement with the previous works of Karabacak et al. (2018), who established an increase in antioxidant properties when MD was used

during the dehydration of celery slices. Valadez-Carmona, Cortez-García, Plazola-Jacinto, Necoechea-Mondragón, and Ortiz-Moreno (2016), further reported an increase in the retention of antioxidant activity when MD was employed during the dehydration of coconut husk.

3.2 | The effect of different drying techniques on the TPC and TFC of dried ginger

One of the techniques of preserving food is drying and in the course of this process conserving of bioactive compounds (TPC and TFC) is of vital interest because bioactive compound particularly phenolic contents play a significant role in the development and strengthen of cells. The outcome from our study revealed that TPC and TFC of the FG were 135.21 mg GAE/gdw and 105.73 mg CE/gdw, respectively (Table 3). These results were higher than the values reported by An et al. (2016), who found 11.97 mg GAE/gdw and 13.49 mg CE/gdw for Chinese ginger. These variations may be ascribed to the geographical location of cultivation, varieties, and the genetic make-up of the sample. Additionally, TPC of FD, RHCD, IR, and MD-ginger slices were 118.70, 101.21, 94.09, and 83.41 mg GAE/gdw, respectively; for FD, RHCD, IR, and MD-ginger slices, TFC were 98.94, 79.13, 66.08, and 51.47 mg CE/gdw, respectively (Table 3).

According to our results, it is evident that the MD attained the lowest preservation of the TPC and TFC compared to the other drying techniques. This reduction may be ascribed to the degradation of the bioactive compounds (TPC and TFC) as a result of the changes in the chemical structures and the degradation of the polyphenols during the drying process (Valadez-Carmona et al., 2017). Also, the loss of the phenolic and the flavonoids may also be attributed to the rapid and intense heat generated from the MD which led to severe destruction of the bioactive compounds. Similar findings were reported for dried tomato (Horuz, Jaafar, and Maskan (2017) and dried celery slices (Karabacak et al., 2018). The IR-dried sample retained a higher amount of TPC and TFC compared to the MD-dried samples. According to Riadh et al. (2015), food dehydration techniques such as IR affect the release of bioactive compounds in many agricultural products due to variations in their microstructure. These alterations could result in an undesirable impact on the quality of the finished product in terms of the preservation of the bioactive compounds. The outcome from this work revealed a positive impact in respect of TPC and TFC of the ginger (i.e., enhanced TPC and TFC). Our findings are in agreement with the previous study of Wang, Zhang, Fang, and Xu (2014) and An et al. (2016), who reported that IR-dried mushroom and ginger retained a greater percentage of the TPC and TFC.

As reported in Table 3, the RHCD-ginger slices attained a greater preservation of TPC and TFC than the IR and MD methods. The higher retention of the bioactive compounds (TPC and TFC) may be ascribed to the fact that during dehydration, RHCD collapse covalent bonds and results in the release of bioactive compounds (Sarpong et al., 2018). This is because most bioactive compounds are linked to the cell wall of most agricultural products (fruits and vegetables), and thermal dehydration can collapse the cell structures and promote the release of these bioactive compounds (Valadez-Carmona et al., 2017). The FD-ginger slices recorded the highest preservation of the bioactive compounds (TPC and TFC) compared to the other drying techniques. The maximum retention of the TPC and TFC may be attributed the low temperature and the vacuum conditions as well as the slow DR which retained the cell structure and led to the highest

preservation of TPC and TFC (Valadez-Carmona et al., 2017). These results are in agreement with the findings of Krzykowski et al. (2018) and Chen et al. (2017) for pepper and black mulberries, respectively.

3.3 | Effect of different drying techniques on RR of dried ginger slices

One of the significant quality indicators of dried product is RR. Thus the higher the rehydration ratio, the better the product. The influence of various drying techniques (FD, RHCD, IR, and MD) on the RR of dried ginger slices are depicted in Figure 2. There was significant ($p < .05$) differences among the four dried ginger slices. The RR of FD, RHCD, MD, and IR-dried ginger slices were 3.6, 4, 3.1, and 2.7, respectively. The highest RR obtained by RHCD-ginger slices may be clarified by the creation of micropores as a result of the synergistic influence of temperature and relative humidity which formed channels on the surface of the ginger slices during the RHC-drying process. This led to higher diffusion of water into the dried samples more effortlessly during the RR process. The current outcomes confirmed the earlier report of Osae, Zhou, Alogla, et al. (2019), who established that the application of RHCD created tunnels and enhanced the RR of dried ginger samples. Ginger slices subjected to FD resulted in higher RR potential than the IR and MD. The phenomenon that led to the higher RR may be ascribed to the fact that freezing of food product prior to drying allowed ice crystals to develop within the cells which caused damage and collapse of the cells by leaving holes inside the structure (Voda et al., 2012). Similar findings were reported for button mushroom (Pei et al., 2014)

