KAMILLA SOARES DE MENDONÇA

MICROWAVE AND MICROWAVE-VACUUM DRYING OF PERUVIAN CARROTS: INFLUENCE OF PROCESS ON THE QUALITY AND KINETIC PARAMETERS

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Orientador

Dr. Jefferson Luiz Gomes Corrêa

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Aos meus pais, Maria das Graças e Francisco de Assis,
pelo incentivo e amor, e por me permitirem sonhar.

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GENERAL ABSTRACT

Many studies have been conducted to better understand the mechanisms of microwave drying of food, and to evaluate the quality parameters of these products. The behavior of the microwaves depends on the dielectric properties of each food matrix. Peruvian carrot is an Andean root that triggers a special interest by food science researchers and industry because it has a wide range of culinary applications and great amount of resistant starch and bioactive compounds (carotenoids, phenolic compounds and minerals). However, trade and consumption of Peruvian carrots are restricted due to its perishability. Microwaves can be used for drying roots, extending the shelf life of foods and promoting a fast drying process. The advantage of microwave use is associated with the volumetric heating mechanism, which assists in the development of products with aggregated value by preserving thermosensitive compounds. Vacuum microwave drying increases the product moisture transfer and preserves the oxidative molecules from oxygen action. The aim of this work is studying the behavior of Peruvian carrots during microwave and microwave-vacuum drying, analysing the influence of microwave power level at kinetics parameters and quality attributes. The power level increases the drying rate, sample surface temperature, energy consumption, reduces the drying time, and improves chip quality compared to convective drying. The research observes that higher microwave power level use increased rehydration and crispness, reduced hardness and shrinkage characteristics and preserved β-carotene content. The vacuum application preserved phenolic compounds, β-carotene and color changes. However, it did not influence the physical characteristics of chips. At the end of the drying, Microwave power level did not influenced the drying rate, which can be reduced without loose in the kinetic parameters. In the treatments with two levels of power, the temperature and the energy consumption were reduced and contributed to preserves carotenoids and phenolic compounds of restructured Peruvian carrots chips. In conclusion, microwave power level and vacuum use affect the final characteristics of the product, and behavior during dehydration.

Keywords: Microwave-vacuum drying, Microwave power level, Two-stage drying, *Arracacia xanthorrhiza*.

RESUMO GERAL

Muitos estudos têm sido realizados visando o melhor entendimento dos mecanismos de secagem dos alimentos por micro-ondas, bem como avaliar os parâmetros de qualidade desses produtos. O comportamento das micro-ondas depende das propriedades dielétricas de cada matriz alimentar. A mandioquinha-salsa é uma raiz andina que desperta interesse dos pesquisadores em ciência de alimentos e da indústria devido à ampla gama de aplicações culinárias e elevadas quantidades de amido resistente e compostos bioativos (carotenóides, compostos fenólicos e minerais). No entanto, o comércio e o consumo de mandioquinha-salsa são restritos devido à sua alta perecebilidade. As micro-ondas podem ser usadas para secar raízes, prolongando a vida útil dos alimentos e promovendo um processo de secagem rápida. A vantagem do uso de micro-ondas está associada ao mecanismo de aquecimento volumétrico, que auxilia no desenvolvimento de produtos com valor agregado por meio da preservação de compostos termosensíveis. A secagem por micro-ondas a vácuo aumenta a transferência de umidade do produto e preserva as moléculas da ação oxidativa do oxigênio. O presente trabalho foi elaborado com o objetivo de estudar o comportamento da mandioquinha-salsa durante a secagem em micro-ondas e micro-ondas a vácuo, analisando a influência do nível de potência de micro-ondas nos parâmetros cinéticos e atributos de qualidade. O nível de potência aumenta a taxa de secagem, a temperatura da superfície da amostra, o consumo de energia, reduz o tempo de secagem e melhora a qualidade dos *chips* em comparação com a secagem por convecção. Observou-se que o uso de maior nível de potência de micro-ondas aumentou a reidratação e a crocância, reduziu a dureza e encolhimento e preservou o conteúdo de β-caroteno. A aplicação do vácuo preservou compostos fenólicos, β-caroteno e mudanças de cor. No entanto, não influenciou as características físicas dos *chips*. A taxa de secagem, no final dessa, não foi influenciada pelo nível de potência de micro-ondas e pode ser reduzida sem perda nos parâmetros cinéticos. Nos tratamentos com dois níveis de potência, a temperatura e o consumo de energia foram reduzidos e contribuíram para preservar carotenóides e compostos fenólicos de *chips* de mandioquinha-salsa reestruturados. Em conclusão, o nível de potência de micro-ondas e o uso de vácuo afetam as características finais do produto e o comportamento durante a desidratação.

