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Research Article

Influence of Drying Parameters and Methods of Fractionation in the Chemical Composition of Dehydrated Ginger (*Zingiber Officinale* Roscoe)

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Abstract: Ginger is widely commercialized in the food, chemical, and pharmaceutical industries, mainly in dehydrated and powdered form. To do this, the raw material must go through a drying process, which can significantly influence its characteristics. This study proposed to investigate the ginger dehydration process under three different fractionation methods: whole, sliced, and grated, and subjected to three other drying processes: oven with forced air circulation and renewal (CC) and without forced air circulation and regeneration (SC), both for temperatures of 50, 60, 70 and 80 °C, and freeze-drying. The data obtained allowed the construction of drying curves depending on time. The samples were analyzed for color, phenolic compounds, substances reactive to thiobarbituric acid (TBARS), acidity titratable capacity, 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging capacity, and chemical composition of the oils essential, obtained by hydrodistillation. The ginger drying kinetics shows that the process efficiency is maximized by combining parameters such as more significant sample fractionation, high temperatures, and forced air circulation. Notably, the preservation of bioactive compounds is more effective under conditions of lower temperature, lower fractionation, and absence of forced air circulation, highlighting the importance of these factors in maintaining the nutritional properties of ginger. The evaluation of the essential oil reinforces the need for appropriate strategies, such as freeze-drying or drying in an oven with forced air circulation at 50 °C, to minimize the degradation of volatile components, contributing to optimizing ginger dehydration processes promoting and preserving its nutritional and functional benefits.

***Keywords*:** drying, ginger, antioxidant activity, bioactive compounds, oils essences

1. Introduction

Ginger (*Zingiber Officinale* Roscoe) is part of the Zingiberaceae family, has around 53 genera and 1,300 species, and is extremely widespread in folk medicine, with reports of its cultivation and processing in China for more than two thousand years [1]. In the morphological spectrum, ginger rhizomes have a horizontal distribution, with branches in the same plane. Although they grow underground, they are not considered roots but as swollen stems [2]. The stem is

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erect and can reach up to 75 cm in height. The flowers are arranged in spikes attached to unique stems directly from the rhizomes, which are tubular, purple, and light yellow. However, ginger flowering only occurs under specific climatic conditions [3].

The commercial use of ginger covers the cosmetics, perfumery, pharmaceutical, and food sectors. In the latter, it is used as a condiment in the manufacture of drinks, preserves, sauces, and bakery and confectionery products, in addition to being used [4]. The main ways of using ginger are decoction, infusion, dehydration, powder, extract, and syrup. Marketing data indicates that fresh rhizomes are offered to the consumer market in new, dried, cured, preserved, frozen, and powder forms [5-6].

The ginger rhizome contains essential oils, composed of monoterpenes, sesquiterpenes, and derivatives, a substance that gives the characteristic aroma and flavor of ginger, and oleoresins, formed by gingerols and shogaols, compounds responsible for the pungency [7]. The compounds in volatile oils have several properties that make them highly valuable, whether for medicinal purposes, food purposes, as flavorings and dyes, or to manufacture perfumes [8]. The aroma responsible for its fragrance is related to Zingiberene, the main component present in the essential oil [9]. Obtaining essential oils, extracts, and concentrates of ginger from the rhizomes has aroused the interest of the pharmaceutical and cosmetic industry due to its active ingredients [10].

Chemically, compounds isolated from ginger can be grouped into pungent and flavoring compounds [11]. Ginger works by stimulating saliva production, significantly stimulating the activity of digestive enzymes in the pancreas, lipase, amylase, and proteases, and the terminal digestive enzymes of the small intestine mucosa [12]. Although ginger stimulates the digestion and absorption of fat in the diet, this spice effectively suppresses the body's cholesterol, exerts anti-obesity effects, and shows cardioprotective potential [13-15].

Food conservation and dehydration processes go together, as preserving dry foods is an essential form of conservation [16]. Dehydrating ginger constitutes an alternative for protection, as it has a high natural water content (moisture varying between 85 and 90%), making it susceptible to degradation by microbial action [17].

This work aims to evaluate the feasibility of some methodologies in the ginger drying process. The drying process was associated with the time required for dehydration and the degradation of bioactive compounds, in addition to assessing the composition of essential oils obtained through extraction by hydrodistillation.

2. Material and methods

Ginger (*Zingiber officinale*) was obtained from a rural property in the Laranjeiras do Sul, central-western region of the State of Paraná, Brazil, Coordinates 25° 24' 28" S and 52° 24' 58" W.

For the experimental procedure, approximately 40 kg of fresh ginger was calculated using the same sample batch at the same maturation stage. Before the drying process, the parameters for preparing the raw material were established to diversify its distribution during drying and thus obtain possible variations in results and provide a possible comparison of them.

Once the initial parameters were established, the experiments were carried out. The ginger was washed in running water for about 10 minutes and drained to remove excess water until samples were obtained without water apparent. The selection was also carried out, removing the defective "fingers". Next, the rhizomes were fragmented into three different forms (Figure 1): grated (slices with a diameter of 0.5 cm), sliced (7.0 cm in length), and whole.

When obtaining the ground ginger, using the Skymsen food processor, model PA-7SE-N, it was found that due to the ginger being made of a fibrous material and associated with the high rotation of the mechanical grinder, part of the ginger was retained in the grinder disc, making continuous grinding of the raw material difficult. Another critical point was that the grinding procedure resulted in considerable water loss and could significantly affect the work results. Consequently, it was decided to manually grate the ginger where the raw material would increase its contact area; however, the water loss during processing was minimal. Another proposed form of ginger fractionation was "chip" slicing, where cuts would occur perpendicular to the ginger's longitudinal direction (largest dimension) in its resting position, thus maintaining the peel on its circumference.

