Ciência e Agrotecnologia
SCIENCE AND AGROTECHNOLOGY
Ciência e Agrotecnologia, 47:e010523, 2023
http://dx.doi.org/10.1590/1413-7054202347010523
Food Science and Techonology
eISSN 1981-1829

Two-stage power level to improve microwave vacuum drying of restructured peruvian carrot chips

Nível de potência em dois estágios para melhoria da secagem micro-ondas-vácuo de chips reestruturados de mandioquinha-salsa

Kamilla Soares de Mendonça[1], Jefferson Luiz Gomes Corrêa[2], João Renato de Jesus Junqueira[3]*, Amanda Umbelina de Souza[1]

[1]Instituto Federal de Minas Gerais/IFMG, Departamento de Ciências Agrárias, Bambuí, MG, Brasil
[2]Universidade Federal de Lavras/UFLA, Escola de Ciências Agrárias, Lavras, MG, Brasil
[3]Universidade Federal de Mato Grosso do Sul/UFMS, Faculdade de Ciências Farmacêuticas, Alimentos e Nutrição, Campo Grande, MS, Brasil
*Corresponding author: joao.junqueira@ufms.br
Received in June 18, 2023 and approved in October 24, 2023

ABSTRACT

The Peruvian carrot is a root that is rich in bioactive compounds. However, owing to the short shelf life of these carrots, their consumption is restricted. In the present study, we investigated the microwave vacuum drying (MWVD) of restructured Peruvian carrot chips. Two microwave power levels, namely, constant and two-stage, were considered and evaluated to determine their relationship with drying time, kinetic parameters, energy consumption, and preservation of carotenoids and phenolic compounds. At the constant microwave power level, drying time decreased with increasing drying rate, sample temperature, and energy consumption. However, it did not affect the drying rate at the end of the drying. At the two-stage microwave power level, the drying time was similar to that observed in constant power level experiments. However, sample temperature and energy consumption were decreased when drying at a lower power level. Nutritional compounds were better preserved by using the highest tested power level at the two-stage level and the lowest tested one at the one-stage power level. Page's and Fick's models presented an excellent fit of the experimental data. Using the two-stage microwave power level at a higher initial power level (MWVD-5–1) saved energy, decreased the drying duration, and preserved the bioactive molecules in restructured chips.

Index terms: *Arracacia xanthorrhiza*; β-carotene; mathematical model; energy consumption; catechin.

RESUMO

A mandioquinha-salsa é um caule subterrâneo rico em compostos bioativos. Devido ao seu reduzido prazo de validade, seu consumo se torna restrito. A secagem micro-ondas-vácuo (MWVD) de chips reestruturados de mandioquinha-salsa foi estudada. Foram utilizados diferentes níveis de potência de micro-ondas (constante e em duplo estágio), e seus efeitos avaliados com relação ao tempo de secagem, parâmetros cinéticos, consumo energético e conservação de carotenóides e compostos fenólicos. Há um nível de potência de micro-ondas constante, o nível de potência reduziu o tempo de secagem, com aumento da taxa de secagem, da temperatura da amostra e do consumo energético. No entanto, o nível de potência do micro-ondas não influenciou na taxa de secagem ao final do processo. Durante tratamentos de nível de potência em dois estágios, o tempo de secagem foi semelhante ao observado em experimentos de nível de potência constante. Ainda assim, a temperatura da amostra e o consumo de energia foram reduzidos durante a secagem a um nível de energia menor. Melhor conservação dos compostos bioativos foi proporcionada em duas situações: por dois estágios com a maior potência testada e por uma etapa com a menor potência testada. Os modelos de Page e Fick apresentaram excelentes ajustes aos dados experimentais. A utilização de dois estágios em um nível de potência inicial mais alto (MWVD-5–1) economizou energia, reduziu a duração da secagem e preservou moléculas bioativas dos chips reestruturados.

Termos para indexação: *Arracacia xanthorrhiza*; β-caroteno; modelagem matemática; consumo energético; catequina.

INTRODUCTION

The Peruvian carrot (*Arracacia xanthorrhiza*, Bancroft), also called arracacha, is a root vegetable native to Andean South America. The high resistant starch content of Peruvian carrots is of nutritional interest (Lovera et al., 2017). Furthermore, this root is a source of carotenoids (pro-vitamin A) and phenolic compounds (Pedreschi et al., 2011), with significant levels of minerals such as calcium, phosphorous, and iron. Owing to these attributes, Peruvian carrots may be characterized as a nutraceutical food (Albano; Franco; Telis, 2014).

All the contents of this journal, except where otherwise noted, is licensed under a Creative Commons Attribution BY.

However, owing to their high respiration rate and fast enzymatic and oxidative degradation process, the harvest time and storage life of Peruvian carrots are short. They can be directly consumed as soups, purées, and stews or processed into starch. Furthermore, they can be dried to extend the shelf life and availability throughout the year, producing instant food and chips (Pedreschi et al., 2011).

Drying is a food conservation technique for several types of foods (Junqueira et al., 2021). It inhibits enzymatic and microbial activity, extending product shelf life. However, the drying process is associated with several changes in food structure (Dadmohammadi; Datta, 2022); heat-sensible compounds are degraded owing to long-term exposure to high temperatures (Ukom; Nwanagba; Okereke, 2020). Therefore, drying parameters should be controlled.

Compared with conventional convective drying, microwave vacuum drying (MWVD) is quicker, more uniform, and more energy-efficient (Zielinska et al., 2020). The rapid energy transfer and pressure decrease caused by the combined use of microwave heating and vacuum (Apinyavisit et al., 2017) result in an alternative fast and low-temperature drying process. Therefore, MWVD can improve energy efficiency and decrease chemical and physical changes in dried products (Bórquez; Melo; Saavedra, 2015). Several fruits and vegetables such as plums (Michalska et al., 2016), blueberries (Zielinska; Michalska, 2016) bananas, grapes, tomatoes, and carrots (Monteiro et al., 2015) have been successfully dried using MWVD, in addition to satisfactory thermosensitive molecule preservation. Changes in the microwave power throughout MWVD has been reported as an exciting alternative for energy-saving and nutrient maintenance for beetroot and carrots (Musielak; Kieca, 2014) and banana, grapes, tomatoes, and carrots (Monteiro et al., 2015).

Theoretical, semi-theoretical, and empirical mathematical modeling of the drying processes can help improve the drying systems or even control the drying process (Zielinska et al., 2020). Researchers have applied theoretical and semi-theoretical models such as Page's model and that derived from the direct solution of Fick's second law, respectively, to identify the drying behavior of agricultural products (Corrêa et al., 2021).

In the present study, we evaluated the effects of the power level during the MWVD of restructured Peruvian carrot chips on drying time (DT), kinetic curves, energy consumption (EC), and preservation of carotenoids and phenolic compounds.