As seen in Figure 2, the MD-ginger slices attained a higher RR than the IR-dried ginger slices. This may be attributed to that higher power levels of MD during drying of food products which caused an irreversible cell disruption and greater breakdown of the cell structure. This leads to loss of plant tissue integrity and produces an extreme structure of high shrinkage and distorted capillaries (Izli & Polat, 2019). Our results are consistent with the earlier study of Horuz et al. (2017) for dried tomato. Furthermore, IR-dried ginger slices exhibited some potential of RR, but the value attained was very low compared to the other driers. This may be clarified by two key reasons. (a) IR-drying at high temperature may create a large vacuum inside the food material and form cell structure which is more porous. This will enhance RR. (b) High IR temperature can also cause the collapse of the cell structure in the food medium during dehydration and this will impede water re-absorbed leading to lower RR (Deng et al., 2018).

3.4 | Effect of different drying techniques on the change in color of dried ginger slices

Color is one of the essential quality indices of dried product that enhances consumer acceptance. Total color change (ΔE) is an important color structure that is used to assess the color alterations of processed (dried) products. The total color change of ginger slices dried

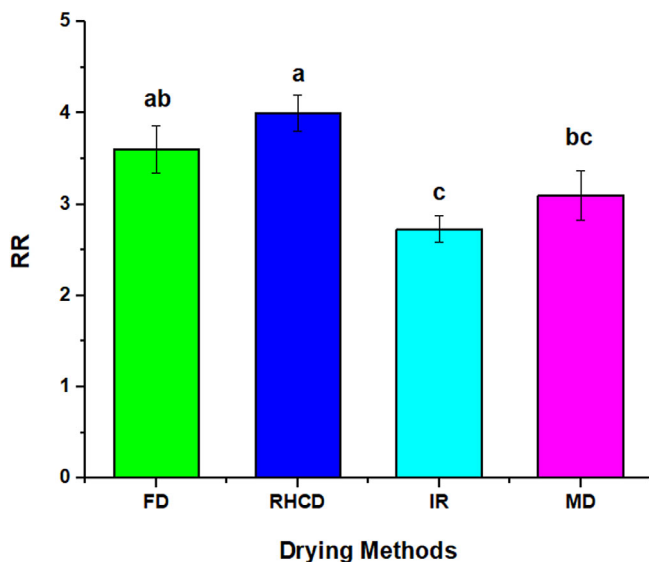


FIGURE 2 Effects of different drying techniques on the rehydration ratio (RR) of dried ginger slices. Different letters on data bars with each treatment show a significant difference ($p < .05$)

under various drying (FD, RHCD, IR, and MD) conditions are presented in Table 4. As observed in Table 4, the ginger slices dried by RHCD (3.71) attained the lowest value ($p < .05$) of the ΔE , while the ginger slices dried by FD (7.43) had the highest influence on the ΔE . The other driers recorded a ΔE of 5.70 and 6.58 for IR and MD, respectively. The lowest ΔE observed for the RHCD-ginger slices may be ascribed to the reduced drying duration (Figure 4), as the shorter drying duration minimized the color degradation and retained the color properties of the dried ginger slices. In agreement with this outcome, Shewale et al. (2019) who study the effect of RHC-drying of vegetable leaves, apple slices and mushroom established that the shorter drying duration of the RHCD preserved the color properties of the dried products (vegetable leaves, apple slices, and mushroom) compared to other driers. Sarpong et al. (2018) also observed that banana slices dried by RHCD showed better retention of the color quality.

