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Determination of the ideal drying temperature for Brazilian Ginseng (*Pfaffia glomerata*) roots: product enhancement, chemical characterization, and color parameters

Fabio Dias Bertoco Júnior[1], Laura Correia Marquezi[1], Creir da Silva[1], Bogdan Demczuk Junior[2], Giselle Giovanna do Couto de Oliveira[1], Otavio Akira. Sakai[1], Marcela Moreira Terhaag[1]*

[1]LACE, Chemistry Department, Federal Institute of Science and Education of Paraná, Umuarama, PR, Brazil
[2]Food Engineer Department, Federal Technological University of Paraná, Campo Mourão, PR, Brazil

***Federal Institute of Science and Education of Parana, Umuarama. Rod. PR 323, KM 302, Parque Industrial. Umuarama - PR – Brazil, CEP 87507-014.**

Corresponding author: marcela.terhaag@ifpr.edu.br,
ORCID 0000-0002-3558-9199

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Abstract: This study investigated the impact of convective drying conditions on the physicochemical properties of *Pfaffia glomerata* (Brazilian Ginseng) sliced roots. Drying experiments were conducted at 40, 60, and 80 °C temperatures, with and without forced air circulation (1 ms^{-1}), to analyze drying kinetics and develop an empirical model. The activation energy (Ae) of the drying process was determined. Colorimetric analysis (ΔE*) and Fourier Transform Infrared Spectroscopy with Attenuated Total Reflectance (FTIR-ATR) were employed to assess changes in color attributes and chemical composition. Results indicated that drying time was primarily influenced by temperature, followed by air velocity. The dominant mass transfer mechanism during drying was identified as diffusion, and a modified Page model effectively described the drying behavior. The calculated activation energy (Ae) was 27.85 kJ mol^{-1}. Compared to fresh roots, dried samples exhibited color alterations, including darkening. Based on FTIR-ATR and colorimetric analysis, optimal drying conditions for maintaining root quality were determined to be 40 and 60 °C with forced air circulation (1 ms^{-1}), achieving desired moisture levels at 900 and 360 minutes, respectively.

Keywords: *Pfaffia glomerata*, drying kinetics, quality parameters, FTIR-ATR, sustainable production.
Abbreviations: FTIR-ATR_Fourier Transform Infrared Spectroscopy with Attenuated Total Reflectance

Introduction

Regarding the production chain of natural products—specifically medicinal and aromatic plants for food or pharmaceutical purposes—it is necessary to preserve the physical and chemical properties, meaning that the plant material must undergo a drying process that can inhibit or reduce enzymatic activity to reduce the material's biological activity (Chudnicka and Matysik)

In this process, the chemical bioactive compounds present in plants must be preserved, as well as their physical properties, such as color, flavor, and quality (Melo et al., 2004).

One way to preserve the content of bioactive compounds in plants is through drying (Akpinar, 2006; Akpinar et al., 2003). In addition to protecting the physical-chemical and biological characteristics of the plant product, the drying method also requires less energy consumption and shorter drying time. There are several types of plant drying, such as natural drying and static or circulating hot air (Inyang et al., 2017; Mujumdar, 2006).

Pfaffia glomerata (Spreng.) Pedersen, known as Brazilian Ginseng, belongs to the Amaranthaceae family, which has a cosmopolitan distribution and includes approximately 170 genera and 2,000 species (Souza and Lorenzi, 2005). *P. glomerata* is an endemic plant found on the islands and floodplains of the Paraná River in Brazil. Although Brazilian Indians have used *P. glomerata* for centuries to prevent and/or treat diseases, the first scientific studies have occurred recently (Ming and Corrêa-Junior, 2004). The cultivation of *P. glomerata* is considered a potential economic alternative for small producers near the Pantanal region (Mattos and Salis, 2004; Corrêa-Júnior et al., 2016).

It stands out for having chemical compounds with great potential for application in pharmaceutical and medicinal applications, such as combating physical and mental exhaustion, lacking memory, and preventing anemia (Yuk et al., 2016;

Shiobara et al., 1993; Martins et al., 2020; Bertoco-Junior et al., 2021; Franco et al., 2024). These findings relate to saponins and ecdysteroids, especially β-ecdysone (Neto et al., 2015; Freitas et al., 2004). Phenolic compounds with potential health benefits are also present in *P. glomerata* roots (Yuk et al., 2016; Shiobara et al., 1993; Neto et al., 2015).

The Association of Small Ginseng Producers of Querência do Norte (ASPAG), in Paraná (Brazil), was created in 2011 to preserve these species and develop sustainable cultivation and production systems. At the ASPAG, approximately 80 kg of roots are manually collected daily (Bertoco-Junior et al., 2021).