MATERIAL AND METHODS

Sample preparation

Peruvian carrot roots (*A. xanthorrhiza* Bancroft) were purchased from a local market (Lavras, Minas Gerais, Brazil). Roots without any injuries and weird odor were selected. All Peruvian carrots were sanitized and stored in a refrigerator at 8 °C ±1 °C before the experiments. The roots were peeled, cut into cylinders (thickness of 2 mm and diameter of 30 mm), and blanched (30 s at 100 °C) to decrease peroxidase activity (Pedreschi et al., 2011).

The blanched roots were ground for 3 min using a blender (RI2087 Philips Walita, Brazil) until a smooth paste was obtained. The paste was pressed and shaped into a plate sheet (3 mm thick, 150 mm × 100 mm) inside a Teflon plate for the MWVD experiments.

MWVD

MWVD was performed in a modified domestic microwave oven (MEC41, Electrolux, Joinville, Brazil) with an internal capacity of 31 L and a maximum microwave power output of 1000 W at 2450 MHz. In the interior of the oven, a polypropylene container was used as the vacuum chamber (Monteiro et al., 2015). The vacuum chamber was connected to a vacuum pump (LC.305, DVP, Rome, Italy) and a semi-analytical scale (3000 ±0.001 g) (Adventure ARC120, Ohaus, Nanikon, Switzerland). A computer recorded changes in sample mass every 10 s. The vapor from the samples was condensed and collected in a buffering bottle, protecting the vacuum pump in case of water spillage.

The drying experiments were performed at five power levels and an absolute pressure of 26.5 kPa until the samples had a final moisture content of 0.10 ±0.02 g H_2O g^{-1} dry basis (d.b.), which was suitable for safe storage. The microwave power settings were measured using the IMPI 2-liter method. Two 1 L beakers were filled with water, followed by measuring the initial temperature of the water. Then, the water was heated with different microwave output power levels for 122 s; the final temperatures were recorded (Demirhan; Özbek, 2011). Each experiment was performed using 50.0 ±0.5 g of samples in triplicate (Table 1).

An infrared sensor thermometer (62 MAX, Fluke, Eindhoven, Holand) was used to measure the surface temperature of the restructured Peruvian carrot chips immediately after taking them out of the vacuum chamber. The external temperature of 10 points of each

experiment was recorded. We assumed that the temperature measured using this method reflected the changes in the mean temperature during MWVD (Bai-Ngew et al., 2015; Michalska et al., 2016).

After drying, the restructured Peruvian carrot chips were cooled in a desiccator at room temperature, sealed in opaque polyethylene bags, and stored in a domestic freezer (DC51 Electrolux, Brazil) at −18 °C ±2 °C.

Analysis of drying experiments

Drying kinetics were analyzed as a function of moisture ratio (MR). Equation (1) presents the dimensionless MR:

$$MR = \frac{\left(M - M_{eq}\right)}{\left(M_0 - M_{eq}\right)} \approx \frac{M}{M_0} \quad (1)$$

where M is the moisture content (g H_2O g^{-1} d.b.), M_{eq} is the moisture content at equilibrium [g H_2O g^{-1} d.b.], and M_0 is the initial moisture content [g H_2O g^{-1} d.b.]. Because the equilibrium moisture content (M_{eq}) value was considerably lower than the initial moisture content and moisture content at time t (min), it was assumed to be zero for the drying conditions (Souza et al., 2022).

The drying rate (DR) of restructured Peruvian carrot chips during MWVD experiments was calculated based on the change in moisture ratio over DT using Equation (2):

$$DR = \frac{dM}{dt} = -\frac{M_{i+1} - M_i}{t_{i+1} - t_i} \quad (2)$$

where M_i is moisture content at time t_i (g H_2O g^{-1} d.b), M_{i+1} is moisture content at time t_{i+1} (g H_2O g^{-1} d.b), and t is the DT (min).

Mathematical modeling of the drying curves

Two exponential mathematical models were used to evaluate the mass transfer parameters of restructured Peruvian carrot chips: the empirical Page's model (Oliveira et al., 2021) and the semi-theoretical unidirectional diffusion model based on Fick's second law (Crank, 1975). In these models, MR was defined using Equation (1).

Page's model

Equation (3) presents the empirical Page equation:

$$MR = \exp\left(-kt^n\right) \quad (3)$$

where MR is the moisture ratio, t is the DT (s), k is the drying constant, and n is the fitting parameter of the Page's model.

Fick's model

Fick's model of effective diffusivity is based on the changes in moisture with time and dimensions, according to Fick's law of diffusion. It can be resolved by considering a semi-infinite plate with thickness L; a uniform initial amount of humidity, $M_{(z,0)} = M_0$; impermeable surface concentration, $\left.\frac{\partial M(t)}{\partial z}\right|_{z=0} = 0$; and equilibrium content at the material surface $M_{(L,t)} = M_{eq}$.

Equation (4) presents Fick's unidirectional diffusion equation (Crank, 1975):

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2}{4}\frac{D_{eff}\,t}{L^2}\right] \quad (4)$$

where D_{eff} is the water effective diffusivity ($m^2\,s^{-1}$), L is the sample thickness (m), n is the number of terms, MR is the moisture ratio, and t is the DT (s).

The effective diffusivities were obtained using the nonlinear regression model (Quasi-Newton) in Statistica software (Statistica 8.0®, Statsoft Inc., Tulsa, OK) by considering the expansion of the equation with five terms.

EC

EC was defined as the energy required to evaporate a unit mass of water from the sample, which was presented using Equation (5) (Kumar; Shrivastava, 2017). It was expressed as MJ kg^{-1} of removed water.

$$EC = \frac{t_{on}\;P\;\left(1 - M_f\right)\;10^{-6}}{m_i\;\left(M_0 - M_f\right)} \quad (5)$$

where t_{on} is the total power on time (s); P is the microwave input power (W); m_i is the initial mass of the sample (kg); M_0 is the initial moisture content (fraction, d.b.), and M_f is the final moisture content (fraction, d.b.).

Quality characteristics of the dried product

Moisture content

The standard method 934.06 proposed by the Association of Official Analytical Chemists (Association

of Official Agricultural Chemists - AOAC, 2016) was used to measure the moisture content of the samples.