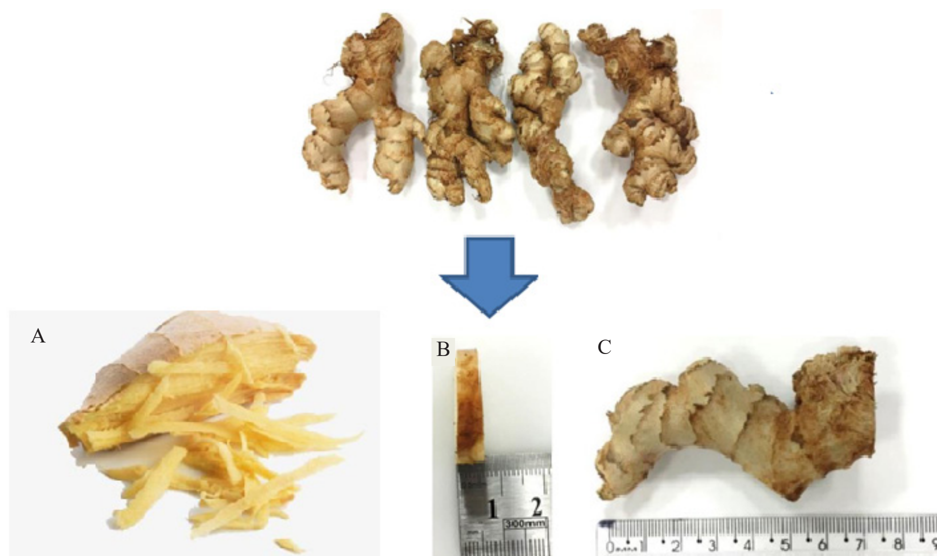

Figure 1. Rhizome fragmentations: A-grated, B-sliced, and C-whole

2.1 *Characterization of fresh ginger*

A representative and random sample was used to characterize ginger during fragmentation. This sample was then crushed using a Cuisinart® food processor until homogeneous before the characterization analysis. The moisture content, water activity, and color of fresh ginger were determined with the ground sample. Subsequently, using mass values of the ginger sample on a dry basis, the levels of phenolic compounds, antioxidant capacity (DPPH), titratable acidity total, and content of substances reactive to thiobarbituric acid (TBARS) were determined.

2.2 *Study of drying kinetics and preparation of the "Xbs x t" graph*

The drying kinetics of ginger was determined using three different drying methodologies: conventional oven without forced air circulation (AmericanLab, SL-100-SOLAB) and oven with renewal. It forced air circulation (AmericanLab, AL-102/480) and freeze-drying (Líotop, L101), and before the freeze-drying process, the ginger samples were placed in an ultra freezer (INDREL, IULT) for 24 hours. The mass values for constructing the drying curves were obtained by measuring the mass of the sample at intervals of 30 minutes, with measurements being carried out until constant mass. Drying curves were then constructed for the three drying processes and for the three ways the sample was presented (whole, sliced, and grated).

$$\text{Xbs} = \frac{\text{wet mass} - \text{drt mass}}{\text{drt mass}} \tag{1}$$

Where:
Xbs = moisture content of a material ((kg of product – kg dry mass) / (kg dry mass)).
Wet mass = mass of the sample at weighing.
Dry mass = the constant dry mass.

2.3 *Oven drying with and without forced air circulation*

The sliced and grated ginger samples were spread separately on Petri dishes, maintaining a sample thickness of 5.0 mm; as for the ginger sample, whole ginger, two samples were placed in a Petri dish reaching the mass of approximately 15.0 g (similar to fractionated samples). The samples were then dehydrated in an oven at 50, 60, 70, and 80 °C

temperatures until constant mass was measured. To avoid temperature disparity within the desiccator between trays, it was decided to conduct all tests on the same desiccator tray [18].

2.4 *Freeze drying*

After 24 hours under freezing at -20 °C, the samples were transferred to the freeze dryer, starting the drying process until the sample reached a constant mass.

2.5 *Characterization of "in natura" ginger*

For the determination of water activity (Aw) and preparation of the "Aw x t" graph, water activity was determined using Aqualab equipment (Novasiva AG). Measurements were carried out during the drying procedures using the same period of 30 minutes, simultaneously measuring the mass of the samples. Measurements were carried out for dry and freeze-dried ginger at temperatures of 80, 70, 60, and 50 °C. After drying, the ginger was ground in a Fortinox hammer mill, model STAR FT 53, using a 20 mesh sieve.

The colorimetric analysis was performed using a colorimeter (Minolta CR-400), and the results were expressed by the parameters L*, C*, and H* [19]. The content of phenolic compounds followed the FolinCiocauteau method, according to Bucic-Kojic et al. [20]. The results were expressed in mg of FA per 100 g of sample. The quantification of substances reactive to thiobarbituric acid was adapted from the methodology proposed by Ohkawa et al. [21]. The result was expressed in milligrams of malonaldehyde (MDA) per kilogram of ginger sample. The AOAC methodology was applied to determine the total titratable acidity, and the results were expressed in milliequivalents of base per 100 g of sample.

The DPPH radical scavenging capacity was determined using absorbance measurements on a spectrophotometer, which were made at 517 nm every minute until the signal stabilized. Antioxidant activity was expressed as the sample mass necessary to reduce the initial concentration of the DPPH radical (EC50) by 50% in g of sample/g of DPPH.

2.6 *Hydrodistillation*

The hydrodistillation procedure to obtain the essential oil from ginger rhizomes was used using the Clevenger apparatus. The results obtained for extraction yield were calculated on a dry basis.

2.7 *Essential oil analysis*

The determination of the chemical composition of essential oils was carried out in a gas chromatograph with a mass detector (SHIMADZU, GC QP 2010-Ultra) equipped with a fused silica capillary column (NTS 0.5 ms; 30 m × 0.25 mm × 0.24 µm) and using helium as carrier gas. Samples prepared for injection were obtained by simply diluting the collected extract in n-hexane. The profile of the oil components was studied using simple area standardization, in which the area of each constituent of the chromatogram was divided by the total size of the detected compounds, and the value obtained was multiplied by 100. The identification of each component was confirmed through comparison with the mass spectrum present in the equipment library (NIST08, NIST08s, NIST11, and NIST11s).

2.8 *Statistical analysis*

The results were subjected to analysis of variance (ANOVA) to determine significant differences with 95% significance ($p < 0.05$). A comparison of means was performed using the Tukey test ($p < 0.05$).

3. Results and discussion

3.1 *Characterization of "in natura" ginger*

Table 1 presents the values obtained for analyzing fresh ground ginger regarding titratable acidity, phenolic

compounds, moisture content, antioxidant activity, TBARS, and color. The results are expressed on a dry basis.

Ginger had a moisture of 88 ± 1% (m/m), similar to Ghafoor et al. [22]. The ginger water activity was 0.97 ± 0.01, a high value and determining factor for the growth of microorganisms [23]. According to Umunna et al. [24], fresh ginger contains 2.3% protein, 0.9% fat, 1.2% minerals, 2.4% fiber, and 12.3% carbohydrates. However, the composition may vary depending on the geographic location in which it was grown.