In the present study, the IR-dried ginger slices preserved better color compared to the MD and FD (Table 4). These results are consistent with the outcomes of Wang, Xu, et al. (2018), who revealed that the exterior color of carrots slices did not change much during IR-drying as a result of the shorter drying time. A similar observation was reported by Zhu, Pan, McHugh, and Barrett (2010) for apple. The total color change of the MD-ginger slices was lower ($p < .05$) than the FD-ginger slices. de Jesus Junqueira, Corrêa, de Oliveira, Avelar, and Pio (2017) reported a lower ΔE during MD of Cape gooseberry and further attributed the changes in total color to browning reactions. Izli and Polat (2019) and Horuz and Maskan (2015) confirmed similar behavior during the MD of pomegranate and mango slices, respectively. However, the FD-ginger slices having the highest color change may be ascribed to a higher concentration of pigment as a result of decrease in moisture during drying. This mechanism led to a higher concentration of the H⁺

during the drying process which resulted in higher browning reactions (Maillard reaction; Chen et al., 2017). Guiné and Barroca (2012) reported similar trend for pumpkin and green pepper during FD.

3.5 | Effect of different drying techniques on the enzyme activity

Reduction of enzyme activity is one of the main intentions of food processors as higher enzyme activity in food products can lead to deteriorations of the product by microorganism. The inactivation of these natural oxidative enzymes in food during drying is some of the factors that improve the preservation of antioxidant activity. The PPO and POD activity of ginger slices dried by different techniques (FD, RHCD, IR, and MD) in addition to the FG are presented in Figure 3a,b. The POD residual activity of FD, RHCD, IR, and MD-ginger slices, as well as the FG, were 27, 22, 33, 35, and 89.67%, respectively. The percentage residual activities for PPO are 22, 17.10, 27.33, 30.67, and 82.33% for FD, RHCD, IR, MD, and FG, respectively. These results show that the PPO enzyme activities values were much lower than the POD enzyme activity and further demonstrated that all the drying techniques were able to inactivate the enzymes with RHCD being more effective. The mechanism of RHCD in the enhancement of the enzyme inactivation may be ascribed to the combined influence of RH and temperature which significantly resulted in effective enzyme inactivation (Osae et al., 2019b). According to Sarpong et al. (2018) the synergistic influence of lower RH (20%) and temperature (60°C) was effective in inactivation of PPO and POD during RHC-drying of banana slices. As observed in Figure 3. The FD was able to inactivate the enzymes (PPO and POD) more effectively ($p < .05$) compared to the IR and MD. These outcomes are consistent with the findings of Valadez-Carmona et al. (2017), who reported that FD was effective in inactivating PPO and POD enzymes during the drying of cacao pod husk. The possible reasons may be due to the fact that during freezing prior to drying, higher H⁺ concentration occur and this alters the pH by three units which makes the enzymes unstable leading the inactivation.

IR-drying was able to inactivate the enzymes ($p < .05$) compared to the MD. These outcomes are in line with Wang et al. (2017) who reported that IR-heating altered the eco-friendly conditions of the enzymes and destroyed the structure of the enzymes of dried red bell pepper. This phenomenon led to the inactivation of the enzymes. Feng et al. (2018) reported similar incidence during IR-drying of garlic slices.

Our results further established that MD is also an appropriate drying technique for inactivating a greater percentage of PPO and POD enzymes. The decrease in POD and PPO enzymes activity may be due to the enzyme-energy interaction of the MD which was responsible for the decreased enzyme activity (POD and PPO). This is because the MD field can disrupt both polar and charged protein moieties (Valadez-Carmona et al., 2017). Similar outcomes have been reported by Benlloch-Tinoco, Igual, Rodrigo, and Martínez-Navarrete (2013).