β-carotene content

Total carotenoids were determined using the method described by Rodrigues-Amaya (Junqueira et al., 2018), with some modifications. Briefly, the dried samples were cooled to cryogenic temperature and ground in an analytic mill (Ika, A11, Brazil). The powder (1.0 g) was placed in a 250 mL flask, followed by exhaustively extracting the carotenoids with cold acetone, partitioning with petroleum ether, and washing with distilled water. Total carotenoid content was determined by measuring the absorbance of β-carotene, the predominant carotenoid in Peruvian carrots (Pedreschi et al., 2011), in a UV/Vis spectrophotometer (Varian, model Cary 50 Probe, Australia) at 450 nm, corresponding to β-carotene determination. β-carotene content was calculated according to Equation (6).

$$\beta\text{-carotene} = \frac{Abs\ V\ 10^3}{E^{1\%}_{1\ cm}\ W} \quad (6)$$

Where Abs is the absorbance, V is the total extract volume (mL), and W is the sample weight (g). The molar extinction coefficient of β-carotene in petroleum ether ($E^{1\%}_{1\ cm}$) was 2592. The results of four replicates were expressed as mg $(100\ g)^{-1}$ of β-carotene (d.b.).

Quantification of phenolic compounds

The dried samples were cooled to cryogenic temperature and ground in an analytic mill (Ika, A11, Brazil). The powder (2.5 g) was placed in a 250 mL flask, followed by the addition of 20 mL of HPLC-grade methanol (70%, v/v) (JP Baker). Then, the solution was homogenized. The extraction flask was placed in an ultrasound bath (USC 2850A Unique, Indaiatuba, Brazil) at room temperature for 1 h. The extract was centrifuged for 15 min at 25000 ×*g* and 4.0°C (SP701, Centrifugal SP Labor, Presidente Prudente, Brazil) and filtered through 0.45-µm HV Millex filter units, in polyethylene (Millipore, Brazil) (Ramaiya et al., 2013).

Phenolic compounds were quantified using an HPLC system (Prominence, Shimadzu, Japan). The system comprised a high-pressure pump (LC-20 AD, Shimadzu), an autosampler (SIL-M 20A Shimadzu), and a diode array detector (DAD) (SPD-M20A, Shimadzu). The following chromatographic conditions were used: HPLC system, DAD; Shim-pack VP-ODS chromatographic column (250 mm × 4.6 mm) fitted with a Shim-Pack VP-ODS guard column (5.0 × 4.0 mm); and mobile phase A comprising 2% (v/v) acetic acid in deionized water and mobile phase B comprising methanol 70% (v/v), deionized water 28% (v/v), and acetic acid 2% (v/v). The flow rate of the mobile phase was maintained at 1 mL min^{-1} at 15°C. The gradient elution method was used. The injection volume was 20 µL. Detection was performed at an absorbance of 280 nm. Phenolic compounds were identified and quantified by comparing their retention time with known previously injected standards (chlorogenic acid and catechin). The results were expressed as milligrams per kilogram on a dry basis (mg kg^{-1} d.b.).

Statistical analyses

Statistical evaluation of the mathematical models

Statistica software (Statistica 8.0®, Statsoft Inc.) was used to perform data analysis. The parameters of the equations were estimated using nonlinear regression analysis. The highest value of R-squared (R^2) and the lowest value of sum square error (SSE) were chosen as the criteria for the goodness of fit, which was calculated using Equation (7).

$$SSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(MR_{pred,i} - MR_{\exp,i}\right)^2\right] \quad (7)$$

Statistical evaluation of the quality analysis

Data were subjected to analysis of variance using the Statistica software (Statistica 8.0®, Statsoft Inc.). Differences between means were compared using the Tukey test. Statistical significance was expressed at the 0.95 probability level ($p \leq 0.05$). All the experiments were conducted in triplicate.

RESULTS AND DISCUSSION

Drying kinetics at constant microwave power level (MPL)

Table 1 summarizes the DT and sample surface temperature (SST) of the restructured Peruvian carrot chips during MWVD at a constant power level. As MPL increased, DT decreased but SST increased significantly ($p \leq 0.05$). This result was expected because the increase in energy provision, with the increase in MPL, results in faster moisture evaporation, resulting in a decrease in process time and an increase in SST (Junqueira et al., 2022; Michalska et al., 2016). The DT required to reach the final moisture

content of the samples was 18.08 ±1.06–47.83 ±0.71 min from higher to lower power levels. A similar effect of decrease in DT with an increase in MPL has been reported for many products, including beetroot and carrots (Musielak; Kieca, 2014), and bacterial culture (Ambros et al., 2018).

Table 1: Drying time (DT) and sample surface temperature (SST) for restructured Peruvian carrot chips obtained using microwave vacuum drying at a constant microwave power level (MPL).

Code	MPL [W]	DT [min]	SST [°C]
MWV-5	428.09±33.95	18.08±1.06^{d}	90.60±5.63^{a}
MWV-4	347.66±27.73	23.83±0.71^{c}	88.95±6.33^{a}
MWV-3	259.80±31.63	25.67±0.94^{c}	84.28±5.47^{a}
MWV-2	180.01±26.71	36.42±0.83^{b}	73.22±5.57^{b}
MWV-1	108.16±23.85	47.83±0.71^{a}	62.69±4.25^{c}

Average value ±standard deviation, n = 10 (for SST); n = 3 (for DT and MPL). Mean followed by different letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

Figure 1 illustrates the drying rate curves for the reconstructed Peruvian carrot chips at each MPL. The drying rate at a higher power level was higher than that at a lower power level. These results corroborate with those of DT (Table 1). Microwave heating occurs because of volumetric heating, a phenomenon comprising the friction of permanent moment dipole molecules such as water because of contact with microwaves (Dadmohammadi; Datta, 2022). The high kinetic energy specifically acquired for water molecules causes their quick vaporization. The increased amount of energy dispensed to the sample increases the drying rate, thereby decreasing the overall duration of the drying process.

Regarding the behavior of the drying rate during the drying process (Figure 1), in all experiments, the drying rate curves had three defined periods. In the first period, the drying rate increased; in the second, it tended to remain constant; and in the third period, the drying rate decreased to levels close to zero when the mass transfer was completed. The increasing drying rate period was because of the initial heating of the sample owing to the conversion of microwave energy into thermal energy within the wet material (Salim et al., 2019). During this period, also called the heating period, the product temperature increased to the boiling point of water (at the pressure used in the present study, i.e., 26.5 kPa, the boiling point of the water was approximately 66°C).