Palavras-chave: Secagem por micro-ondas a vácuo, Nível de potência de micro-ondas, Dois estágios de secagem, *Arracacia xanthorrhiza*.

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LIST OF ACRONYMS

Abs	Absorbance
CAPES	Coordination for the Improvement of Higher Education Personnel
CD	Convective drying
cm	Centimeter
CNPq	National Council for Scientific and Technological Development
COR	Coefficient of rehydration
DAD	Diode array detector
d.b.	Dry basis
g	Gram
FAPEMIG	State of Minas Gerais Research Foundation
h	Hour
HPLC	High Performance Liquid Chromatography
Hz	Hertz
H_2O	Water
kg	kilogram
kPa	kilopascal
L	Liter
m	Meter
mg	Milligram
MHz	Megahertz
min	Minutes
MJ	Megajoule
mL	Milliliter
mm	Millimeter
MPL	Microwave power level
MW	Microwave

MWD	Microwave drying
MWV	Microwave vacuum
MWVD	Microwave-vacuum drying
n	Number of observations
N	Maximum force/Hardness
nm	Nanometer
RR	Rehydration ratio
s	Second
SSE	Sum square error
SST	Sample surface temperature
tan	Tangent
UV/Vis	Ultraviolet visible
v/v	Volume/volume
W	Watt
w.b.	Wet basis
µL	Microliter
µm	Micrometer

LIST OF SYMBOLS

ε^*	Relative permittivity
ε'	Dielectric constant
ε''	Loss factor
P_a	Absorbed energy [Wm^{-3}]
f	frequency of electromagnetic wave [Hz]
ε_0	Absolute permittivity
tan δ	Dissipation factor
D_p	Penetration depth
e	Euler number
λ_0	Wavelength of microwave
g	Gravity force
V	Total extract volume [mL]
W	Sample weight [g]
$E^{1\%}$	Molar extinction coefficient
L^*	Lightness
a^*	Redness
b^*	Yellowness
C^*	Chroma
h^o	Hue angle
V_0	Volume of blanched sample [cm^3]
V_d	Volume of dried sample [cm^3]
m_{rh}	Mass of rehydrated sample [g]
m_{dh}	Mass of dehydrated sample [g]
X_{dh}	Moisture content of dehydrated sample [%]

X_0	Moisture content of fresh sample [%]
MR	Dimensionless moisture ratio
M	Moisture content [g H_2O g^{-1}]
M_{eq}	Moisture content at equilibrium [g H_2O g^{-1}]
M_0	Initial moisture content [g H_2O g^{-1}]
t	Time [min]
DR	Drying rate [g H_2O g^{-1} min^{-1}]
k	Adjustment coefficient
L	Half of sample thickness [m]
D_{eff}	Water effective of diffusivity [m^2 min^{-1}]
EC	Energy consumption [MJ kg^{-1} H_2O]
t_{on}	Total power on time [s]
P	Microwave input power [W]
M_f	Final moisture content
R^2	R-square
Dt	Drying time

SUMMARY

FIRST SECTION

1 GENERAL INTRODUCTION

Currently, the quest search for life quality has aroused interest in the identification and consumption of food product that contribute to the health maintenance, act in the treatment or prevention of diseases and present nutritionally balanced. The Peruvian carrot (*Arracacia xanthorrhiza* Bancroft) is a plant of the Apiaceae family, whose root are a source of nutrients and presents economic importance. Although this vegetable is rich in phenolic compounds, carotenoids, minerals and vitamins, the high perishability of Peruvian carrot difficult its commercialization. The logistic distribution of the Peruvian carrot requires specific conditions for its adequate storage besides high waste of the roots due to the short shelf life, which raises its cost. An alternative for avoiding these undesirable factors is the diversification of their industrialization, since the roots can be used for some purposes as a raw material for chips, flour and starch production. The supply of high-quality processed products may increase the consumption and Peruvian carrot production in Brazil and worldwide.