The acidity of fresh ginger presented a value of 10.8 ± 0.3 mEq/100 g. The primary phenolic acids in ginger are pyrogallol, p-hydroxybenzoic acid, ferulic acid, p-coumaric, salicylic, caffeic, and gallic acids [22]. The determination of phenolic compounds showed a value of 1,103 ± 8 mg FA/100 g, close to those reported by Osae et al. [25]. The concentration of bioactive compounds in ginger can vary according to the species of ginger, the type of soil in which it was grown, the climate, and harvest time, among others.

Table 1. Physical and chemical characteristics of fresh ground ginger

Analysis	Results
Moisture (%, m/m)	88 ± 1
Water activity (Aw)	0.97 ± 0.01
Titratable acidity (milliequivalents of base/100 g)	10.8 ± 0.3
Phenolic compounds (mg FA/100 g)	1,103 ± 8
Antioxidant capacity (g sample/g DPPH)	6.0 ± 0.1
TBARS (mg MDA/kg)	2.8 ± 0.2
L*	57 ± 1
C*	29 ± 2
H*	80 ± 2

Mean ± standard deviation (n = 3)

Regarding the DPPH radical scavenging capacity measured by EC50, the value obtained was 6.0 ± 0.1 g (g sample/g DPPH). This value demonstrates that fresh ginger has a high antioxidant capacity, as following the principle, 6 g of sample is needed to reduce 1 g of the DPPH radical by 50% [26].

The value obtained for the TBARS test was 2.8 ± 0.2 mg MDA/kg. The TBA test measures total carbonyls (malonaldehyde), or selective carbonyl compounds, and off-flavor odors due to the formation of volatile hydroperoxide decomposition products.

For the ginger color analysis, 57 ± 1 was obtained for the L* parameter (Lightness), 29 ± 2 for C* (Saturation), and 80 ± 2 for H* (Hue). The H* parameter had a value consistent with the ginger sample since the shade of ginger must vary between 0° and 90°, with the closer to 90°, the more intense the yellow color, and the closer to 0°, the more intense. It will be red; therefore, the color of natural ginger has a color that tends towards yellow [27].

3.2 *Study of drying kinetics*

From the drying kinetic data, moisture curves were constructed Xbs(t). These curves identified the time required for drying each sample at each temperature and respective equipment. Figure 2 shows the Xbs(t) curves of CC and SC oven drying for the different forms of ginger fractionation.

As shown in Figure 2, the increase in temperature promoted more efficient dehydration of ginger, that is, in less time. This is due to the increased drying potential. The increase in energy supplied causes an increase in air temperature and, consequently, a reduction in the relative moisture of the drying air [28]. The differences between the processes

become more evident when comparing the times to obtain a constant mass for each test, shown in Table 2.

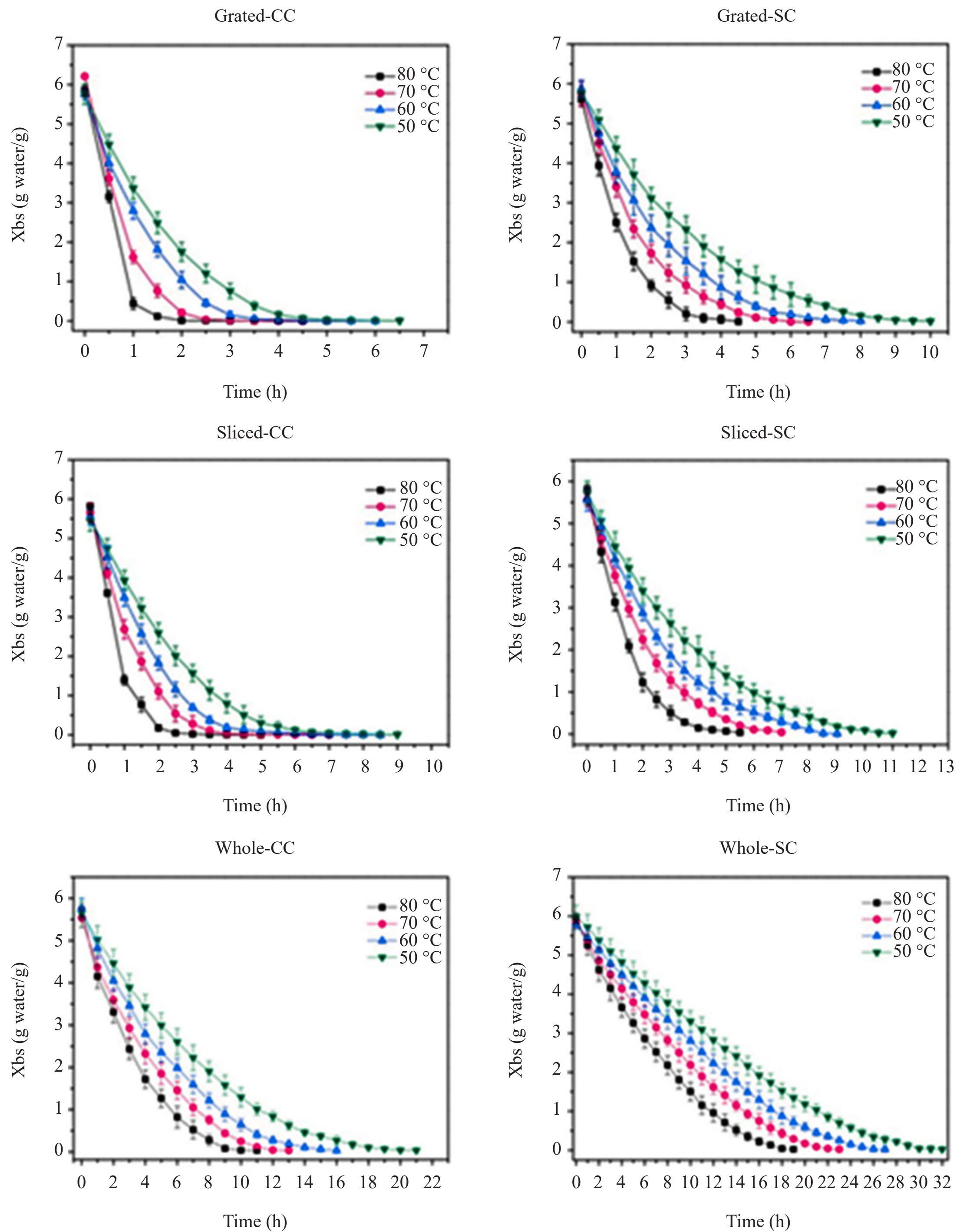

Figure 2. Graphical representation Xbs(t) for different methods of greenhouse dehydration and different temperatures: (CC-greenhouse with circulation and air renewal; SC-greenhouse without circulation and air renewal)

Dehydration times varied statistically for different temperatures, as shown in Figure 2 and Table 2. The grated sample had the shortest dehydration time at 80 °C in a CC oven. In freeze-drying, the times were 4.5 ± 0.5, 5.7 ± 0.3,

and 19.0 ± 0.3 hours for the grated, sliced, and whole forms, respectively. These freeze-drying times were similar to the temperature times of 50 to 60 °C in a CC oven and 70 to 80 °C in a SC oven, considering the corresponding fractionation method.