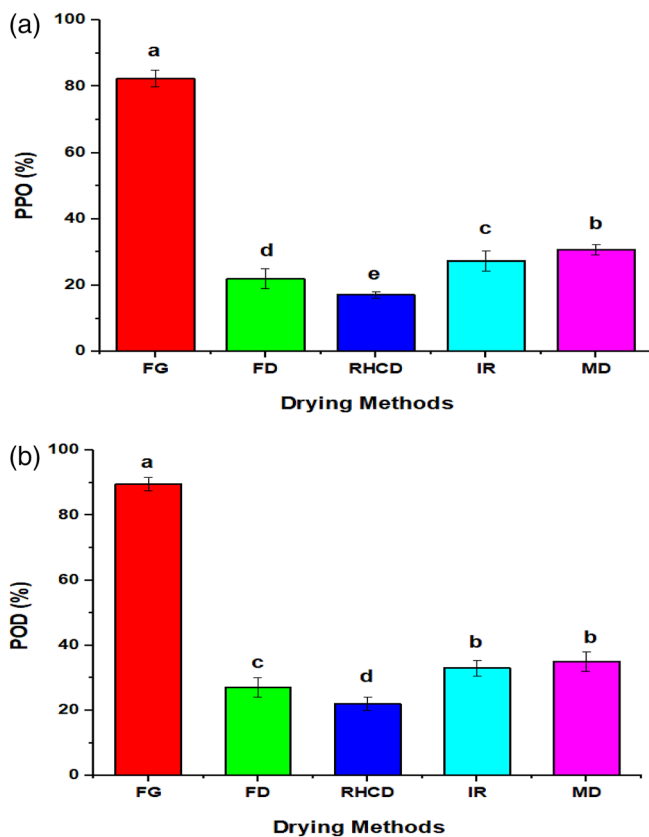


FIGURE 3 Effects of different drying techniques on (a) PPO and (b) POD of fresh and dried ginger slices. Different letters on data bars with each treatment show a significant difference ($p < .05$)

3.6 | Effect of different drying techniques on the drying kinetics of ginger slices

Figure 4 depicts the drying kinetics graph (MR against drying time) of ginger slices dried under different conditions (FD, RHCD, IR, and MD). The initial MC of the ginger slices was 81.55%. During the drying process, the assessment of the moisture content was done at 30 min interval until constant MC was attained. As observed in Figure 4, all the drying techniques (FD, RHCD, IR, and MD) improved the moisture kinetics of the ginger slices during the drying process. The drying period for RHCD, FD, IR, and MD were established to be 5.5 hr (330 min), 10.5 hr (630 min), 6 hr (360 min), and 7 hr (420 min), respectively. Ginger slices dried by RHCD achieved the shortest drying time while FD-ginger slices attained the longest drying duration. The lesser drying time attained by the RHCD may be ascribed to the creation of pores in the internal region of the ginger slices which enhances higher moisture migration due to the combined influence of the RH and temperature. Krzykowski et al. (2018) revealed that RHC-drying of apple slices lessened the overall drying duration by 27.3%. A similar outcome was confirmed by Sarpong et al. (2018), who reported a reduction in dehydration time during RHC-drying of banana slices. Nalawade et al. (2018) observed that the application of IR-drying was more effective in the reduction of drying time during the dehydration

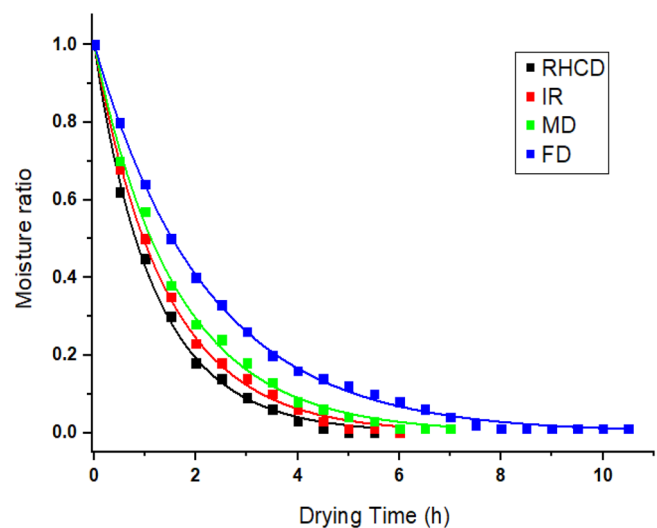


FIGURE 4 Effects of different drying techniques on moisture ratio of dried ginger slices

of bitter gourd slices. Horuz et al. (2017) and Izli and Polat (2019) established that the use of MD led to a decrease in the drying time of 46.4 and 57.14% during the drying of tomato and ginger, respectively. This could be due to the fact the heat source of the MD device advance at greater temperatures and hasten the moisture evaporation in the ginger slices during the drying process leading to shorter drying duration (Beigi, 2016). Furthermore, Krzykowski et al. (2018) stated that the application of FD at a temperature of 60°C reduced the dehydration time of pepper by 50%.