In Brazil, Peruvian carrot production is almost exclusively destined for domestic consumption in culinary preparations, except for the small production of dried purees employed for instantaneous soups and production straw fried chips production, and the exportation to Japan in precooked form, preserved at room temperature, and precooked frozen.

Drying is an alternative which promotes food products available in regions far from those in where it is originally found, protects against enzymatic and oxidative degradation, reduces weight, product volume and costs with packaging and transport, dispenses refrigeration and allows seasonal products to be available to the market even outside the harvest period (MUJUMDAR; LAW, 2010). However, this process can lead to losses in physical, chemical and nutritional quality in relation to the fresh product, mainly in respect of heat sensible and oxidizable compounds. Thus, it is necessary to study alternative dehydration processes that are able to smooth the damages caused by the classic processes, provide products with high sensorial and nutritional characteristics, as well as prolonged shelf life.

Microwave drying is promoted by electromagnetic waves that provide the instantaneous volumetric heating in dielectric materials, being absorbed more intensely in the wetter regions compared to drier regions. Microwave drying presents high drying rates, attributed to the vapors formation inside of the food matrix, which generate an internal pressure gradient, and promotes the fast water removal. The association of vacuum to microwave drying favors the vapors formation under reduced temperatures, further increasing the drying rates of the process and promoting the sensitive molecules protection against thermal and oxidative degradation. The use of microwave energy associated with vacuum in the slices and flour of Peruvian carrot drying is a good option for shortening the total drying process time and to assure the obtained product quality, with molecules preservation with antioxidant properties, like carotenoids and phenolic compounds.

Among these possibilities, the microwave-vacuum drying use in Peruvian carrot processing is a promising alternative for the development of high quality products with market potential. This thesis was developed in three chapters. The first section presents a literature review with the general aspects and nutritional characteristics of the Peruvian carrot, food drying, and technical aspects of microwaves and microwave-vacuum used for food drying. The second section evaluates the influence of the microwave power variation on the quality attributes of the Peruvian carrot obtained by microwaves and microwave-vacuum drying, considering the drying time, color change, rehydration, shrinkage, texture, carotenoid content and phenolic compound profile of the dried slices. The third section evaluates the influence of the constant microwave power level and the variation of the power level in two stages during the microwave-vacuum drying of restructured chips of Peruvian carrot regarding to the drying time, kinetic behavior, energy consumption and bioactive compounds (carotenoids and phenolics) preservation parameters. Thus, the objective of this work was to evaluate the microwave and vacuum-microwave drying aspects in order to obtain quality Peruvian carrot chips.

2. THEORETICAL REFERENCE

2.1. General aspects of the Peruvian carrot (*Arracacia xanthorrhiza*)

The Peruvian carrot is a root (*Arracacia xanthorrhiza* Bancroft) of the Apiaceae family from the Andean region of South America, which was introduced in Brazil at the beginning of the 19th century (MORILLO; KNUDSEN; SÉCOND, 2017). The edible portion of the

plant consists of six or more tuberous roots, which may be elongated, cylindrical or conical with a length ranging from 4 to 20 cm and lustrous skin (ALBANO; FRANCO; TELIS, 2014).