Table 2. Time, in hours, to obtain constant mass for dehydration methods in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
80	3.7 ± 0.3^{dC}	5.0 ± 0.6^{dB}	18.2 ± 0.3^{dA}	1.8 ± 0.3^{cC}	2.5 ± 0.3^{dB}	10.0 ± 0.6^{dA}
70	5.8 ± 0.3^{cC}	6.8 ± 0.3^{cB}	22.0 ± 0.6^{cA}	2.7 ± 0.3^{bC}	4.2 ± 0.3^{cB}	12.0 ± 0.6^{cA}
60	6.7 ± 0.3^{bC}	8.5 ± 0.3^{bB}	25.8 ± 0.3^{bA}	3.5 ± 0.6^{bC}	5.7 ± 0.3^{bB}	15.0 ± 0.6^{bA}
50	9.0 ± 0.6^{aC}	10.5 ± 0.6^{aB}	30.2 ± 0.3^{aA}	4.8 ± 0.3^{aC}	7.5 ± 0.3^{aB}	19.7 ± 0.8^{aA}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

Figure 3 shows the Xbs(t) dehydration curves in a freeze dryer for the different ways of fractionating ginger. Evaluating Figures 2 and 3 and Table 2, it can be seen that there was a difference in drying times between the different temperatures, the various forms of fractionation, and the drying methods used. This is due to each process's mass and heat transfer phenomenon. It is observed that the Xbs(t) curves presented well-defined shapes without significant disparities at the points, demonstrating a condition of homogeneity in the dryer and following a typical behavior of dehydration of solids with heated air.

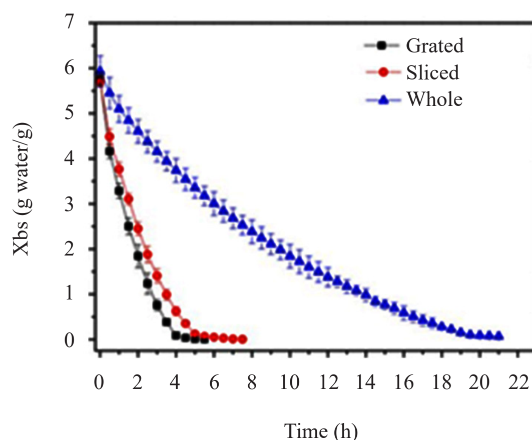

Figure 3. Graphical representation Xbs(t) of the different fractionation methods of ginger dehydrated in a freeze dryer

The period of stabilization or induction of drying, an adaptation of the object to the drying medium (the first values obtained), of ginger was negligible, as the solid's response to the sudden variation in external conditions occurred almost instantly. When drying ginger, there was a period of constant drying rate, resulting from a layer of saturated water on the surface of the solid. In this situation, drying occurs the same way as in a mass of pure water, without the direct influence of the solid material upon drying [29].

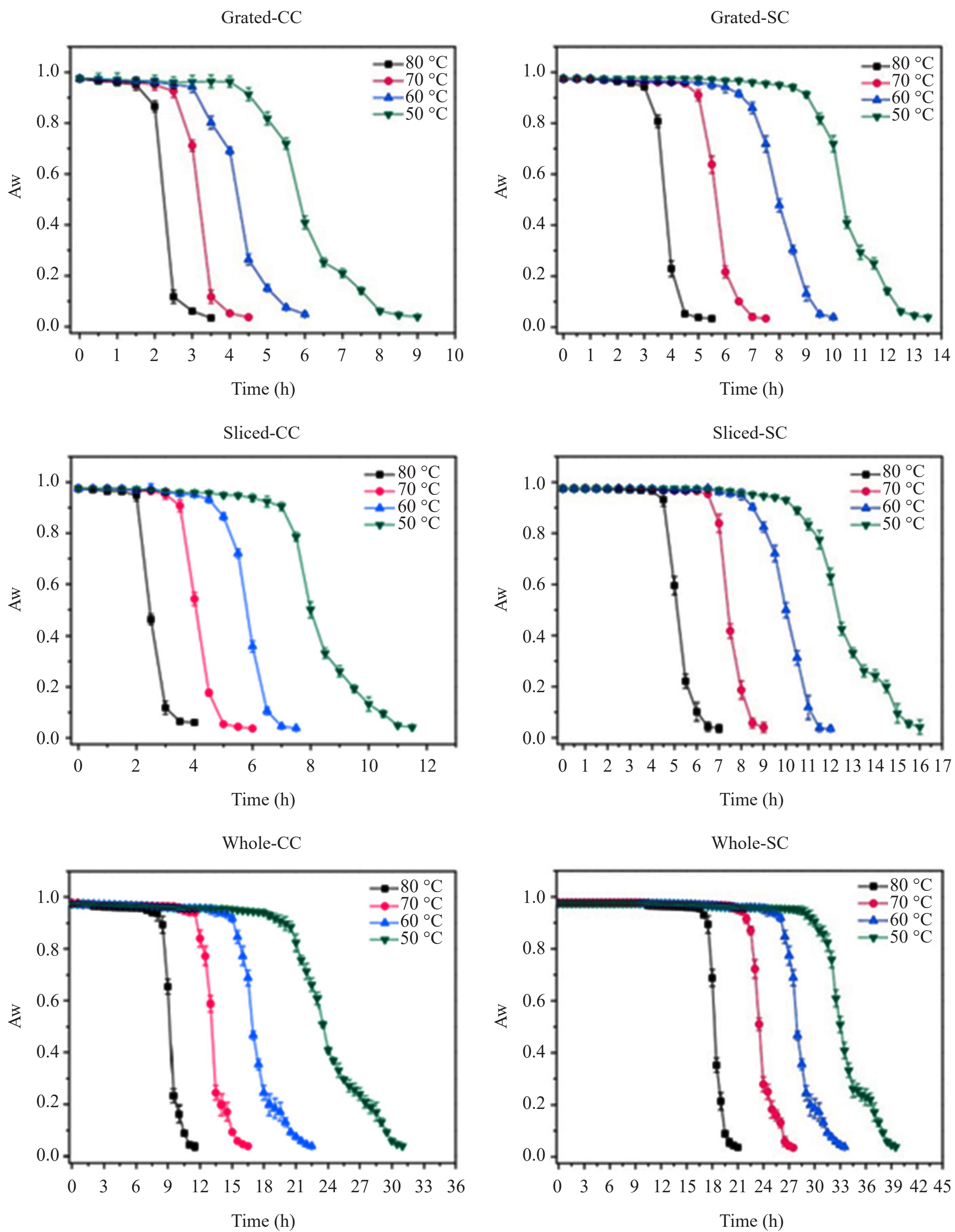

Figure 4. Graphical representation of Aw for the different ways of fractionating dehydrated ginger at different temperatures and drying in CC and SC ovens