As can be seen in Figure 5, there was significant ($p < .05$) increase in the DR of all ginger slices dried by the various methods (FD, RHCD, IR, and MD). Ginger slices dried by RHCD showed higher DR compared to the IR, MD, and FD. The mechanism that resulted in the higher DR for the RHCD-ginger slices has been clarified above and stated earlier under the rehydration ratio section. Consistently, Osaе, Zhou, Xu, et al. (2019b) and Sarpong et al. (2018) confirmed that swift DR was attained during RHC-drying of ginger and banana slices. Nalawade et al. (2018) stated that the use of IR-drying enhanced the DR of bitter gourd slices. Furthermore, Pei et al. (2014) also established that a higher DR was attained with FD and MD for mushroom slices. They further explained that the application of these driers (FD and MD) developed several pores and micro channels within the cell structure of the mushroom slices and enhanced the drying rate.

3.7 | Mathematical modeling of drying kinetics

Weibull, Newton, first-order, and Page models were the four models that were selected and used for the modeling of the drying kinetics of ginger slices dried by FD, RHCD, IR, and MD methods (Table 5). To assess the best model for the experimental results, the χ^2 (Chi-square), root means square error (RMSE), and the R^2 (coefficients of determination) were

used. The best model was selected based on the model with the highest R^2 and lowest χ^2 and RMSE, respectively (Table 5). It was observed in Table 5 that the Page model best fitted the drying kinetics of the ginger slices with the lowest χ^2 , RMSE, and the highest R^2 compared with the other models (Weibull, Newton, first-order). Page model has been established by many researchers as the most appropriate model to enhance the drying kinetics of various agricultural crops including pepper (Krzykowski et al., 2018), mushroom (Pei et al., 2014), white mulberry (Evin, 2011), and ginger (Izli & Polat, 2019).

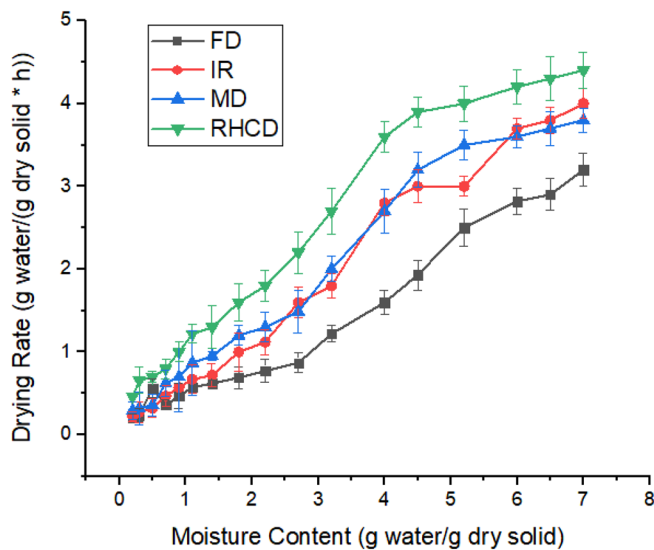


FIGURE 5 Effects of different drying techniques on the drying rate of dried ginger slices

3.8 | Energy consumption rate

The estimated energy consumption rate for the various drying techniques (FD, RHCD, IR, and MD) used for the dehydration of the ginger slices are presented in Table 6. As observed in Table 6, the energy consumption rate for FD, RHCD, IR, and MD are 20.24, 7.86, 10.37, and 9.63 kWh/kg, respectively. The RHCD-ginger slices attained the lowest energy consumption compared to the other driers (FD, IR, and MD). According to Shewale et al. (2019), the application of RHCD in dehydration of apple slices resulted in the reduction of the rate of energy consumption (3.37–5.36 kWh/kg) compared to IR and MD. The energy efficiency of the RHCD may be ascribed to the dehumidification of the drying air during the drying process which decreases the rate of energy consumption (Atuonwu, Jin, van Straten, van Deventer Antonius, & Van Boxtel, 2011). Motevali, Minaei, and Khoshtagaza (2011) and Nalawade et al. (2018) established that the

TABLE 6 Evaluation of energy consumption rate in different drying methods

Drying methods	Energy consumption rate (kWh/kg)
FD	20.24 ^a
RHCD	7.86 ^d
IR	10.37 ^b
MD	9.63 ^c

Note: Difference values followed by the different letters (a–d) in the column are significantly different ($p < .05$) according to Tukey test. Abbreviations: FD, freeze drier; IR, infrared drier; MD, microwave drier; RHCD, relative humidity convective drier.