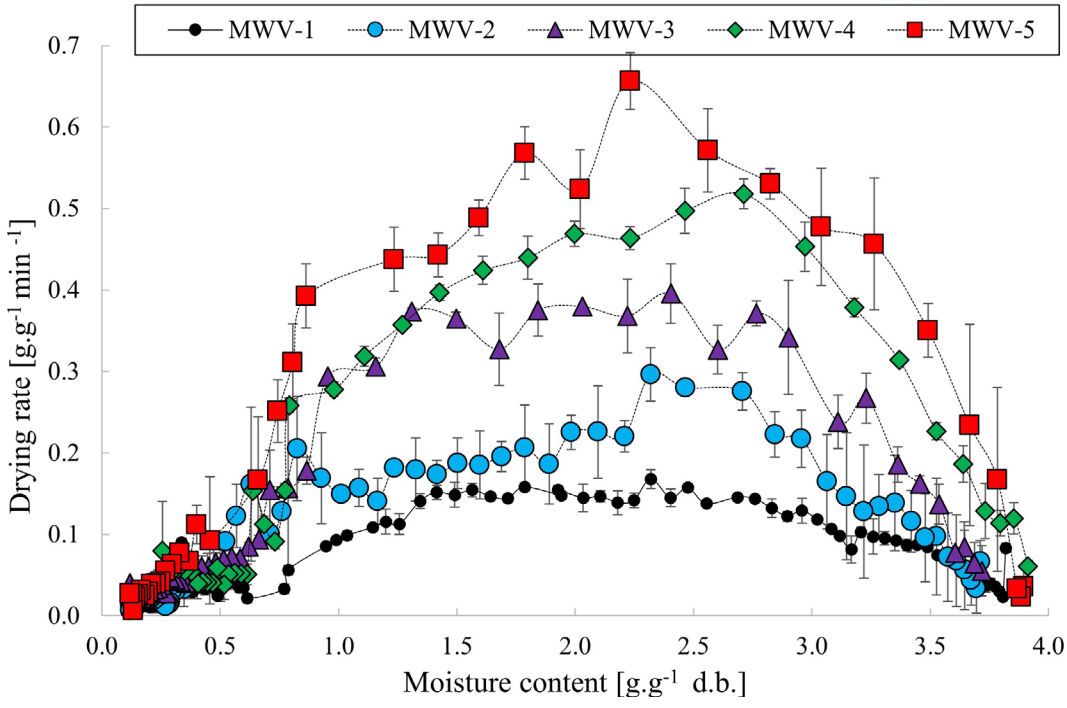

Figure 1:- Variations in drying rate with the moisture content of the restructured Peruvian carrot chips dehydrated under microwave vacuum at a constant microwave power level.

The second period is more relevant in terms of moisture reduction. The high and relatively constant drying rates observed in this period were owing to the microwave energy applied to the sample, providing latent heat of free water vaporization to the wet matrix of the Peruvian carrots. The moisture content maintains a high drying rate because of the relationship between volumetric heating and sample moisture content (Yan et al., 2013). Figure 1 illustrates the constant drying rate period obtained from the drying curves. For MWV-1 and MWV-2, the drying rates were constant in the second drying period. A slight but continuous decrease in drying rate was observed at higher power levels after the material reached the maximum value. As in convective drying, the constant drying rate in MWVD is not easy to observe owing to process complexity. Microwave absorption depends on the dielectric loss factor, which decreases with moisture content. Then, the slight variation in the drying rate during the second drying period is owing to the decrease in the dielectric loss factor (Rosa; Marsaioli; Rocha, 2013). Because the food matrix had abundant moisture content during that period, increasing the microwave power (for different power level curves) increased the drying rate.

Similarly, decreasing the moisture content (over the process) kept the drying rate almost constant at each power level. This indicates that the mass transfer is more affected by MPL than by moisture content at a constant rate during the drying period. Based on the microwave heating theory, the sample temperature does not change at high drying rates (Khaing et al., 2018), which is desirable for the drying process.

When the moisture content reached approximately 0.8 g g^{-1} d.b., the drying rate drastically decreased, beginning the decreased drying rate period. During this period, the low water content does not favor vapor generation, contributing to internal resistance to mass transfer, decreasing the drying rates, and increasing the product temperature (Khaing et al., 2019). Notably, Figure 1 illustrates that independent of the power level, all treatments exhibited similar low drying rates after the samples reached the critical moisture content. This confirms that the decreased drying rate during the third drying period is owing to the significance of the internal resistance to mass transfer. However, this is not directly related to limited moisture content because it does not gradually decrease as the moisture content in this period. Ambros, Foerst and Kulozik (2018) have reported a similar drastic decrease in drying rate during the MWVD of lactic acid bacteria.

Therefore, high MPL may provide high drying rates for wet products with the microwave drying process. However, the drying rate was not affected by the power level at the final drying stage. This explicitly occurred when the moisture content reached approximately 0.8 g g^{-1} for the reconstructed Peruvian carrot chips. This behavior is probably owing to the internal resistance of the food matrix and the depletion of dielectric loss factor. Then, the MPL should be decreased to save energy and prevent possible overheating of the sample (a more detailed analysis of the effect of the internal resistance of the material on the low microwave drying rate is not within the scope of the present work).

In summary, we observed that the drying rate is affected by microwave drying power depending on the increase in drying power. Çelen (2019) reported similar findings during the microwave drying (MWD) of persimmon slices. Furthermore, Li et al. (2021) and Chahbani et al. (2018) have reported that the drying rate increases with an increase in the microwave level for mushrooms and green peas, respectively.

Mathematical modeling of the drying curves at a constant MPL

Table 2 presents the coefficients of the drying models and the statistical criteria obtained by applying Page's and Fick's equations to the experimental drying data.

The k coefficient of Page's model increased from 0.1451×10^{-2} to 2.9216×10^{-2} s^{-1} with the MPL, from the lowest (MWV-1) to the highest (MWV-5) power level, respectively. However, for the fitting parameter (n value), no trends were observed. We observed that R^2 was >0.99, indicating lower SSE in all treatments when this model is used.

Table 2 presents the effective diffusivity (D_{eff}) results obtained using the unidirectional Fick's model. The values ranged from 1.57×10^{-10} to 4.70×10^{-10} $m^2 s^{-1}$, with a R^2 value of >0.92. It is possible to verify that the D_{eff} (from Fick's Equation) and k coefficient (from Page's model) represent the effects of the MPL, increasing both D_{eff} and the k value with the energy microwave level used in the process.

Based on the statistical parameters of the mathematical models, the highest R^2 and lowest SSE values indicate that Page's model presents a better fit than Fick's model. The lack of fit in Fick's model may be because of this model's underlying assumption that the drying rate is only controlled by internal water diffusion within solid materials, neglecting the transfer resistance of external mass.

However, as previously commented, MPL is the primary factor limiting the microwave drying rate until it reaches the critical moisture content (and not water diffusion, as considered in Fick's equation). In this case, Page's model can be used to predict the drying kinetics of the reconstructed Peruvian carrot chips obtained using MWVD at a constant power level. Page's model has adequately represented the drying behavior of microwave-dried pumpkin samples (Bai-Ngew et al., 2015), MWVD of leaves of *Anoectochilus roxburghii* (Ambros et al., 2018) and MWVD of shiitake mushroom (Kantrong; Tansakul; Mittal, 2014).