Peruvian carrot is also called, in Brazil, as *mandioquinha-salsa, batata-baroa, batata-fiúza, batata-cenoura, batata-tupinambá, batata-arracacha, batata-jujuba, batata-suíça batata-aipo, batata-galinha, batata-salsa, barão, baroa, carotole, pastinaca* and others (CASALI; SEDIYAMA, 1997; SANTOS; CARMO, 1998) according to the region. In the scientific and commercial environment has tried to standardize a nomenclature for the Peruvian carrot, Apio or Arracacha. The color of the Peruvian carrot roots depends on the variety, varying from white, yellow, cream-colored and purple, with flavor and aroma differentiation. Despite the different names, we find two commercial cultivars in Brazil: "Amarela de Carandaí or Amarela Comum" and the most currently cultivated "Amarela de Senador Amaral", which has higher productivity, roots with commercial pattern, intense yellow coloration and early harvest (SANTOS; MADEIRA, 2008).

The Peruvian carrot commercial value is remarkably superior to that of other roots and tubers, therefore it is a great alternative for small and medium producers, especially within the concepts of family agriculture, due to the considerable demand for labor, mainly in the planting and harvesting phases (ALBANO; FRANCO; TELIS, 2014). The production data in Brazil are scarce, because much of the production is directly marketed with the retailers, and the data obtained from supply centers is a partial sample of the production. It is estimated that the annual production of Peruvian carrot in Brazil reaches 200 thousand tons, with

São Paulo, Minas Gerais and Paraná as the states with the highest production volumes, being the last one, the largest market pole (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA, 2018; MADEIRA; CARVALHO, 2013). Most of the production is destined to the domestic consumer, it is estimated that only 5 % of the production is industrially processed (SANTOS; MADEIRA, 2008). For domestic consumption, it can be cooked, baked, fried or soaked. However, there is a growing demand for Peruvian carrot for the food industry, where they are processed in the form of creams, soups, infant foods, fried slices, purees, dried purees used in the instant soup industry or in minimally processed forms (ALBANO; FRANCO; TELIS, 2014; BOTREL; MADEIRA, 2012), enabling to increase the consumption and production of Peruvian carrot in Brazil and worldwide. According to Hermann (1997), Peruvian carrot is a promising crop for the food industry, because it has a wide range of culinary applications and is free of undesirable substances that usually limit the use and acceptance of Andean roots such as oca (oxalates), ulluco (mucilage), mashua (isothiocyanates) and mauka (astringent principles).

2.1.1. Nutritional composition of Peruvian carrot

The Peruvian carrot is considered a food with predominantly energetic function, due to the outstanding content of carbohydrates. Resistant starch content triggers a special interest in this food (LOVERA; PÉREZ; LAURENTINA, 2017). However, it also presents high carotenoids, phenolic compounds and minerals contents (CARMO; LEONEL, 2012; PEDRESCHI et al., 2011; SEDIYAMA et al., 2005).

The Food and Agriculture Organization of the United Nations (FAO) recognizes the Peruvian carrot as a specie of high nutritional, economic and productive value, with potential for industry and medicinal uses (CARMO; LEONEL, 2012). Table 1 shows data of the Peruvian carrot composition according to several authors.

Table 1 - Composition of fresh Peruvian carrot roots.

Components [g(100 g)$^{-1}$] (w.b.)	Hermann (1997)	Leonel and Cereda (2002)	Matsuguma et al. (2009)	Carmo and Leonel (2012)
Moisture	74.0	79.70	69.9-74.5	76.03-81.97
Ash	1.30	1.03	1.30-1.45	0.93-1.16
Crude fiber	0.85	0.38	2.75-3.27	0.47-0.89
Lipids	0.26	0.20	0.18-0.42	0.10-0.22
Protein	0.96	0.56	1.25-1.83	0.39-0.67
Carbohydrates	24.9	-	23.25-25.66	-
Reducing sugars	-	0.36	-	0.30-1.17
Total sugars	-	1.34	-	0.73-2.48
Starch	23.5	15.75	23.25-24.6	14.96-21.41

The yellow coloration of the Peruvian carrot is directly associated to the carotenoid pigment content, which may differ with the variety, creating a range of colors in the roots, varying from cream-colored to yellow and orange (HERMANN, 1997). The main carotenoid found in Peruvian carrot is the β-carotene, besides others as gamma-carotene, zeta-carotene and beta-zeta-carotene (ALMEIDA; PENTEADO, 1987).