TABLE 5 Modeling of drying kinetics of ginger slices under different drying techniques

Drying methods	Model name	R^2	$\chi^2 \times 10^{-5}$	RMSE
FD	Newton	0.9819	1.56	0.003938
	First-order	0.9989	8.90815	0.00169
	Weibull	0.9984	13.8632	0.00263
	Page	0.9992	0.0224	0.000468
RHCD	Newton	0.9738	22.3	0.01483
	First-order	0.9847	27.0024	0.0027
	Weibull	0.9973	25.0977	0.00251
	Page	0.9983	0.0948	0.00094
IR	Newton	0.9885	2.89	0.00532
	First-order	0.9891	19.8069	0.00218
	Weibull	0.9968	32.8405	0.00361
	Page	0.9986	0.092	0.00061
MD	Newton	0.9800	9.48	0.00963
	First-order	0.9967	27.3379	0.00409
	Weibull	0.9857	31.2744	0.00407
	Page	0.9984	0.0626	0.00076

Note: Bold font indicates the suitability of the Page model to explain the drying kinetics among the other tested models based on the statistical criteria. Abbreviations: FD, freeze drying; IR, infrared drying; MD, microwave drying; RHCD, relative humidity convective drying.

application of MD and IR during the drying of pomegranate arils and bitter melon slices correspondingly decreased the energy consumption rate to 36.4 and 79%. However, the FD-ginger slices recorded the highest energy consumption compared the other driers and this may be due to the longer drying hours as well as the high energy consumption pattern (power rate) of the drier. Duan et al. (2016) established a similar phenomenon.

3.9 | Microstructural analysis

One of the significant tools to predict and show the physical properties of dehydrated product is the microstructure analysis. Figure 6 depicts the microstructural images of FG (Figure 6a) and dehydrated ginger samples dried with FD, IR, RHCD, and MD. As observed in Figure 6a, the cell structure of FG were complete and undamaged with normal morphology showing no visible pores (spaces) and fractures. The microstructural alterations of the ginger samples dried by the various dehydration techniques (Figure 6b–e) are linked with water movement from the structure of the cell which causes loss of turgor and cell stress resulting in the collapse of the cell structure. As depicted in Figure 6e, MD-ginger samples produced more severe alterations and damages on the cell structure compared to the FD, IR, and RHCD. This outcome may be ascribed to the fast conversion of MD radiations into heat energy which restricted the inner moisture from evaporating outside. The accumulated inner moisture caused a higher degree of pressure which led to the creation of a dry layer, shrinkage, and collapse of the cell structure (An et al., 2016). In Figure 6d, the cell structure of the RHCD-dried ginger were partially damaged with less retention of the starch grains and pores. This might be attributed to the quick dehydration of superficial moisture which caused crust formation and collapse

of the cell structure as a result of internal stress. This outcome is consistent with the previous investigation of Osaie, Zhou, Xu, et al. (2019b).

Ginger samples dried by FD and IR showed well preserved and intact cell structure (Figure 6b,c) but the FD was more similar to the FG (Figure 6a) than IR. The retained cell structure of the IR sample may due to less extreme heating and shorter dehydration duration. An et al. (2016) reported a similar outcome. The well-preserved cell structure with minimum structural damage of the FD-ginger samples might be ascribed to an increase of ice crystals which compacted the cell structure into the formation of porous and a spongy structure which resulted in the avoidance of shrinkage and collapse of the cell walls (Valadez-Carmona et al., 2017).