During this period, the driving force that defines the movement of water vapor along the thin layer of static air is the water vapor pressure gradient between the sample surface and the primary drying air current, which is dependent on the temperature. Therefore, the higher the drying temperature, the greater the water vapor pressure gradient and the faster the evaporation of water from the surface of the ginger occurs. This explains the need for a longer drying time to reach the critical moisture at 50 °C. Given this situation, the temperature can be considered a significant influence

when drying ginger on trays; a fact also reported in the literature by Muthukumar et al. [29] when evaluating the drying process of black ginger slices at temperatures of 40 at 80 °C.

3.2.1 *Obtaining the "Aw x t" curves*

Aw is a parameter that relates to any product's stability and storage time, as its values are directly related to water reaction availability. Figure 4 shows the behavior of Aw evaluated during the dehydration process of different forms of ginger fractionation, dried in CC and SC ovens.

Evaluating Figure 4 and Table 3, it is possible to observe that the form of fractionation of ginger that obtains Aw < 0.3 the fastest was for the type of grated fractionation, dehydrated in a CC oven, in which it took 2.5, 3.5, 4.5 and 6.5 hours at temperatures of 80, 70, 60 and 50 °C, respectively. In contrast, the whole fractionation form dehydrated in the SC oven took 19, 24, 29.5, and 34.5 hours to reach the same condition. The times to get Aw values < 0.3 were more significant for lower temperatures, less fractionated samples, and processes in the SC oven. This fact is related to the evaporation of water during the drying process [30].

Table 3. Time, in hours, to obtain the water activity value (Aw) below 0.3 for the dehydration methods in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
80	4.0 ± 0.3^{dC}	5.5 ± 0.6^{dB}	19.0 ± 0.3^{dA}	2.5 ± 0.3^{dC}	3.0 ± 0.3^{dB}	9.5 ± 0.6^{dA}
70	6.0 ± 0.3^{cC}	8.0 ± 0.3^{cB}	24.5 ± 0.3^{cA}	3.5 ± 0.6^{cC}	4.5 ± 0.3^{cB}	13.5 ± 0.3^{cA}
60	8.5 ± 0.6^{bC}	11.0 ± 0.3^{bB}	29.0 ± 0.6^{bA}	4.5 ± 0.3^{bC}	6.5 ± 0.6^{bB}	18.0 ± 0.3^{bA}
50	11.0 ± 0.3^{aC}	13.5 ± 0.6^{aB}	34.5 ± 0.3^{aA}	6.5 ± 0.3^{aC}	9.0 ± 0.6^{aB}	25.5 ± 0.6^{aA}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

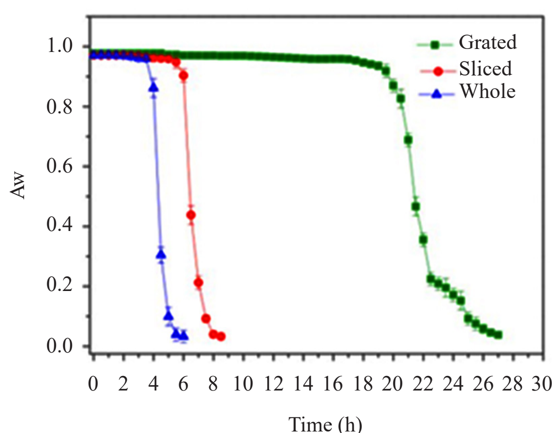

Figure 5. Representation of Aw for the different fractionation methods of ginger dehydrated in a freeze-dryer

It can be seen that the drying kinetics graphs in Figure 3 showed very different behavior when compared to the charts in Figure 4, as the water initially eliminated during drying is free water, a period in which the water activity is not changed. Only at the end of the drying process does the water activity show abrupt drops; this effect demonstrates that the portion of bound water is small, which may be linked by hydrogen bonds and dipole-dipole interactions in the more

structured layers of the ginger sample [31].

The same behavior of Aw reduction during different drying processes was observed by Kraiem et al. [32] during apple dehydration at 60 °C. In the ginger dehydration process in a freeze dryer, an Aw value < 0.3, 5, 7, and 22.5 hours of drying were required for the grated, sliced, and whole samples, respectively. Figure 5 shows the graph of Aw as a function of freeze-drying dehydration time for the different ways of fractionating ginger.

Comparing the Aw values obtained for the three different drying processes (CC and SC oven and freeze dryer), it can be seen that the reduction in Aw for all forms of fractionation in the freeze dryer is close to the results obtained in drying in a CC oven at the temperature of 50 to 60 °C and in the SC oven at a temperature between 70 to 80 °C.

3.3 *Characterization of dry ginger*

3.3.1 *Color*

The color of dehydrated products is an important characteristic, as it represents a quality parameter influencing the consumer's acceptance of the product. Table 4 presents the values of the parameters L*, C*, and H*.

In Table 4, it is possible to observe that for the parameter L*, the values obtained showed a statistical difference between the ways of fractioning the sample for the two drying processes when comparing the temperatures used in dehydration. However, the increase in temperature reduced the luminosity (darker sample); the results did not show a significant difference. That is, the increase in temperature did not significantly change the luminosity of the dehydrated ginger in either of the two oven-drying methodologies.