The carotenoid content (1.00 mg of β-carotene equivalent (100 g)$^{-1}$) in Peruvian carrot and the profile of phenolic compounds were determined by Pedreschi et al. (2011), chlorogenic acids (76.43 mg (100

g)$^{-1}$), caffeic acid (1.21 mg (100 g)$^{-1}$) and derivatives were found. The same authors concluded that the blanching use prior to processes such as cooking in water, microwave and hot air reduced the phenolic compounds losses due to the polyphenol oxidase enzyme inactivation. Furthermore, we observed that the processing contributed to the phenolic compounds loss due to oxidation, since the process temperature did not influence the increased degradation of the phenolic compounds. The carotenoids were degraded by up to 59.3 % after the cooking processes.

Carotenoids and phenolic compounds are molecules with antioxidant properties, which have gained importance in the contribution to human health, since they assist in the cellular protection against damages caused by oxygen radicals, which present serious consequences in heart diseases and cancer development (HORUZ et al., 2018; YAN et al., 2013). During the root processing, it is important to avoid the carotenoids and phenolic compounds oxidation (PEDRESCHI et al., 2011), in order to assure the nutritional value of the food maintenance.

The Peruvian carrot chips production is still commercially scarce. Considering the large amount of soluble solids in this root, a technological potential and promising economic are demonstrated. Besides, the consumer search for ready-to-eat products, with functional properties and pleasant sensory characteristics.

2.2. Food drying

Drying is a unit operation applied to reduce the moisture content in order to extend the shelf life of biological products. In this process, the water activity of the product is reduced to a low level, preventing the microorganisms growth, the development of enzymatic and other degradative reactions that reduce the product quality after harvesting (MUJUMDAR; LAW, 2010).

In addition to the conservation of the product promotion, due to the moisture removal, drying provides greater labile components stability, enzymatic and oxidative degradation protection, weight and product volume reduction, and costs with packaging and transportation, dispensing refrigeration and allowing seasonal products available in the market even outside the harvest period (HAMROUNI-SELLAMI et al., 2013; MUJUMDAR; LAW, 2010).

Drying is characterized by the simultaneous occurrence of energy transfer from the environment or from an external agent to extract the moisture from the food by vaporization (MUJUMDAR, 2007). The heat supplied to promote drying can reach the product by radiation, conduction, convection, or even the energy supplied can generate heat inside the food, as in dielectric, infrared, microwave and radio frequency cases (MUJUMDAR, 2007). Depending on the type of dryer employed in the process, drying can occur by combining these effects.

2.2.1 Food convective drying

In convective drying, the transfer of humid mass from the interior to the material surface is promoted mainly by the liquid diffusion (attributed to the solvent concentration gradient), vapor diffusion (generated by differences in temperature inside the food) and the flow of liquid and vapor (occurring by capillarity, high temperature and differences of external pressure and concentration) (SADEGHI; KESBI; MIREEI, 2013). The heat transfer process is limited by the thermal conductivity of the product, while the mass transfer is proportional to the molecular diffusion of water vapor in the unsaturated air at constant drying rate step, and inside the food matrix, at decreasing drying rate step (SINGH; HELDMAN, 2009).

The drying process is studied for the drying rate and can be divided into induction period (1), constant drying rate (2) and decreasing drying rate (3) (MUJUMDAR, 2007):

(1): The induction period has negligible extension to the entire drying process and is characterized by the product heating and gradual increase of the mass transfer until the rate of energy supplied equals the free water vaporization of the product (latent heat of vaporization) rate. At this point, the constant drying rate period starts.

(2): The constant drying rate step is governed by mass and heat transfer at the air-product interface and is responsible for the quick removal of the water from the product. The water vapor pressure at the surface is constant and equal to the pure water vapor pressure at the product temperature. This period extends until the water transport from the

interior to the food surface is sufficient to follow the loss by water evaporation on the surface. When this ceases to occur, the stage in which the drying rate is decreasing begins.

(3): During the decreasing drying rate, the moisture removal demands more energy, due to the internal resistance to water migration. There is lowering of the water vapor partial pressure on the surface and elevation of the food temperature. At the end of this period, the drying rate will be zero (equilibrium condition).