Currently, the roots of *P. glomerata* are dug up using a hoe or shovel and placed in polyethylene bags. Then, the roots are washed, pre-dried, chopped, and crushed, forming a paste that is dried in the sun until it reaches 10-12% moisture. Such processes can be slow and occur at variable temperatures, which can cause the degradation of chemical compounds and color changes. To obtain uniformity in the chemical, physical, and sensory characteristics of dried roots, artificial drying (associated or not with ventilation) can be used. For *Panax notoginseng*, numerous studies have already been conducted to evaluate drying kinetics and quality parameters. According to Hadibi et al. (2025), for this plant, numerous techniques have already been evaluated in various studies, such as sun drying and hot air drying, pulsed vacuum drying, air impingement drying, step-down relative humidity convective hot air dryer, infrared-assisted hot air drying, spray drying, combined infrared and hot-air drying, combined microwave vacuum/hot air drying, providing relevant information for the processing of this plant. Kong et al. (2022) verified important changes in *Panax notoginseng* color attributes depending on the choice of the drying process. They indicated less color alteration when using a hybrid drying system powered by a solar photovoltaic/thermal air collector and wind turbine instead of sun drying.

Another type of Ginseng called red Ginseng, also known as Korean Ginseng, is a type of *P. ginseng* produced when fresh roots are steamed and then dried, resulting in a root with a reddish color. For this root, the typical drying methods used for red Ginseng are sun drying and hot-air drying, but other methods are been researched, like far-infrared drying and short-wave infrared (Ning et al., 2015; Park et al., 2023).

However, no studies in the literature indicate parameters for oven drying of *P. glomerata* roots seeking to minimize undesirable color or composition changes.

Therefore, this study aimed to investigate the effect of different drying temperatures and air circulation conditions on Brazilian ginseng roots' chemical and physical characteristics and to develop an empirical mathematical model to describe the drying process under the proposed drying conditions. From these data, we sought to standardize the preprocessing of Brazilian ginseng roots and provide sustainable processing.

Results and Discussion

Effect of drying air temperature on drying kinetic curves

The equilibrium moisture concentrations of the ginseng roots were 2.00±0.27, 1.21±0.29, and 2.03±0.38 g 100 g^{-1} after drying at 40, 60 and 80 °C, respectively. It was reached at 900 minutes (40 °C), 360 minutes (60 °C), and 330 minutes (80 °C), in static drying. Using forced air circulation, the equilibrium humidities determined for drying at 40, 60, and 80 °C were 2.04±0.16, 1.47±0.19, and 1.64±0.35 g 100 g^{-1}, respectively. The time required to reach equilibrium moisture was 900, 270, and 240 minutes at 40, 60, and 80 °C, respectively (Figure 1). These results indicate that dryings conducted at higher temperatures were faster than at 40 °C. Comparing drying at 60 and 80 °C with that at 40 °C, the time reduction reaches 60% and 64%, respectively. At 80 °C, the air circulation confers a 67% reduction in the time needed for moisture stabilization. These results were expected since, at higher temperatures, there is a greater rate of drying (Akpinar, 2006) and, consequently, leaving water from the roots of Brazilian Ginseng. Higher temperatures reduce drying time by increasing water molecules' kinetic energy, allowing them to overcome cohesive forces and evaporate more readily (Phitakwinai et al., 2019). This mechanism was also observed in the drying process of American Ginseng, Korean Ginseng, and apples (Ju et al., 2019; Ning et al., 2015; Cuccurullo et al., 2018). Ning et al. (2015) verified that an increase in the drying temperature of red Ginseng resulted in a decrease in drying time, which may be due to the increase in heat transfer between the air and the red Ginseng and the acceleration of water migration inside the Ginseng.

There was, in general, a period of constant rate for the initial thirty minutes of drying of the Brazilian ginseng roots (Figure 2 a-c). This behavior was not verified only after drying at 40 °C without air circulation. According to Richardson et al. (2002), during this period, the surface of the dried material is saturated with water, and factors like the difference between the air temperature and the wet-bulb temperature govern the evaporation rate. Overall, diffusion through the air-water interface is the primary mechanism for removing water from the interior of Brazilian ginseng roots. In hot air drying, the heat was diffused into the drying matter by air convection and propagated by conduction, promoting water exit from inside the root (Nsibi; Lajili, 2023).