Table 4. Color parameters L* (Lightness), C* (Saturation), and H* (Hue) in ginger samples dehydrated in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
			L*			
50	52.9 ± 0.6^{aB}	54.8 ± 1.0^{aB}	59.8 ± 1.3^{aA}	54.0 ± 0.6^{aC}	55.8 ± 1.0^{aB}	60.8 ± 1.2^{aA}
60	52.8 ± 0.4^{aC}	54.5 ± 0.7^{aB}	59.4 ± 0.9^{aA}	53.6 ± 0.3^{aC}	55.4 ± 0.6^{aB}	60.3 ± 0.9^{aA}
70	52.7 ± 0.2^{aC}	54.4 ± 0.8^{aB}	59.2 ± 1.0^{aA}	53.3 ± 0.1^{aC}	55.1 ± 0.8^{aB}	59.9 ± 1.0^{aA}
80	52.6 ± 0.4^{aC}	54.4 ± 0.7^{aB}	59.2 ± 1.0^{aA}	53.1 ± 0.4^{aC}	54.8 ± 0.7^{aB}	59.7 ± 0.9^{aA}
			H*			
50	68.9 ± 0.6^{aB}	70.0 ± 0.6^{aB}	75.9 ± 0.2^{aA}	70.5 ± 0.6^{aB}	71.5 ± 0.6^{aB}	77.0 ± 0.2^{aA}
60	68.9 ± 1.3^{aB}	70.2 ± 0.2^{aB}	75.9 ± 1.6^{aA}	70.6 ± 1.3^{aB}	71.7 ± 0.3^{aB}	77.0 ± 1.5^{aA}
70	68.2 ± 0.3^{aB}	69.9 ± 0.4^{aB}	76.0 ± 1.5^{aA}	70.5 ± 0.3^{aB}	71.6 ± 0.5^{aB}	77.1 ± 1.4^{aA}
80	68.4 ± 0.6^{aB}	70.1 ± 0.7^{aB}	76.1 ± 2.0^{aA}	70.4 ± 0.6^{aB}	71.5 ± 0.7^{aB}	76.9 ± 1.9^{aA}
			C*			
50	24.1 ± 0.8^{aA}	20.0 ± 0.4^{aB}	19.4 ± 0.3^{aB}	23.5 ± 0.8^{aA}	19.4 ± 0.4^{aB}	18.9 ± 0.3^{aB}
60	24.3 ± 0.5^{aA}	20.3 ± 0.5^{aB}	19.6 ± 0.5^{aB}	23.6 ± 0.4^{aA}	19.5 ± 0.5^{aB}	19.0 ± 0.5^{aB}
70	24.6 ± 1.7^{aA}	20.2 ± 0.4^{aB}	19.9 ± 0.5^{aB}	24.0 ± 1.8^{aA}	20.0 ± 0.4^{aB}	19.3 ± 0.5^{aB}
80	24.5 ± 1.1^{aA}	20.6 ± 0.2^{aB}	20.0 ± 0.3^{aB}	24.0 ± 1.0^{aA}	20.2 ± 0.2^{aB}	19.3 ± 0.3^{aB}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

Compared to the fresh sample, both drying in a conventional oven (SC) and in a forced convection oven (CC) reduced the luminosity of the samples, except for the integer fractionation form. Freeze-drying did not show significant differences in luminosity values (L* parameter) between the grated, sliced, and whole samples (Figure 6). Oven drying resulted in lower L* values than freeze drying, attributed to the action of temperature and oxygen on the formation of melanoidins, reducing luminosity. Regarding the color saturation parameter (C*), the whole and sliced forms did not differ statistically, but both differed significantly from the grated form. Freeze drying showed lower saturation compared to oven drying. As for the tone parameter (H*), a tendency towards yellow color was observed, especially in whole samples, attributed to the intensification of Maillard reactions. In summary, the choice of drying method influences the color properties of ginger, with freeze-drying being associated with more preserved color characteristics than oven-drying [33].

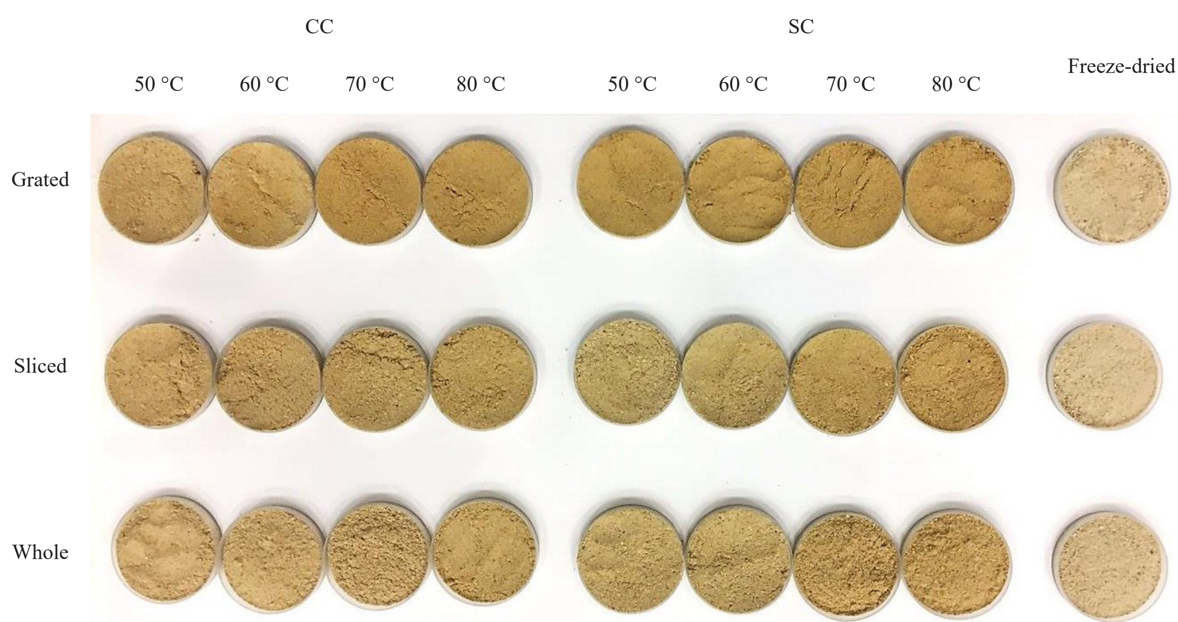

Figure 6. Ginger powder was obtained after drying the different forms of fractionation of the samples in the oven with air circulation (CC), oven without air circulation (SC), and freeze-drying

3.3.2 *Phenolic compounds*

Table 5 presents the results of determining phenolic compounds for the two drying procedures, CC and SC. Table 6 shows the percentages of loss of phenolic compounds, taking as a parameter the value obtained for the fresh sample.

It is observed that drying the ginger led to the degradation of phenolic compounds, being more pronounced with increasing temperature and fractionation of the ginger, with significant losses in all comparisons. For the sliced form, losses ranged from 20 to 31% and 11 to 23% in dehydration in SC and CC ovens, respectively. As for the grated form, the reductions were more significant, with values of 28 to 44% and 18 to 34% in dehydration in SC and CC ovens, respectively.