The determination of each of these periods duration and, consequently, of the drying rate extent, is a function of the internal and external conditions of the process. The heat transfer from the environment to the material surface is controlled according to the exposed surface area, pressure, temperature, moisture and air flow, whereas internal mass transfer is influenced by the physical nature of the material, temperature, initial moisture and geometry (MUJUMDAR, 2007).

Among the dryer types, convective dryers are the most traditionally used for food drying, using hot air as a drying agent, transferring heat to the product by convection and operating at atmospheric pressure. These equipment have a number of limitations, such as homogeneous drying absence, long drying period, hardening and shrinkage of the product, in addition to significant changes in color, taste, appearance and chemical composition after the drying (ONWUDE; HASHIM; CHEN, 2016; SADEGHI; KESBI; MIREEI, 2013).

In this context, many works have been developed for improvement in the quality of dried products and the development of economically and energy-efficient technologies. In general, these works propose the

associated use of different techniques or technologies, such as intermittent heat application (ESTURK, 2012; FILIPPIN et al., 2018), vacuum drying (WANG et al., 2018), microwave drying (SOYSAL et al., 2009; ZIELINSKA; MICHALSKA, 2016), infrared drying (CHAYJAN; DIBAGAR; ALAEI, 2017), ultrasound drying (KOWALSKI et al., 2016), ohmic heating (MORENO et al., 2016) and others.

2.3. Microwave

Microwaves are electromagnetic waves, ranging from 300 MHz to 300 GHz and wavelengths from 1m to 1 mm, within the electromagnetic spectrum (CHANDRASEKARAN; RAMANATHAN; BASAK, 2013). Intrinsic property is the energy of electromagnetic waves in thermal energy.

The microwaves are generated by an oscillator tube, whose most common type is magnetron, capable of converting power supplied by the source (60 Hz) into electromagnetic energy at the microwave frequencies. The alternation of the electric fields promotes the direction change of the polarized molecules rotation according to the orientation of the electric field. The most common domestic and industrial frequencies are 2450 and 915 MHz, respectively, indicating the reversal of the rotation direction of polarized molecules 2.45 billion times per second and 915 million times per second, respectively (DATTA; ANANTHESWARAN, 2001).

In the magnetron, a constant potential difference is applied between the anode (hollow circular cylinder) and the cathode. The electrons are accelerated from the cathode to the anode, but the presence of a strong magnetic field from the electromagnet placed between the two

poles causes the electrons to describe a spiral trajectory. Afterwards, by a more complex mechanism, the emission of electromagnetic waves occurs by an antenna placed directly on the anode (CHANDRASEKARAN; RAMANATHAN; BASAK, 2013).

The propagation of the electromagnetic wave generated in the oscillator occurs through waveguides, which are highly conductive metal tubes that direct the wave to the injection cavity. The injection cavity consists of the chamber of metal walls that act as a Faraday cage, preventing the waves from flowing out of the microwave oven. The injection cavity door and the lamp cavity are both covered by metal grids. The holes in these grids are small in comparison to the microwaves wavelength, therefore, the grids act as metal plates (VOLLMER, 2004).

The injection cavity interacts between the electromagnetic waves and the dielectric material to be heated takes place. The metallic walls promote numerous reflections of the electric field, these reflections, in turn, promote the phenomenon of interference, in which zones of reinforcement are observed contrasting with adjacent zones of annulment of the electric field intensity. The diversity in the intensity of the electric field at different points inside the chamber is one of the biggest problems in the use of microwaves to heat foods. Heterogeneous heating can be overcome by the association of techniques such as the intermittent application of energy, injection cavity project, sample rotation, microwave power limitation, the vacuum use (ESTURK, 2012; KUMAR et al., 2016; SILVA; MARSAIOLI JÚNIOR, 2003).

2.3.1 Microwave heating mechanisms

The instantaneous heating provided by the microwave energy is the result of two main mechanisms, dipole rotation and ionic polarization, consequence of the interaction of the food chemical constituents with the electromagnetic field.