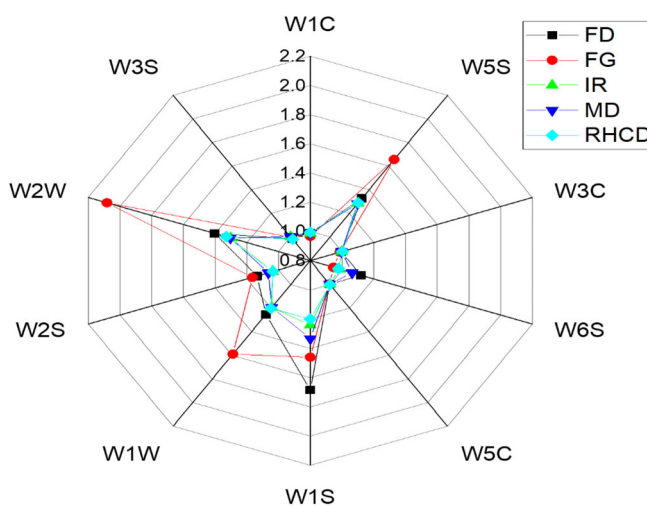


FIGURE 7 Radar plots of E-nose sensor response for FG, FD, RHCD, IR, and MD

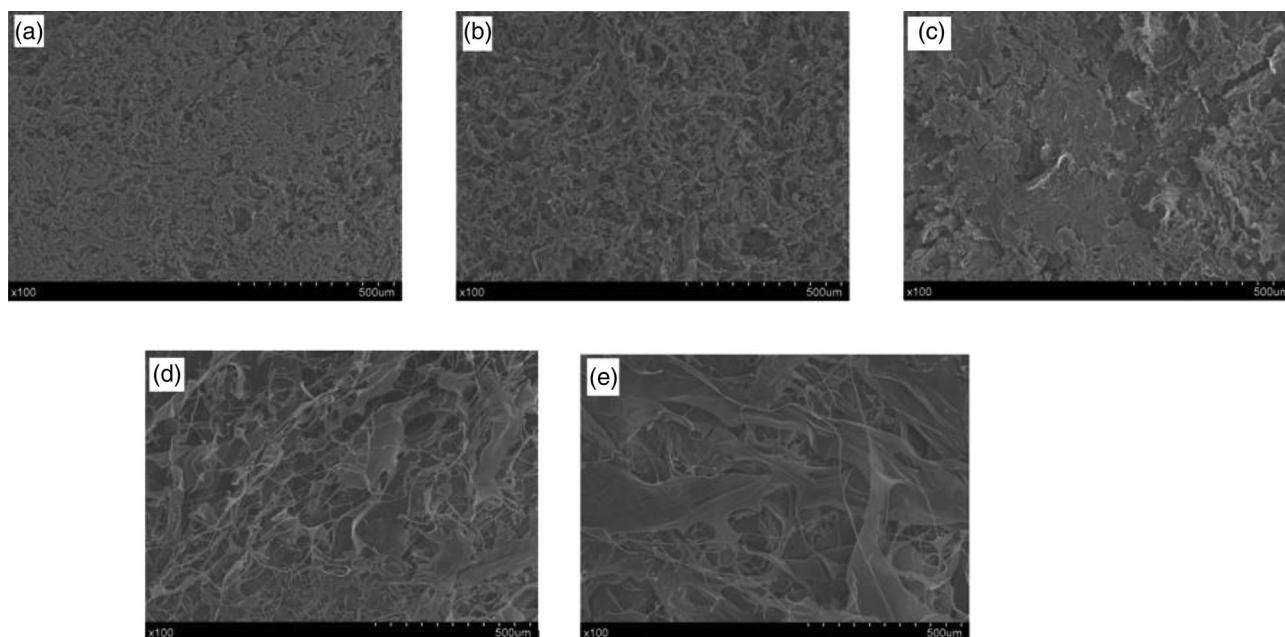


FIGURE 6 Scanning electron micrographs (SEM) of FG (a) and dried ginger slices using FD (b), IR (c), RHCD (d), and MD (e). FD, freeze-drying; FG, fresh ginger; IR, infrared drying; MD, microwave drying; RHCD, relative humidity convective drying