In Figure 2 a-c, a falling rate period in the drying was observed. At this point, drying may continue with water exit through capillarity (Mujumdar, 2006). The forces controlling the vapor diffusion determine the final drying rate, independent of the conditions outside the material (Richardson et al., 2002). Thus, the chemical composition and organization of the Brazilian ginseng root tissue determine the water release in this way.

Modelling of drying curves

To determine the moisture content as a function of drying, the MR data obtained at different drying temperatures and RHs (Table 3, materials and methods section) were fitted to five empirical models listed below (Equations 4-8). The R^2 and RMSE values for different drying conditions determined by nonlinear regression analysis are presented in Table 1.

Table 1. Design for the experiments with run conditions included

Experiment	Material plant	Drying temperature (°C)	Velocity (m s^{-1})
1	Roots	40	0
2	Roots	60	0
3	Roots	80	0
4	Roots	40	1
5	Roots	60	1
6	Roots	80	1

The coefficients of determination of most of the models were greater than 0.96 for all drying temperatures, which indicates a satisfactory fit of the mathematical models to the experimental data. (Onwude et al., 2016). According to Draper and Smith (1998), the capacity of a model to describe a certain physical process is inversely proportional to the standard deviation of the estimate. Therefore, higher R^2 values and lower RMSE values provided a better fit.

Among the models considered, the modified Page presented the highest R^2 and the lowest RMSE values in all cases, which varied between 0.9938 and 0.9999 and 0.0260 and 2.0469, respectively. Therefore, within the experimental range, the modified Page model was selected to describe the drying behavior of Brazilian ginseng roots during convective hot air drying. Similar conclusions were reported by Ferreira et al. (2012) for fermented grape pomace, by Akpinar et al. (2003) for basil and mint leaves, and by Oyefeso and Raji (2020) for fresh tannia (*Xanthosoma sagittifolium*) cormels. According to Onwude et al. (2016), models based on the new law of cooling and Fick's second law of diffusion, such as the modified Page, Page, and others, have commonly been used to describe the drying behavior of various fruits and vegetables. These models are generally effective in explaining thin-layer drying (Simpson et al., 2017), which is in agreement with this study since Brazilian Ginseng, after slicing, was stored in the oven in thin layers of up to 20 mm. A lower R^2 was observed for the adjustment of data from experiments 1 and 3 (40 and 80 °C without circulation) in the Wang and Sing model.

In the modified Page model, the 'n' parameter determines how rapidly the drying rate decreases over time. A higher 'n' value indicates a more rapid decrease in drying rate, leading to a steeper drying curve.

Activation energy (Ae)

The activation energy indicates the energy required to remove moisture from the product during drying. The drying activation energy of the Brazilian ginseng roots was 27.85 kJ mol^{-1}, as determined by the Arrhenius equation, as shown in Eq. (9). This result is that of Zogzas et al. (1996), who reported a range between 12.7–110 kJ $mol^{-1,}$ and with that of Onwude et al. (2016), who reported a range of 14.42 to 43.26 kJ mol^{-1} for various food materials.

The Ae of Brazilian ginseng roots was lower than the Ae of American ginseng roots (51.14 kJ mol^{-1}) and slices (46.64 kJ mol^{-1}) (Ju et al., 2019; Wang et al., 2015) and near carrot pomace (24.51 kJ mol^{-1}) (Wang et al., 2007), okara (28.15 kJ mol^{-1}) (Guimaraes et al., 2018), fermented grape pomace (26.44 kJ mol^{-1}) (Ferreira et al., 2012) and crambe seeds (37.07 kJ mol^{-1}) (Costa et al., 2011).

Colour analysis

Color affects the overall impression and is an important indicator of ginseng quality (Xiao et al., 2014). According to Ju et al. (2019), dried roots of American ginseng roots with higher L* and lower a* values are considered higher-quality products.

In general, drying darkened the Brazilian Ginseng (Table 2), possibly due to the degradation of pigments or nonenzymatic Maillard browning (Xiao et al., 2014). Only after drying with air circulation at 80 °C was the sample whitening compared to the fresh root, possibly because of the dryness and crusting of the dehydrated root slices. Xiao et al. (2015) reported that L* decreased with increasing drying temperature in American ginseng roots

Regarding the red–green component (a*) (Table 2), there was no change in the color of dried roots without air circulation at 40 °C and 60 °C or when drying under circulation at 60 °C. A greater degradation of red compounds possibly occurred in the sample dried at 80 °C under air circulation since the sample became more greenish than the fresh root. In a study with American Ginseng, Ju et al. [17] reported that a relatively high humidity at the beginning of drying can contribute to the maintenance of root color. After drying under circulation at 40 °C and 80 °C and without circulation at 40 °C and 60 °C, the same intensity of the yellow color (b*) was maintained (Table 2). On the other hand, greater yellowing of roots dried at 80 °C was observed in the absence of forced air. Xiao et al. (2019) reported a reduction in American ginseng components' a* and b* with increasing drying temperature.