In the freeze-dried samples, phenolic compounds were found at concentrations of 992 ± 10^{b}, 1,033 ± 6^{a}, and 1,039 ± 4 mg AG/100 g for the grated, sliced, and whole samples, respectively, being significantly lower in the grated form, with a loss of 10%, 6%, and 6%, respectively, compared to the phenolic compound content of the fresh sample. When comparing the ovens, dehydration in the CC oven resulted in less loss of phenolic compounds compared to the SC oven. Tests with grated ginger showed more significant degradation, even during freeze-drying. This effect is related to the greater exposure of cellular material due to the grinding process, exposing polyphenols to enzymatic and non-enzymatic oxidation. Studies highlight that ginger extract has a high content of phenolic compounds. Gingerols, the main compounds of ginger oleoresins, are phenolic ketones with high antioxidant properties and spice; however, heat

treatment can reduce the extracts' antioxidant activity and total phenolic content. Combining the whole fractionation form with dehydration in a CC oven at 50 or 60 °C resulted in the lowest losses of phenolic compounds [34].

Table 5. Content of phenolic compounds (mg of FA/100 g) in ginger samples dehydrated in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
50	795 ± 4^{aC}	887 ± 8^{aB}	972 ± 4^{aA}	901 ± 7^{aC}	979 ± 5^{aB}	1,023 ± 9^{aA}
60	757 ± 8^{bC}	817 ± 9^{bB}	931 ± 4^{bA}	882 ± 7^{bC}	901 ± 6^{bB}	1,013 ± 8^{abA}
70	660 ± 9^{cC}	783 ± 7^{cB}	879 ± 9^{cA}	765 ± 9^{cC}	878 ± 1^{cB}	998 ± 7^{bcA}
80	619 ± 6^{dC}	760 ± 2^{dB}	842 ± 6^{dA}	724 ± 10^{dC}	844 ± 2^{dB}	992 ± 8^{cA}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

Table 6. Percentage of loss of phenolic compounds for dried ginger samples, when compared with the value obtained for the fresh sample

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
50	28%	20%	12%	18%	11%	7%
60	31%	26%	16%	20%	18%	8%
70	40%	29%	20%	31%	20%	10%
80	44%	31%	24%	34%	23%	10%

3.3.3 *Lipid oxidation analysis (TBARS)*

Free radicals resulting from lipid peroxidation are substances reactive to thiobarbituric acid (TBARS), with the main compound produced being malonaldehyde. The formation of malonaldehyde occurs through the breakdown of unsaturated fatty acids and hydrocarbons, and the dosage of this compound is a critical method for determining the degree of lipid peroxidation and a tool for verifying the antioxidant properties of certain substances. Table 7 presents the results of quantifying the TBARS value of the samples subjected to the two oven drying processes, CC and SC.

From the values presented in Table 7, it is possible to identify that with the increase in temperature and sample fractionation, the TBARS values increased; thus, it is observed that lipid oxidation in ginger increased with the temperature rise, generating in this situation, a significant difference between the results obtained.

Lipid oxidation leads to side reactions (polymerization, cyclization, and scission), typically small at average storage temperatures. Drying in a direct current (DC) oven has been shown to have lower values for TBARS compared to an alternating current (SC) oven. In the CC oven, volatilization of the malonaldehyde formed can occur due to the continuous air current or due to the shorter drying time, resulting in less exposure to high temperatures and atmospheric oxygen, reducing the formation of malonaldehyde [35].

It is observed that minimizing the effects of temperature and preventing lipid oxidation through combining parameters in ginger dehydration is possible. Combining whole fractionation with dehydration in a CC or SC oven at 50 °C resulted in a significant reduction in the formation of MDA, with values close to those obtained for the fresh sample. Similar results were observed in freeze-drying dehydration for whole and sliced fractionation forms.

Table 7. Content of substances reactive to thiobarbituric acid (mg MDA/ kg) in ginger samples dehydrated in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
50	3.8 ± 0.1^{dA}	3.5 ± 0.1^{cB}	3.0 ± 0.1^{dC}	3.7 ± 0.1^{dA}	3.4 ± 0.2^{cAB}	3.1 ± 0.2^{dB}
60	4.4 ± 0.2^{cA}	4.1 ± 0.2^{bAB}	3.9 ± 0.2^{cB}	4.2 ± 0.1^{cA}	4.0 ± 0.2^{bA}	3.6 ± 0.1^{cB}
70	4.8 ± 0.2^{bA}	4.6 ± 0.2^{bAB}	4.4 ± 0.1^{bB}	4.6 ± 0.3^{bA}	4.4 ± 0.2^{bA}	3.9 ± 0.1^{bB}
80	5.6 ± 0.3^{aA}	5.2 ± 0.1^{aA}	4.8 ± 0.1^{aB}	5.2 ± 0.2^{aA}	5.0 ± 0.1^{aA}	4.4 ± 0.2^{aB}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

3.3.4 *Titratable acidity*

Table 8 presents the titratable acidity values for the different fractionations of ginger subjected to dehydration in an oven without (SC) forced air circulation and with (CC). Data are expressed in mEq/100 g.

It was found that acidity increased with the increase in temperature and also with the increase in sample fractionation, comparing the two drying methods, with drying in the SC oven showing higher acidity results. This characteristic may be directly related to the oxidation process of organic compounds in the sample, mainly aliphatic molecules with an OH group (primary alcohol). The OH groups in aliphatic molecules are oxidized to aldehyde and carboxylic acid, the most oxidized state of organic compounds. Furthermore, high drying temperatures and high water reduction rates would degrade the structure of cell membranes, causing an increase in the availability of compounds with acidic characteristics.

Table 8. Titratable acidity (mEq/100 g) of ginger samples dehydrated in an oven without air circulation (SC) and with air circulation (CC)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
50	13.2 ± 0.5^{cA}	12.8 ± 0.3^{dAB}	12.1 ± 0.2^{cB}	12.9 ± 0.2^{cA}	12.2 ± 0.4^{cB}	11.5 ± 0.1^{cC}
60	14.3 ± 0.2^{bA}	13.9 ± 0.3^{cAB}	13.5 ± 0.1^{bB}	14.2 ± 0.1^{bA}	13.6 ± 0.5^{bAB}	13.0 ± 0.2^{bB}
70	14.7 ± 0.3^{bA}	14.5 ± 0.2^{bAB}	14.0 ± 0.5^{bB}	14.3 ± 0.3^{bA}	13.9 ± 0.3^{bA}	13.1 ± 0.3^{bB}
80	16.4 ± 0.4^{aA}	16.2 ± 0.2^{aA}	15.0 ± 0.3^{aB}	16.0 ± 0.3^{aA}	15.7 ± 0.1^{aA}	14.1 ± 0.1^{aB}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

3.3.5 *DPPH radical sequestration capacity*

From the calibration curve obtained by linear regression of the concentration values of the DPPH radical and its absorbances at 515 nm, the percentages of the radical remaining in the reactions were determined for various concentrations of active extracts and the EC50 efficiency coefficients (mg of extract), defined as the necessary amount of active extract so that the initial concentration of the DPPH· radical in the reaction decreases by 50%. Table 9 shows the values obtained for the antioxidant capacity (EC50) of powdered ginger extracts subjected to dehydration in an oven with (CC) and without (SC) forced air circulation.