Table 2: Modeling and statistical parameters of the reconstructed Peruvian carrot chips obtained using different power levels of microwave vacuum drying

Treatments				
Page's model	$k \times 10^2$ [s^{-1}]	n	R^2	SSE × 10^4
MWV-5	2.92	2.16	0.9947	5.35
MWV-4	2.29	1.76	0.9903	1.42
MWV-3	1.37	1.87	0.9905	0.11
MWV-2	0.59	1.91	0.9941	6.96
MWV-1	0.15	2.10	0.9965	4.26
Average			0.9932	3.62
Fick's model	$D_{eff} \times 10^{10}$ [$m^2\ s^{-1}$]		R^2	SSE × 10^3
MWV-5	4.70		0.9467	7.86
MWV-4	4.48		0.9730	0.34
MWV-3	3.66		0.9302	6.55
MWV-2	2.54		0.9675	2.57
MWV-1	1.57		0.9263	6.64
Average			0.9487	4.79

k: drying constant; n: fitting parameter of Page's model; R^2: R-square; SSE: sum square error.

Drying kinetics at the two-stage MPL

A second drying series was performed by applying a higher microwave power at the beginning of the process until the almost constant and high drying rate period was completed (set moisture content of 0.8 g g^{-1} (d.b.) for restructured Peruvian carrot chips). Before reaching this point, the microwave power was decreased to MWV-1 (108.16 ±23.85 W). This created four series of experiments coded based on the power level applied at each stage (Table 3). The first number indicates the power level initially used, whereas the second stage was always MWV-1 (108.16 ±23.85 W) to finish the drying process.

Table 3: Drying time (DT) and sample surface temperature (SST) of restructured Peruvian carrot chips obtained using microwave vacuum drying at a two-stage microwave power level (MPL)

Code	MPL at first stage [W]	SST [°C]	DT [min]
MWV-5–1	428.09±33.95	63.49±6.48^a	20.17±0.94^c
MWV-4–1	347.66±27.73	64.28±5.85^a	25.58±1.06^b
MWV-3–1	259.80±31.63	63.73±5.88^a	27.67±1.18^b
MWV-2–1	180.01±26.71	64.09±6.32^a	37.92±0.82^a

MPL in the second stage was about 108.16 W. Average value ±standard deviation, n = 10 (for sample surface temperature); n = 3 (for drying time). Mean followed by different letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

Table 3 presents the DT and SST of the restructured Peruvian carrot chips obtained using MWVD at the two-stage MPL. As expected, the DT was inversely related to the power level applied at the first stage of the process ($p \leq 0.05$), remaining in the range of 20.17 ±0.94–37.92 ±0.82 min. The DT of two-stage treatments at the same MPL was statistically similar to that reported in constant MPL experiments ($p > 0.05$) (Table 1). However, the SST was not affected by the MPL ($p > 0.05$) at two-stage treatments because the final power level was the same for all experiments.

Musielak and Kieca (2014) have concluded that the two-stage treatment program, with the highest difference between the two microwave powers that were used, is the best MWVD method for carrots and beetroots slices. They observed a decrease in DT at a higher initial MPL.

Figure 2 illustrates the drying rate curves for the reconstructed Peruvian carrot chips obtained using MWVD at the two-stage MPL.

Collectively, these results indicate that decreasing the MPL at the end of the second drying period (almost constant drying rate period) does not change the behavior of the kinetic curves compared with those at the constant power level (Figure 1). Furthermore, it is possible to define three distinct periods: increasing, almost constant rate, and decreased rate drying periods (Ambros et al., 2018).

The similarity between the constant and two-stage kinetic curves at the third period of MWVD (Figures 1 and 2) confirms that the drying rate at this period is determined by the internal resistance of the food matrix and is not affected by the microwave power. Therefore, decreasing the power level at the third drying period does not change the drying rates.

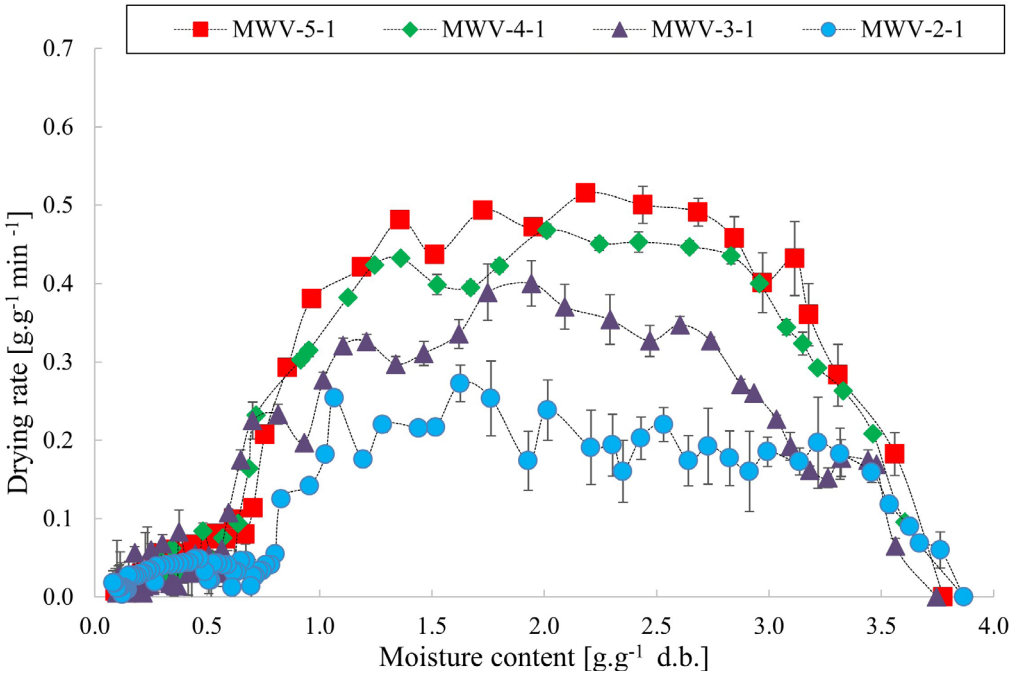

Figure 2: Variations in drying rate with the moisture content of restructured Peruvian carrot chips obtained using microwave vacuum drying at the two-stage microwave power level.

The moisture content data obtained in the two-stage MPL experiments were converted to dimensionless moisture ratio using Equation (1) and then fitted to Page's and Fick's drying models. Table 4 presents the R^2 and SSE for the different drying conditions determined using nonlinear regression analysis. In all cases, the higher R^2 values and lower SSE reveal a great fit, with values ranging between 0.9874 and 0.9996 and 0.41×10^{-4} and 7.21×10^{-4}, respectively.

Page's model represented the drying kinetics of the reconstructed Peruvian carrot chips obtained using MWVD at a constant power level, with high R^2 values (>0.99) and low SSE for all treatments (Table 4).