However, considering the total color variation (ΔE*) (Table 2), there was a change in the overall color of the samples compared to that of fresh roots. This result is in agreement with that presented by Xiao et al. (2015), who noted a greater deterioration of the colored components of American Ginseng as the drying temperature increased. There was no color difference ($p < 0.05$) between the dry roots without air circulation and those dried in circulating air at 40 and 60 °C. Ning et al. (2013) verified that an increasing drying temperature and ginseng size (*P. ginseng* C.A. Meyer) showed larger Δ*E* values. These authors suggest that increasing drying duration and temperatures reduce ginseng pigments' stability.

ATR-FTIR analysis

Figure 3 shows the ATR-FTIR spectra of the β-ecdysone analytical standard and fresh and dry Brazilian ginseng roots (experiments 1 to 6). In general, similar spectra were obtained for fresh ginseng roots (control sample) and standard β-ecdysone, indicating the presence of this substance, which is considered a chemical marker for Ginseng, in the roots of this plant. However, differences in peak intensities are observed when comparing the ATR-FTIR spectra (Figure 3) of the control

Table 2. Parameter and coefficients from Brazilian ginseng roots drying models at different conditions[§]

Model	Experiment	Model result	R^2	RMSE (%)
Lewis	1	k=0.0098	0.9967	1.0167
MR=exp(-*k*t)	2	k=0.0178	0.9975	0.5273
	3	k=0.0227	0.9880	2.5132
	4	k=0.0025	0.9661	13.198
	5	k=0.0145	0.9937	1.1804
	6	k=0.0114	0.9828	3.8302
Henderson and Pabis	1	k=0.0095; a=0.9787	0.9971	0.8779
MR=*a*exp(-kt)	2	k=0.0186; a=1.0306	0.9985	0.3202
	3	k=0.0246; a=1.066	0.9920	1.6630
	4	k=0.0027; a=1.0665	0.9733	10.404
	5	k=0.0139; a=0.9708	0.9948	0.9716
	6	k=0.121; a=1.0532	0.9865	3.0074
Page	1	k=0.0146; n=0.9158	0.9979	0.6489
MR = exp (-*k* t^n)	2	k=0.0112; n=1.1169	0.9994	0.1202
	3	k=0.0055; n=1.3845	0.9998	0.0260
	4	k=0.0005; n=1.2599	0.9912	3.4370
	5	k=0.0227; n=0.8953	0.9965	0.6516
	6	there was no fit		
Modified Page	1	k=0.0099; n=0.9158	0.9979	0.6489
MR=exp[(*k*t)^n]	2	k=0.0179;n =1.1170	0.9994	0.1202
	3	k=0.0233; n=1.3847	0.9999	0.0260
	4	k=0.0024; n=1.4262	0.9948	2.0469
	5	k=0.0146; n=1.4262	0.9966	0.6516
	6	k=0.0112; n=1.2740	0.9938	1.3884
Wang and Singh	1	a=-0.0038; b=3.2984 E-06	0.7606	73.100
MR=1+*a*t+*b*t^2	2	a=-0.0092; b=1.8943 E-05	0.9231	16.154
	3	a=-0.0107; b=2.4706 E-05	0.8833	24.340
	4	a=-0.0018; b=6.9591E-07	0.9991	0.3674
	5	a=-0.0082; b=1.5948 E-05	0.9242	14.152
	6	a=-0.0079; b=1.5192E-05	0.9945	1.2307

[§]Drying conditions: temperatures (40, 60 and 80 °C)/ hot air velocities (absence (A) or 1 m s^{-1}(circulation: C)): 1: 40/A; 2: 60/A; 3: 80/A; 4:40/C; 5: 60/C; 6: 80/C

Table 3. Color evaluation of the dried Brazilian ginseng[a]

Experiment	L*	a*	b*	ΔE*
Fresh	67.50 ± 5.39b	-1.77 ± 0.14c	21.34 ± 1.31c	0.00±0.00c
1	46.58 ± 0.07d	0.38 ± 0.02a	21.46 ± 0.03c	21.07±5.34a
2	55.53 ± 0.01c	0.25 ± 0.01a	21.59 ± 0.21c	12.22±5.04ab
3	56.27 ± 0.63c	-0.47 ± 0.07b	26.11 ± 0.44a	12.68±5.28ab
4	54.66 ± 0.47c	-0.43 ± 0.04b	22.12 ± 0.08c	13.00±4.95ab
5	48.78 ± 0.63 d	0.48 ± 0.09a	24.21 ± 0.32b	19.14±5.08a
6	73.13 ± 0.04a	-2.44 ± 0.01d	21.47 ± 0.01c	6.21±4.77b