Considering that the lower the EC50 value, the greater the antioxidant capacity of the material analyzed, the results

indicate that fresh ginger has greater antioxidant power than dry samples. As shown in Table 9, the EC50 value showed a statistical difference between the fractionation methods for all temperatures and the two drying methodologies. The best results were obtained for the entire sample dehydrated in a CC oven, as it was the one that presented the closest value to that found for the fresh sample. A trend was also observed that the higher the temperature and the greater the fragmentation of the sample subject to dehydration, the higher the EC50 results.

For the freeze-dried samples, the values obtained were 12.4 ± 0.2^{a}, 12.3 ± 0.3^{ab}, and 12.0 ± 0.2^{b} for the grated, sliced, and whole samples, respectively. It was found that the values obtained were better than those obtained in oven dehydration processes. There was a statistical difference in the freeze-drying process, where the best results were for the whole and sliced samples. The antioxidant capacity may also be related to the speed of the reducing reaction of the compounds.

The determination of the antioxidant capacity of DPPH radical scavenging is directly related to the concentration of phenolic compounds, as phenolic compounds, which are formed by one or more aromatic rings and with at least one hydroxyl group, in general, can react with free radicals, due to the ease with which the hydrogen atom of the hydroxyl group can be separated by a free radical, generating a quinoid structure that supports the presence of an unpaired electron [36].

Table 9. DPPH radical scavenging capacity of ginger strata dehydrated in the oven without air circulation (SC) and with air circulation (CC), expressed by the efficiency coefficient EC50 (g of sample/g of DPPH)

T (°C)	SC			CC		
	Whole	Sliced	Grated	Whole	Sliced	Grated
50	27.8 ± 1.5^{bA}	19.8 ± 0.3^{bB}	15.2 ± 0.4^{bC}	20.8 ± 1.4^{cA}	15.6 ± 0.2^{cB}	13.3 ± 0.2^{cC}
60	31.9 ± 1.9^{bA}	22.7 ± 1.4^{bB}	16.6 ± 0.4^{bC}	24.3 ± 1.9^{bcA}	17.4 ± 0.2^{bcB}	13.6 ± 0.3^{cC}
70	38.4 ± 2.7^{aA}	27.5 ± 2.3^{aB}	18.2 ± 0.6^{bC}	27.1 ± 2.2abA	19.6 ± 0.3^{bB}	15.4 ± 0.4^{bC}
80	41.3 ± 2.5^{aA}	31.2 ± 2.8^{aB}	23.1 ± 2.9^{aC}	30.2 ± 3.1^{aA}	22.1 ± 1.9^{aB}	18.8 ± 0.7^{aC}

Mean ± confidence interval (n = 3) for 95% reliability. Means followed by the same lowercase letters in the same column and followed by the same capital letter in the same row are not statistically different from each other using the Tukey test ($p < 0.05$)

3.3.6 *Composition of ginger oil*

It is observed that the hydrodistillation, carried out for 3 hours, achieved an extraction yield that varied from 1.53 to 1.64%, with the extract from the fresh sample showing a higher yield, although the values obtained are very close.

Based on the composition results obtained, it was found that ginger has a large number of active and aromatic substances. The chromatograms demonstrated similarity between the chemical profiles of the extracts, and according to the GC-MS library, ginger contains monoterpenes, terpenoids, and sesquiterpenes. Since the majority components for fresh ginger were: α-zingiberene (32.11%), α-farnesene (9.97%), camphene (9.59%), β-phellandrene (8.95%), geranial (8.24%), sesquiphellandrene (7.46%), neral (5.30%) and eucalyptol (2.13%).

Although there are variations, the results in the literature were compatible with the values obtained in the present work, both for the fresh sample and those brought in dehydrated samples. These variations in the composition of the main volatile components of the ginger rhizome can be attributed to the origin of the material, the cultivation, the vegetative stage and growth phase of the plant under study, as well as the extraction methods and types of solvents used. The many constituents present in ginger essential oil are responsible for its bioactive properties and aromatic characteristics. Neral and geranial possibly contribute to the strong lemon aroma, and these compounds can be isolated and used by the perfume and food industry as raw materials in synthesizing vitamin A and β-carotene. Furthermore, they can be transformed into geraniol and nerol, which have a high market price because they have a rose and orange odor. The compounds α-zingiberene and β-phellandrene are responsible for the characteristic aroma of fresh ginger [9, 37].

From the evaluation of the results between the dehydration processes, it was found that there was a similarity

between some of the processes. In the first case, it was observed that the majority of components for the fresh sample and for the entire fractionated form dehydrated in a freeze dryer and dehydrated in a CC oven at a temperature of 50 °C were the same, although they were small. The study revealed that ginger has a rich composition of active and intense substances, as evidenced by the chromatograms that show similarities in the chemical profiles of the extracts.

4. Conclusions

The ginger drying kinetics shows that the process efficiency is maximized by combining parameters such as more significant sample fractionation, high temperatures, and forced air circulation. Notably, the preservation of bioactive compounds is more effective under conditions of lower temperature, lower fractionation, and absence of forced air circulation, highlighting the importance of these factors in maintaining the nutritional properties of ginger. The evaluation of the essential oil reinforces the need for appropriate strategies, such as freeze-drying or drying in an oven with forced air circulation at 50 °C, to minimize the degradation of volatile components. Contributing to optimizing ginger dehydration processes, promoting and preserving its nutritional and functional benefits.

Authors' contributions

Cristian Jose Cristofel and Luciano Tormen conceived and designed the study.

Cláudia Moreira Santa Catharina Weis and Giovanna Camile Vaz Gonçalves analyzed the data and drafted the manuscript.

Helen Treichel and Larissa Canhadas Bertan critically reviewed and supervised the development of the paper.

All authors reviewed and approved the final manuscript.

Availability of data and materials

The datasets generated for this study are available to the corresponding author on request.

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Conflict of interest

There are no competing interests.

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