The moisture presence in the sample causes dielectric heating due to the bipolar nature of water molecule, which causes its align according to the field direction when exposed to an electric field. Due to the high frequency of the electromagnetic field, the polar molecules spin millions of times per second to maintain alignment with the field direction. The molecules permanent rotation causes intermolecular friction and the hydrogen bonds rupture during the rotation of the water molecules dipoles, which generate heat and, consequently, increase the material temperature (CHANDRASEKARAN; RAMANATHAN; BASAK, 2013; SINGH; HELDMAN, 2009). Microwave heating can also occur by the electrophoretic migration of free salts into an electric field, causing the rapidly direction variation, whose collision between accelerating ions releases kinetic energy in the heat form (MUJUMDAR, 2007). Therefore, the aqueous and polar ionic constituents of foods, and their associated solid constituents, have a direct influence on the heat mechanism (MARSAIOLI JÚNIOR, 1991).

There are many factors influencing the microwave heating, and the most important are the dielectric properties, the field penetration depth and the energy absorbed by the sample. The material dielectric properties reflect the interaction between the dielectric material and the

applied electromagnetic field, that is, its ability to convert microwave energy into heat. The dielectric constant (ε') refers to the ability of a material to couple with microwave energy depending on to the electromagnetic field distribution in the product matrix. The loss factor (ε") expresses the propensity of materials to dissipate electromagnetic energy as heat (ORSAT et al., 2007). The relative permittivity (ε*) is the property that expresses the relation between the storage and the dissipation of the applied electric energy. The real part (ε'), constant dielectric, indicates the electric energy storage ability. The imaginary part (ε") represents the electric energy ability dissipation, and is described as (Equation 1) (VENKATESH; RAGHAVAN, 2004):

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

where $j = \sqrt{-1}$, is the phase shift between the real (ε') and imaginary (ε") portions of the dielectric constant.

The dissipation factor (tan δ) indicates the material ability to be penetrated by an electric field and to dissipate that energy in form of heat (CURET; ROUAUD; BOILLEREAUX, 2014). It is described as (Equation 2):

$$\tan\delta = \frac{\varepsilon'}{\varepsilon''} \quad (2)$$

Penetration depth (D_p) is defined as the distance into a sample at which the applied energy at surface is dissipated at 1/e (Euler number e ≈ 2.718) (VON HIPPEL, 1954). The microwaves penetration extent inside the material influences the temperature profile inside the sample (DATTA; ANANTHESWARAN, 2001)

This can be expressing in terms of the dielectric properties as the material and is given as (Equation 3) (VON HIPPEL, 1954):

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1+\left(\frac{\varepsilon'}{\varepsilon''}\right)^2}-1\right]^{\frac{1}{2}} \quad (3)$$

Where λ_0 is the microwave wavelength in free space.

The dielectric materials answer to an electric field is the increase in rotational and vibrational energy. However, the dielectric properties vary with the applied field frequency, temperature, moisture content, salt content and other solutes, and product particle density (HOLTZ et al., 2010). The food moisture content presents great importance in the process, besides being the most common dipole in biological materials, the water has high relative permissiveness (ε^*) and dissipation factor (tan δ). Thus, the reduction in the moisture during the drying extension causes the reduction in the dielectric constant (ε') and loss factor (ε"). Consequently, the moisture content and its state of mobility influence the material dielectric properties (VENKATESH; RAGHAVAN, 2004). In addition to the dielectric properties, the material heating is also related to the microwaves propagation governed by the Maxwell equations (referring to electromagnetic waves) and the thermal and transport properties that regulate heat and mass transfer both in conventional heating processes with the dielectric (YANG; TANG, 2002).

The energy absorbed (P_a) by the sample is given by the Equation 4 (ORSAT et al., 2007):

$$P_a = 2\pi f \varepsilon_0 \varepsilon'' E^2 \quad (4)$$

where P_a (in Wm^{-3}) is the energy developed per unit volume, *f* is the electromagnetic wave frequency in Hertz (Hz), ε_0 is the vacuum absolute permittivity ($8.854188x10^{-12}$ Fm^{-1}), ε" is the loss factor, and E is the electric field (in Vm^{-1}) strength.