[a] Results expressed as average (n = 6) ± standard deviation. Different lower-case letters in the same column represent significant differences ($p < 0.05$). L*: luminosity: black (L* = 0) and white (L* = 100); a*: green color (−) and red color (+); b*: blue color (−) and yellow color (+);ΔE*: total color variation. Drying conditions: temperatures (40, 60 and 80 °C)/ hot air velocities (absence (A) or 1 m s^{-1}(circulation: C)): 1: 40/A; 2: 60/A; 3: 80/A; 4:40/C; 5: 60/C; 6: 80/C. Drying conditions: temperatures (40, 60 and 80 °C)/ hot air velocities (absence (A) or 1 m s^{-1}(circulation: C)): 1: 40/C; 2: 60/C; 3: 80/C; 4:40/A; 5: 60/A; 6: 80/A

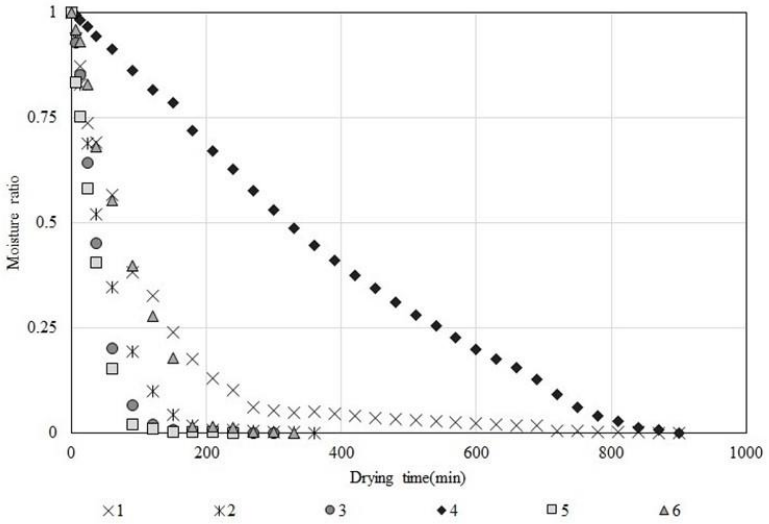

Figure 1

sample with those of the samples from the drying experiments (experiments 1-6). The spectra (Figure 3) can be divided into two intervals: between 3700 and 2400 cm^{-1} and between 800 and 1800 cm^{-1} (fingerprint region). In the first, O-H, N-H, and C-H stretch bonds predominate, while in the second, several stretch vibrations and angular deformations occur (Turker-Kaya & Huck, 2017).

The broad band observed between 3500 and 3200 cm^{-1} is characteristic of O-H and N-H stretching, which is mainly attributed to water, carbohydrates, carboxylic acids, alcohols, phenolic compounds, and saponins (Turker-Kaya and Huck, 2017; Kareru et al., 2008)]. This band's intensity is reduced (Figure 3) when *P. glomerata* is subjected to drying due to the loss of water and other compounds present in the samples. A more significant loss occurred in experiments 1 and 2 (40 °C and 60 °C, respectively, without air circulation). Regarding the analytical pattern of β-ecdysone, a saponin, there are bands in this region, as its molecule has OH bonds, as shown in Figure 4 (He et al., 2015; Balateri et al., 2018). The peaks observed in the region from 2900 to 2840 cm-1 are related to CH_2 and CH_3 symmetric and asymmetric stretch vibrations and are attributed to lipids, proteins, carbohydrates, and nucleic acids (Turker-Kaya and Huck, 2017).

According to Abbas et al. (2017), there are no relevant data for chemical characterization in the region between 2500 and 1800 cm^{-1}, only bands referring to the interference of CO_2 present in the air.

The fingerprint region (1800 to 800 cm^{-1}) has a large amount of chemical information, with specific bands of molecular structures present in the samples often superimposed on each other (Turker-Kaya and Huck, 2017). The peak observed at ~1725 cm^{-1} is associated with the C=O stretch of esters present in phospholipids, cellulose, pectin, and hemicellulose (Xu and Wang, 2014). The peak at ~1635 cm^{-1} corresponds to C=C stretch vibrations associated with phenolic compounds (Turker-Kaya and Huck, 2017; Abbas et al., 2017). Both peaks are observed for β-ecdysone and fresh Ginseng, and their intensities decrease with sample drying. It is possible that greater degradation is observed at 60 °C without air circulation (experiment 2). According to Barbosa et al. (2016), high drying temperatures can be harmful because they can cause the degradation of thermolabile compounds, such as phenolic compounds. Therefore, some of these compounds may have degraded when the Brazilian ginseng roots were subjected to drying.