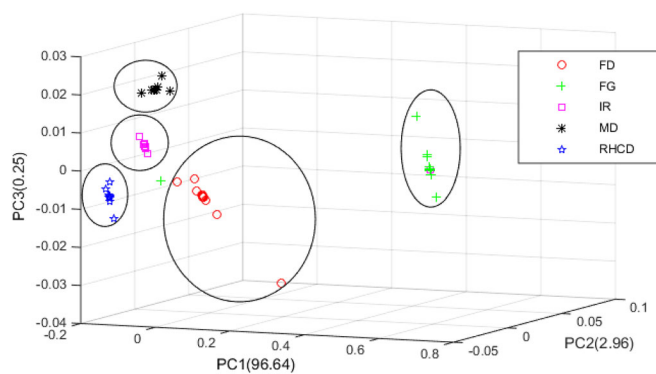


FIGURE 8 Principal component analysis (PCA) for FG, FD, RHCD, IR, and MD

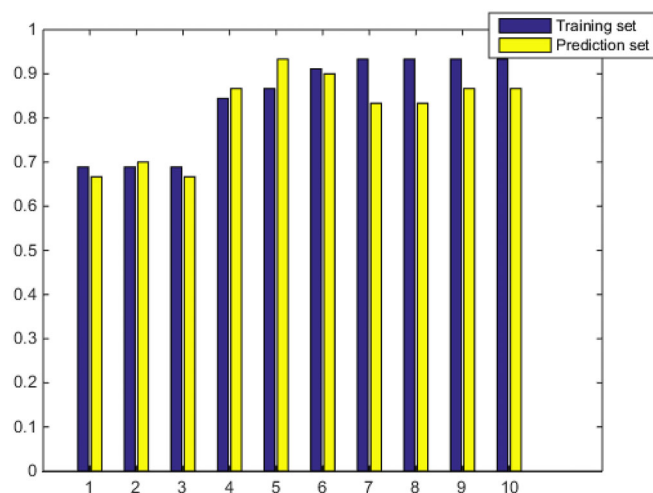


FIGURE 9 Linear discrimination analysis (LDA) showing training and prediction classification accuracies

3.10 | Volatile compounds (E-nose signal response analysis)

One of the most significant quality indicators of dried products particularly spices is the volatile compounds (aroma profiles) and this is often destroyed or altered during dehydration leading to an undesirable product. The radar plot in Figure 7 depicts the volatile compounds of ginger samples dried by different techniques and assessed by electronic nose analysis (E-nose). All response values of the 10 sensors were different in terms of their sensitivity and selectivity. W2W and W5C sensors showed higher peak values than the other sensors (Figure 7). These sensors are sensitive to aromatic compounds, organic compounds and Inorganic sulfur (W2W) and Alkanes, aromatic compounds, and nonpolar organic compounds (W5C).

According to An et al. (2016), the main organic compounds that are responsible for the characteristic flavor and aroma properties ginger are zingiberene, α -curcumene, β -phellandrene, β -sesquiphellandrene, geraniol and β -bisabolene, and Terpenes (geraniol, Citral, and linalool).

These are consistent in the rise of the W2W and W5C which are sensitive to aromatic compounds. The volatile composition was markedly higher in the FG than the dried ginger samples (Figure 7). Ding et al. (2012) further established that one of the significant organic compounds that play a key role in the flavor and aroma profile of ginger is alkanes and aldehydes. The various drying techniques resulted in diverse changes of the volatile compounds (aroma and flavor) of the dried ginger samples in the following trend: FG > FD > RHCD > MD > IR.

The principal component analysis (PCA) and linear discrimination analysis (LDA) of the ginger samples dried by the four dehydration methods are presented in Figures 8 and 9. From Figure 8, the rate of contribution is 99.85% with PC1, PC2, and PC3 contributing 96.64, 2.96, and 0.25%, respectively accounting for a total PCA value of 99.85%. The distinct separation of the dried ginger samples based on the various drying method employed can clearly be observed in Figure 8. It can also be observed that apart from FG sample, the FD, RHCD, IR, and MD-ginger samples showed much nearer distance between them, which suggests a similarity in their volatile profiles compared to the FG sample. A previous investigation by Ding et al. (2012) and An et al. (2016) on the volatile composition of ginger documented similar outcomes.

The LDA was also employed to develop a classification model to discriminate the variations in the samples based on the E-nose data. The result yielded a classification accuracy of 91.11% for the training set and 90% for the prediction set (Figure 9).

4 | CONCLUSION

The influence of four various drying techniques (FD, RHCD, IR, and MD) on antioxidant activity (ABTS, CUPRAC, DPPH and FRAP), bioactive compounds (TPC and TFC), rehydration ratio (RR), color, enzyme activity (PPO and POD), energy consumption rate, microstructure, volatile compounds, and drying kinetics of ginger slices were evaluated. Based on the outcome of the present study, we conclude that FD and RHCD are the best drying techniques for ginger. These drying techniques best preserved and enhanced antioxidation, TPC, TFC, rehydration ratio, color retention, microstructure, and aroma attributes as well as minimized enzyme activity. However, the RHCD was more effective in the reduction of energy consumption rate and enhancement of drying kinetics.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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