The effective diffusivity (D_{eff}) values were between 2.83×10^{-10} and 4.31×10^{-10} m^2 s^{-1} (Table 4). These values are similar to those observed in the constant MPL experiments (Table 2); furthermore, they tended to increase with a higher power level. Fick's model presented a good fit to the data when a variable power level was applied during MWVD. Even with the decrease in the power level in the second stage, the maintenance of the D_{eff} values suggests no effect on the MPL.

Although the maintenance of DT by itself is not an advantage, checking whether this results in a significant decrease in process energy and the effect of the decreased microwave power on preserving the bioactive compounds in reconstructed carrot chips is vital. Such evaluations would confer additional advantages to the two-stage drying process.

Table 4: Modeling and statistical parameters of the reconstructed Peruvian carrot chips obtained using microwave vacuum drying at variable power levels

Treatments				
Page's model	$k \times 10^2$ [s^{-1}]	n	R^2	SSE $\times 10^4$
MWV-5–1	2.73	1.91	0.9927	6.34
MWV-4–1	2.32	1.99	0.9996	0.41
MWV-3–1	1.29	1.93	0.9931	6.02
MWV-2–1	0.72	1.88	0.9914	7.21
Average			0.9942	4.99
Fick's model	$D_{eff} \times 10^{10}$ [m^2 s^{-1}]		R^2	SSE $\times 10^3$
MWV-5–1	4.31		0.9895	0.91
MWV-4–1	4.93		0.9874	1.25
MWV-3–1	3.37		0.9884	1.01
MWV-2–1	2.83		0.9909	0.76
Average			0.9891	0.98

k: drying constant; n: fitting parameter of Page's model; R^2: R-square; SSE: sum square error.

EC

Table 5 presents the EC during MWVD at constant and two-stage power levels; the values ranged from 7.44 ±0.16 to 13.11 ±0.39 MJ kg^{-1} H_2O.

Table 5: Energy consumption (EC) during microwave vacuum drying of the restructured Peruvian carrot chips at constant and two-stage power levels.

Treatments	EC [MJ kg^{-1} H_2O]
Constant microwave power level	
MWV-5	12.25±0.72[a]
MWV-4	13.11±0.39[a]
MWV-3	10.55±0.39[b]
MWV-2	10.37±0.24[b]
MWV-1	7.96±0.12[c]
Two-stage microwave power level	
MWV-5–1	7.44±0.16[c]
MWV-4–1	8.29±0.18[c]
MWV-3–1	7.66±0.20[c]
MWV-2–1	8.15±0.14[c]

Average value ±standard deviation, n = 3. Mean followed by different letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

In general, owing to the quality of the heating mechanism, the drying methods using MWV have lower EC (Jiang et al., 2017).

The lowest EC value was observed for the two-stage MPL and MWV-1 treatments ($p \leq 0.05$). At the constant MPL, the lower the MPL, the lower the EC ($p \leq 0.05$). Despite shortening the DT (Table 1), higher microwave power increases the EC.

At the two-stage power level, differences in MPL did not significantly affect the EC ($p > 0.05$). The use of higher microwave power is restricted to a relatively short period from the beginning of the drying until 0.8 g g^{-1} (d.b.) (the critical moisture content point for restructured Peruvian carrot chips) was reached. Then, the two-stage power level can be used to save energy during the MWVD of restructured Peruvian carrot chips, irrespective of the power level applied at the beginning of the process.

Carotenoid retention in restructured Peruvian carrot chips obtained using MWVD at the constant and two-stage power levels

Carotenoids are a group of compounds susceptible to degradation by heat and oxidation (Saini et al., 2015). Therefore, carotene content is a quality index for evaluating the effect of MWVD. The β-carotene content of blanched Peruvian carrots was 635.32 ±4.71 mg $(100\ g)^{-1}$ (d.b.). Table 6 presents β-carotene retention in restructured Peruvian carrot chips obtained using MWVD at constant and two-stage power levels.

Table 6: Values of β-carotene retention obtained for restructured Peruvian carrot chips in microwave vacuum drying at constant and two-stage power levels.

Treatment	β-carotene retention [%]
Constant microwave power level	
MWV-5	80.68±1.70[b]
MWV-4	61.40±0.88[d]
MWV-3	50.37±0.73[e]
MWV-2	62.16±1.53[d]
MWV-1	87.42±1.98[a]
Two-stage microwave power level	
MWV-5–1	84.32±1.98[a]
MWV-4–1	71.43±2.15[c]
MWV-3–1	70.98±1.52[c]
MWV-2–1	73.52±1.35[c]

Average value ±standard deviation (n = 4). Mean followed by different superscript letters in the same column indicates a significant difference ($p \leq 0.05$), according to Tukey's test.

High amounts of β-carotene were observed in MWV-5, MWV-1, and MWV-5–1 treatments ($p \leq 0.05$). In intermediate MPL treatments, increased MPL negatively affected β-carotene retention ($p \leq 0.05$), particularly at constant power levels.

This result can be explained by the expressive shortening of DT, promoted by using higher MPL; this can improve the retention of heat-sensitive compounds. On the other hand, lower power level treatments, despite longer process durations, decrease their temperature, improving carotenoid retention. The carotenoid molecule is degraded by exposure to heat for a prolonged time (Al Juhaimi et al., 2016). Higher or lower microwave power, for both constant and higher power levels in the two-stage treatments, contributed to preserving β-carotene content.

The thermal energy generated by collisions owing to ionic polarization and dipole rotations and high vapor pressure inside plant tissues owing to the strong squeezing of water molecules can degrade pigments in MWD (Cao et al., 2020; Junqueira et al., 2022).

Nevertheless, no statistical differences ($p > 0.05$) in β-carotene content were observed during the MWD of broccoli florets (Cao et al., 2020) at different MPLs (500 and 900 W). Moreover, Alibas et al. (2021) observed that a higher MPL preserved the β-carotene content during the MWD of basil leaves.

Phenolic compound content in restructured Peruvian carrot chips obtained using MWVD at constant and two-stage power levels

Catechin and chlorogenic acid were identified as the major phenolic compounds in Peruvian carrots. The amount of these compounds in blanched Peruvian carrot samples were 583.92 ±5.56 and 1049.00 ±73.48 mg kg^{-1} (d.b), respectively. Table 7 presents the phenolic compounds in the restructured Peruvian carrot chips obtained using MWVD at constant and variable power levels. The amount of each phenolic compound decreased with an increase in MPL.