The region between 1200 and 900 cm^{-1} is dominated by C-O-C and OH stretching vibrations, which are characteristic of cellulose and hemicellulose (Zhang et al., 2015), and symmetrical acyclic stretching, CH_2, OH, and CO bonds of polysaccharides such as glycogen, amylose and amylopectin (Turker-Kaya and Huck, 2017; Zhang et al., 2015). It also contains C-O-H, C-C, and C-H bonds, which Kačuráková et al. (2000) associate pectin and the C-O, C-C, and C-C-O bonds of cellulose, hemicellulose and lignin, which are present in the plant wall, in addition to monosaccharides such as ribose, glucose and galactose (Xu and Wang, 2014; Zhang et al., 2015). Figure 3 shows that there was no significant reduction in the intensity of these bands compared to fresh Ginseng and β-ecdysone to the roots subjected to drying, except in experiment 2 (60 °C without circulation), where there was a decrease in the intensity of these bands, possibly due to the collapse of the sample structure and the formation of a gel layer on its surface and, therefore, loss of material porosity, which is responsible for helping to reduce the water in the material and reduce drying time (Mujumdar, 2006; Ju et al., 2019).

While higher temperatures accelerate the drying of Brazilian Ginseng, they can also negatively impact the chemical composition of the dried roots. Ning et al. (2015) demonstrated that increased drying temperatures affected the chemical profile of Korean Ginseng, indicating that the temperature should be kept below 60°C during the drying process. The same trend was observed for American ginseng roots dried at 60 °C by Ju et al. (2019). In general, among the conditions analyzed, there were smaller reductions in the content of related β-ecdysone in experiments 4 and 5 (40 °C and 60 °C, with air circulating at 1 ms^{-1}).

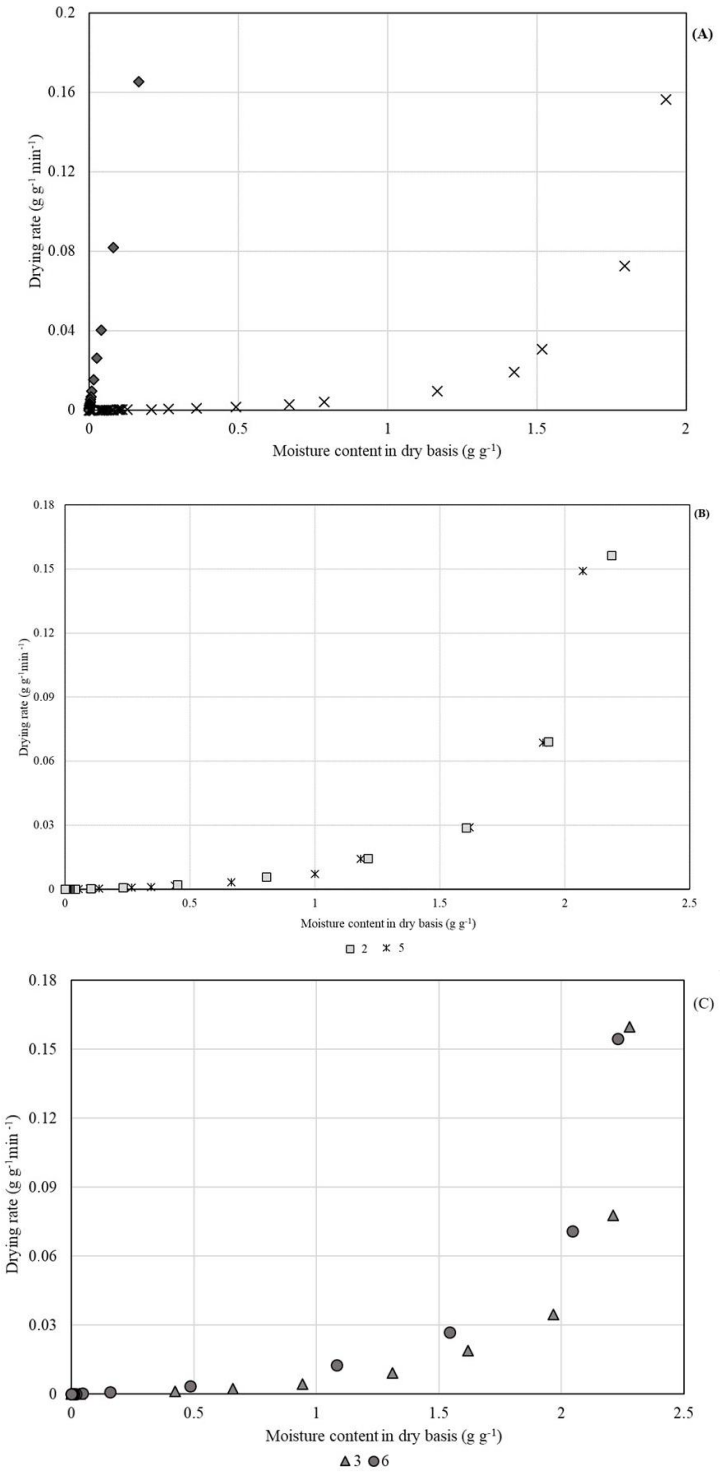

Figure 2.

Materials and methods

Raw material

Freshly harvested Brazilian Ginseng (*Pfaffia glomerata*) roots from 4-year-old cultivated plants were obtained in Brazil (latitude: 23° 5' 2'' S, longitude: 53° 29' 3'' W). Samples of similar characteristics (development, appearance, absence of pests) were selected for the tests. The average initial moisture content of the Brazilian ginseng roots was 73.2±0.7 g 100 g^{-1}, as determined by vacuum drying at 105 °C for 8 h.

The samples were cleaned with water to remove dust and then cut using a kitchen cutter. The roots were cut into slices (~1 mm) and stored in polyethylene bags in a freezer at -4 ±1 °C.

Experimental procedure

The drying experiments were carried out in a forced-air oven (Ethik Technology/400-4ND) at different drying temperatures (40, 60, and 80 °C) and hot air velocities (absence and 1 m s^{-1}), as shown in Table 3. After slicing, the Brazilian Ginseng was

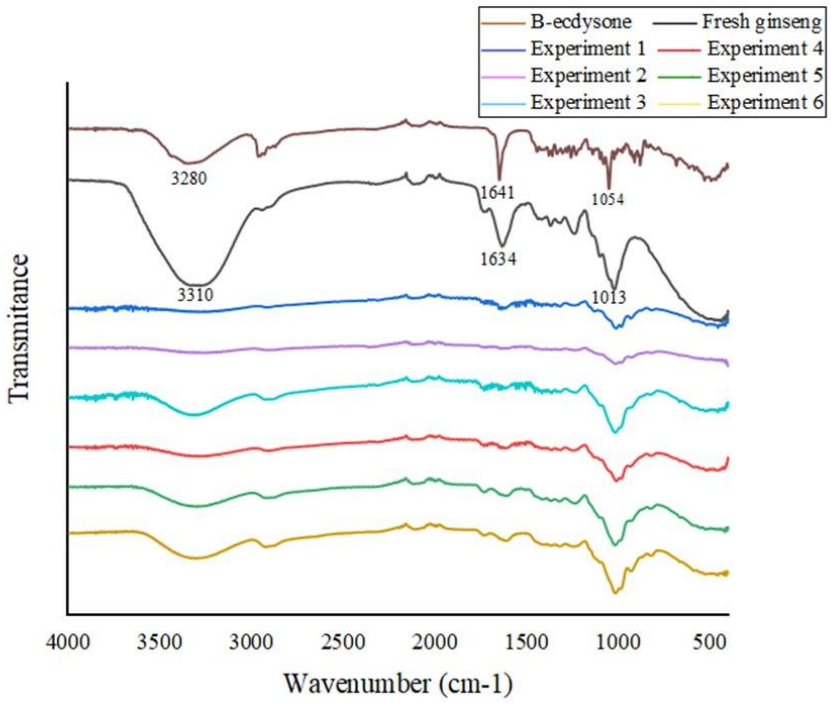

Figure 3.

stored in thin layers of up to 20 mm in the oven. Mass reduction during drying was monitored using a semi-analytical balance (Shimadzu BL-3200H). The mass was recorded periodically at 6, 12, 24, 36, and 60 min during the first hour and every 30 min thereafter until the samples reached moisture equilibrium (<0.2%). All the experiments were carried out in triplicate, and the average moisture content was used to calculate the drying curves.
The color parameters and the results obtained with an infrared spectrophotometer with an attenuated total reflectance accessory (ATR-FTIR) profile were evaluated at initial, 1 h, and 3 h after the sample reached equilibrium moisture.