The results (Table 7) also demonstrated that the restructured Peruvian carrot chips dried at lower and intermediate power levels in the constant microwave treatments (MWV-1, MWV-2, and MWV-3) and higher and lower power levels in the two-stage drying process (MWV-5–1 and MWV-2–1) contained the highest amount of catechins ($p \leq 0.05$). The lowest level of catechins was observed in the chips dried at MWV-5 ($p \leq 0.05$). On the other hand, the amount of chlorogenic acid was higher at MWV-1 and MWV-5–1 ($p \leq 0.05$). This data may result from decreased catechin and chlorogenic acid degradation when a lower MPL was applied (Liu; Zhang; Wang, 2016).

High temperatures induced by high microwave powers may lead to faster degradation of catechins in dried chips (Hirun et al., 2014). Increasing the MPL increases the sample temperature. MWV-5–1 in the two-stage treatment presented high catechin and chlorogenic acid preservation. This result can be explained by the fact that the higher microwave power in the two-stage treatment could expressively shorten the DT, thereby improving the retention of heat-sensitive compounds despite exposure to high power.

Saifullah et al. (2019) concluded that the major individual phenolic compounds present different behaviors during the MWD of lemon myrtle leaves. They observed that MPL had a significant effect on gallic acid but not hesperitin. The sample dried at intermediate MPL had the highest amount of gallic acid, followed by those dried at higher MPL; the leaf dried at lower MPL had the lowest amount of gallic acid.

Table 7: Amount of phenolic compounds in restructured Peruvian carrot chips obtained using MWVD at constant and two-stage power levels (mg kg^{-1} d.b.)

Treatment	Catechin	Chlorogenic acid
Constant microwave power level		
MWV-5	194.54±1.93^{e}	491.68±11.83^{b}
MWV-4	253.71±2.86^{d}	504.81±5.41^{b}
MWV-3	334.77±12.34^{ab}	569.37±3.96^{b}
MWV-2	327.35±8.27^{ab}	538.17±3.16^{b}
MWV-1	352.35±4.63^{a}	711.03±11.02^{a}
Two-stage microwave power level		
MWV-5–1	325.88±5.61^{ab}	702.61±12.20^{a}
MWV-4–1	286.78±4.77^{cd}	548.35±16.07^{b}
MWV-3–1	304.33±5.30^{bc}	550.36±12.80^{b}
MWV-2–1	322.30±9.33^{ab}	560.16±2.44^{b}

Average value ±standard deviation (n = 4). Mean followed by different superscript letters in the same column indicates a significant difference ($p \leq 0.05$), according to Tukey's test.

General remarks

Microwaves can be used in combination with other drying techniques such as convective drying (Kumar; Karim, 2019), freeze-drying (Sun et al., 2021), pulsed fluidized bed (Jiang et al., 2021), infrared (Nanvakenari et al., 2022) and vacuum (Monteiro et al., 2020).

At the industrial level, microwave fields are used to finish drying products. Microwave quickens the process, significantly decreases the process period, and enhances the functional characteristics of the product, including increasing volume and porosity in the puffing process. Our study findings provide a basis for developing new processes and products with added value and desirable characteristics.

CONCLUSIONS

We observed that different treatments affected the drying kinetics. When using constant MPL in MWVD, we observed that the power level directly increased the sample temperature and decreased DT. At two-stage power level, DT decreased with an increase in MPL; saving energy and time and preserving the quality attributes of restructured Peruvian carrot chips. Our study supports the development of new processes and products with desirable characteristics, in which the two-stage MPL treatments, particularly MWVD-5–1, achieved the best results.

AUTHORS CONTRIBUTION

Conceptual idea: Mendonça, K. S.; Corrêa, J. L. G.; Methodology design: Mendonça, K. S.; Junqueira, J. R. J.; Data collection: Mendonça, K. S.; Souza, A. U.; Data analysis and interpretation: Corrêa, J. L. G.; Mendonça, K. S.; and Writing and editing: Mendonça, K. S.; Junqueira, J. R. J.; Corrêa, J. L. G.

ACKNOWLEDGMENTS

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, FAPEMIG and CNPq.

REFERENCES

AL JUHAIMI, F. et al. Effects of oven and microwave drying on phenolic contents and antioxidant activities in four apple cultivars. Quality Assurance and Safety of Crops and Foods, 8(1):51-55, 2016.

ALBANO, K. M.; FRANCO, C. M. L.; TELIS, V. R. N. Rheological behavior of Peruvian carrot starch gels as affected by temperature and concentration. Food Hydrocolloids, 40:30-43, 2014.

ALIBAS, I. et al. Influence of drying methods on the nutrients, protein content and vitamin profile of basil leaves. Journal of Food Composition and Analysis, 96: 103758, 2021.

AMBROS, S.; FOERST, P.; KULOZIK, U. Temperature-controlled microwave-vacuum drying of lactic acid bacteria: Impact of drying conditions on process and product characteristics. Journal of Food Engineering, 224:80-87, 2018.

ASSOCIATION OF OFFICIAL AGRICULTURAL CHEMISTS - AOAC. Official methods of analysis of aoac international. 20th Ed, Rockville, Maryland, USA, 2016. 3172p

APINYAVISIT, K. et al. A Comparative study of combined microwave techniques for longan (*Dimocarpus longan Lour.*) drying with hot air or vacuum. International Journal of Food Engineering, 13(7):20160263 2017.

BAI-NGEW, S. et al. Effect of microwave vacuum drying and hot air drying on the physicochemical properties of durian flour. International Journal of Food Science & Technology, 50(2):305-312, 2015.

BÓRQUEZ, R.; MELO, D.; SAAVEDRA, C. Microwave-vacuum drying of strawberries with automatic temperature control. Food and Bioprocess Technology, 8:266-276, 2015.

CAO, Y. et al. Effect of microwave and air-borne ultrasound-assisted air drying on drying kinetics and phytochemical properties of broccoli floret. Drying Technology, 38(13):1733-1748, 2020.

ÇELEN, S. Effect of microwave drying on the drying characteristics, color, microstructure, and thermal properties of *Trabzon persimmon*. Foods, 8(2):7-9, 2019.

CHAHBANI, A. et al. Microwave drying effects on drying kinetics, bioactive compounds and antioxidant activity of green peas (*Pisum sativum* L.). Food Bioscience, 25:32-38, 2018.

CORRÊA, J. L. G. et al. Dried yacon with high fructooligosaccharide content. Journal of Food Process Engineering, 44(12):e13884, 2021.

CRANK, J. The mathematics of diffusion. Clarendon Press; 2nd edition. 1975. 424p.

DADMOHAMMADI, Y.; DATTA, A. K. Food as porous media: A review of the dynamics of porous properties during processing. Food Reviews International, 38(5)953-985, 2022.

DEMIRHAN, E.; ÖZBEK, B. Color change kinetics of celery leaves undergoing microwave heating. Chemical Engineering Communications, 198(10):1189-1205, 2011.

HIRUN, S. et al. Investigating the commercial microwave vacuum drying conditions on physicochemical properties and radical scavenging ability of thai green tea. Drying Technology, 32(1):47-54, 2014.

JIANG, J. et al. Effect of ultrasound-assisted osmotic dehydration pretreatments on drying and quality characteristics of pulsed fluidized bed microwave freeze-dried strawberries. LWT - Food Science and Technology, 145:111300, 2021.

JIANG, N. et al. Evaluation of freeze drying combined with microwave vacuum drying for functional okra snacks: Antioxidant properties, sensory quality, and energy consumption. LWT - Food Science and Technology, 82:216-226, 2017.

JUNQUEIRA, J. R. J. de. et al. Microwave drying of sweet potato: Drying kinetics and energetic analysis. Australian Journal of Crop Science, 16(10):1185-1192, 2022.

JUNQUEIRA, J. R. J. de. et al. Pulsed vacuum osmotic dehydration of beetroot, carrot and eggplant slices: Effect of vacuum pressure on the quality parameters. Food and Bioprocess Technology, 11:1863-1875, 2018.

JUNQUEIRA, J. R. de J. et al. Ethanol pretreatment in taioba leaves during vacuum drying. Ciência e Agrotecnologia, 45:e020421, 2021.

KANTRONG, H.; TANSAKUL, A.; MITTAL, G. S. Drying characteristics and quality of shiitake mushroom undergoing microwave-vacuum drying and microwave-vacuum combined with infrared drying. Journal of Food Science and Technology, 51(12):3594-3608, 2014.

KHAING, H. K. et al. Emerging food drying technologies with energy-saving characteristics: A review. Drying Technology, 37(12):1465-1480, 2019.

KHAING, K. H. et al. Emerging food drying technologies with energy-saving characteristics: A review. Drying Technology, 37(12):1465-1480, 2018.

KUMAR, C.; KARIM, M. A. Microwave-convective drying of food materials: A critical review. Critical Reviews in Food Science and Nutrition, 59(3):379-394, 2019.

KUMAR, V.; SHRIVASTAVA, S. L. Optimization of vacuum-assisted microwave drying parameters of green bell pepper using response surface methodology. Journal of Food Measurement and Characterization, 11(4):1761-1772, 2017.

LI, X. et al. Drying characteristics and processing optimization of combined microwave drying and hot air drying of Termitomyces albuminosus mushroom. Journal of Food Processing and Preservation, 45(12):e16022, 2021.

LIU, Z.; ZHANG, M.; WANG, Y. Drying of restructured chips made from the old stalks of Asparagus officinalis: Impact of different drying methods. Journal of the Science of Food and Agriculture, 96(8):2815-2824, 2016.

LOVERA, M.; PÉREZ, E.; LAURENTIN, A. Digestibility of starches isolated from stem and root tubers of arracacha, cassava, cush-cush yam, potato and taro. Carbohydrate Polymers, 176:50-55, 2017.

MICHALSKA, A. et al. Physicochemical properties of whole fruit plum powders obtained using different drying technologies. Food Chemistry, 207:223-232, 2016.

MONTEIRO, R. L. et al. Microwave vacuum drying of foods with temperature control by power modulation. Innovative Food Science and Emerging Technologies, 65:102473, 2020.

MONTEIRO, R. L. et al. How to make a microwave vacuum dryer with turntable. Journal of Food Engineering, 166:276-284, 2015.

MUSIELAK, G.; KIECA, A. Influence of varying microwave power during microwave-vacuum drying on the drying time and quality of beetroot and carrot slices. Drying Technology, 32(11):1326-1333, 2014.

NANVAKENARI, S.; MOVAGHARNEJAD, K.; LATIFI, A. Modelling and experimental analysis of rice drying in new fluidized bed assisted hybrid infrared-microwave dryer. Food Research International, 159:111617, 2022.

OLIVEIRA, L. F. et al. Drying of yacon pretreated by pulsed vacuum osmotic dehydration. Brazilian Journal of Agricultural and Environmental Engineering, 25(8):560-565, 2021.

PEDRESCHI, R. et al. Impact of cooking and drying on the phenolic, carotenoid contents and in vitro antioxidant capacity of Andean Arracacha (*Arracacia xanthorrhiza* Bancr.) root. Food Science and Technology International, 17(4):319-330, 2011.

RAMAIYA, S. D. et al. Sugars, ascorbic acid, total phenolic content and total antioxidant activity in passion fruit (*Passiflora*) cultivars. Journal of the Science of Food and Agriculture, 93(5):1198-1205, 2013

ROSA, G. S. da.; MARSAIOLI, A.; ROCHA, S. C. S. dos. Energy analysis of poly-hydroxybutirate (PHB) Drying using a combined microwave/rotating pulsed fluidized bed (MW/RPFB) dryer. Drying Technology, 31(7):795-801, 2013.

SAIFULLAH, M. et al. Effects of different drying methods on extractable phenolic compounds and antioxidant properties from lemon myrtle dried leaves. Heliyon, 5(12):e03044, 2019.

SAINI, R. K.; NILE, S. H.; PARK, S. W. Carotenoids from fruits and vegetables: Chemistry, analysis, occurrence, bioavailability and biological activities. Food Research International, 76:735-750, 2015.

SALIM, N. S.; GARIÈPY, Y.; RAGHAVAN, V. Effects of processing on quality attributes of osmo-dried broccoli stalk slices. Food and Bioprocess Technology, 12:1174-1184, 2019.

SOUZA, A. U. de. et al. Hybrid microwave-hot air drying of the osmotically treated carrots. LWT, 156:113046, 2022.

SUN, Y. et al. Pulse-spouted microwave freeze drying of raspberry: Control of moisture using ANN model aided by LF-NMR. Journal of Food Engineering, 292:110354, 2021.

UKOM, A.; NWANAGBA, N.; OKEREKE, D. Effect of drying methods on the chemical composition and anti- nutrtional properties of a cocoyam (Xanthosoma Maffafa Schott) tuber flour and leaf powder. EAS Journal of Nutrition and Food Sciences, 1873(4):197-203, 2020.

YAN, W. Q. et al. Influence of microwave drying method on the characteristics of the sweet potato dices. Journal of Food Processing and Preservation, 37(5):662-669, 2019.

ZIELINSKA, M.; MICHALSKA, A. Microwave-assisted drying of blueberry (*Vaccinium corymbosum* L.) fruits: Drying kinetics, polyphenols, anthocyanins, antioxidant capacity, colour and texture. Food Chemistry, 212:671-680, 2016.

ZIELINSKA, M. et al. Review of recent applications and research progress in hybrid and combined microwave-assisted drying of food products: Quality properties. Critical Reviews in Food Science and Nutrition, 60(13):2212-2264, 2020.