Moisture ratio
The moisture ratio (MR) of the material was defined by the following equation (Equation 1) [6]:

$$MR = \frac{Mt-Me}{M0-Me} \quad (1)$$

M_0, M_t, and M_e are the moisture content (kg^{-1}) at the initial stage, at time t, and in equilibrium with the drying air, respectively.

Modelling of drying curves
Linear and nonlinear regression analyses were performed to determine the best model for describing the drying process using Statistica Software (version 7.1). The goodness of fit of the models described by Alkpinar (2006) and Mujumdar (2006) was tested by calculating statistical parameters, such as the coefficient of determination (R^2) (Equation 2) and root mean square error (RMSE) (Equation 3), between the experimental and predicted data.

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{ei}-MR_{pi})^2\right]^{1/2} \quad (3)$$

Higher R^2 values and lower RMSEs were indicators of goodness of fit. Equations 4-8 were used:
$MR = \exp(-kt)$ (4) Lewis
$MR = a \exp(-kt)$ (5) Henderson and Pabis
$MR = \exp(-k\,t^n)$ (6) Page
$MR = \exp[(k\,t)^n]$ (7) Modified Page
$MR = 1 + a\,t + b\,t^2$ (8) Wang and Singh, where:
t - drying time (h);
k - drying constant ($h\ s^{-1}$); and
a, b, c, n - coefficients of the models.

3.5 Activation energy

The activation energy, Ae, was the minimum amount of energy that must be supplied to make the process realizable. The Ae value had the following dependence on temperature, as expressed by the Arrhenius model (Equation 9) (Mujumdar, 2006):

$$D_{eff} = D_0 \exp\left(-\frac{A_e}{R_g T}\right) \quad (9)$$

where D_0 is the preexponential factor of the Arrhenius equation ($m^2\ s^{-1}$), Ae is the activation energy (kJ mol^{-1}), R_g is the perfect gas constant (8.314 J $mol^{-1}K^{-1}$), and T (in K) is the temperature of the drying air.

Colour measurement

The color of the dried root samples was measured before and after drying using a colorimeter (D65 illuminant with CIELAB scale CR400, Konica Minolta, Japan). The color parameters (L* (lightness), a* (redness/greenness), and b* (yellowness/blueness)) were measured on the surface of fresh and dried Brazilian ginseng roots. The total color difference (ΔE*) was calculated using Equation 10.

$$\Delta E = \sqrt{(L_0 - L^*)^2 + (a_0 - a^*)^2 + (b_0 - b^*)^2} \quad (10)$$

3.7 FTIR-ATR analysis

Spectral analysis of the ginseng roots and β-ecdysone analytical standard (Sigma–Aldrich, USA, ≥93%) was carried out with an infrared spectrophotometer (model Cary 630, Agilent Technologies) using an attenuated total reflectance accessory (ATR) with a diamond crystal. All the spectra were acquired between 4000 and 400 cm-1 with 64 scans and a precision of 4 cm^{-1}. The analyses were performed in triplicate.

Statistical analysis

The experiment was conducted using a completely randomized design. Statistical analysis of color data was conducted using Statistica version 7.1 (Statsoft TIBCO Software Inc., Tulsa, OK, USA). The color data were analyzed by ANOVA and Tukey's test ($p \leq 0.05$).

Conclusions

The results showed that the drying time was affected by the drying temperature, followed by the air velocity. Diffusion is the primary mechanism for removing water from the interior of a material. The modified Page model effectively described the drying behavior of Brazilian ginseng roots. The activation energy was 27.85 kJ mol^{-1}. The drying process darkened the Brazilian Ginseng and changed the fresh root samples' general color (ΔE*). Through FTIR-ATR, the best temperatures for drying Brazilian ginseng roots were 40 and 60 °C, with air circulation at 1 ms^{-1}.

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Author Contributions

Fabio D. Bertoco Júnior: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Conceptualization, Review, Editing. Laura C. Marquezi: Data curation, Formal analysis, Investigation, Methodology, Writing-original draft. Creir da Silva: Formal analysis, Investigation, Methodology. Bogdan Demczuk Junior: Data curation, Investigation, Methodology, Software, Conceptualization, Review. Otávio A. Sakai: Conceptualization, supervision, funding acquisition, investigation, methodology, data curation, and review and editing. Giselle Giovanna do Couto de Oliveira: Conceptualization, supervision, funding acquisition, investigation, methodology, data curation, and review and editing. Marcela M. Terhaag: Conceptualization, supervision, data curation, methodology, software funding acquisition, and investigation.

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