Mujumdar (2007) proposes a classification for materials according to their interaction with the electromagnetic fields, establishing four categories. The conductors are materials with free electrons, such as metals, that reflect electromagnetic waves and are used to contain and give direction to electromagnetic waves, such as in waveguides. The insulators consist of electrically non-conductive materials, such as glass, ceramic and air, act as insulators, being transparent to the electromagnetic waves, reflecting and absorbing them in an insignificant way. The dielectrics, which are materials that absorb electromagnetic energy and convert it into heat, such as water, oils, wood, food. The fourth category is the magnetic compounds, defined as materials, such as ferrites, which interact with the magnetic component of the electromagnetic wave, is often used as shielding devices that prevent the electromagnetic energy escape.

In addition to the dielectric properties of the material and the microwave frequency, the microwave oven design, the position of the sample in the oven, the density, chemical composition, sample loading and sample geometry are factors that may also influence the microwaved food processing (SOSA-MORALES et al., 2010).

2.3.2. Microwave food drying (MWD)

The convective drying presents low drying rates in the final period of the process, extending the total drying period. Moreover, the prolongation of this period leads to a higher heating of the product, with possibility of thermal degradation of interest compounds and decrease in the dried product quality (ZHANG et al., 2006).

The main MWD attribution is to achieve high rates of mass and heat transfer. This is due to the electromagnetic waves that promote the instant volumetric heating in dielectric materials, being absorbed more intensely in the wet regions compared to drier regions. The drying rate is accelerated by the formation of vapors inside the food matrix, generating an internal pressure gradient, which promotes rapid water outflow (PU; SUN, 2017; ZHANG et al., 2006). The microwave energy use allows shortening the total drying time and improving the product obtained quality.

The MWD process occurs in a different way from the convective drying mentioned above. In their analysis, three periods are established (BAL et al., 2010; BOURAOUI; RICHARD; DURANCE, 1994):

(1): The heating period in which the microwave energy is converted into thermal energy, vaporizes the moisture inside the wet material and raises its temperature. The vapor generated in this process causes the vapor pressure inside the food to be greater than the vapor pressure in the environment; this gradient starts the moisture loss product to the environment.

(2): The temperature stabilization period, in which microwave energy converted to thermal energy is used to vaporize moisture, and no longer to heat the product. Moisture vaporization rates at this stage are the highest, but may vary at each point in the food, depending on the local rates of conversion of microwave energy into thermal energy.

(3): Period of drying reduction rates and product temperature elevation. In this step, the converted thermal energy is greater than the energy demand used in the vaporization because the product moisture content is greatly reduced at this stage. Although the reduction of the dielectric properties decreases the microwaves energy conversion to the heat, the temperature of the product can still continue to rise, resulting in extremes of overheating and carbonization.

The literature describes the MWD advantages compared to conventional convective drying (DEMIRHAN; OZBEK, 2010; WANG et al., 2013; WOJDYLO et al., 2013; ZIELINSKA; SADOWSKI; BŁASZCZAK, 2015):

a) Efficiency: heating is selective because, in general, the energy goes to the solvent, not to the sample. The heating occurs only in the sample, not requiring air or oven heating;

b) Non-destructive: drying can be done at low temperatures, since evaporation does not occur on the surface; there is no need to keep it at a high temperature;

c) Migration reduction: solvent is extracted from the matrix in the vaporized form, reducing the transport of other materials to the surface;

d) Leveling effects: heating tends to the wet areas;

e) Process duration: the drying times may be reduced by 50 % or more;

f) Operating system: reduced space, reduced handling;

g) Product Structure: texture components which offer sharpness and rehydration ability can be ensured by rapid heating;

h) Nutrients preservation: compared to other drying processes, the microwaves were related to the vitamins, antioxidants and proteins preservation;

i) Sensorial quality: optical proportions maintenance such as color and appearance, besides taste and smell.

In addition to these advantages, Vadivambal and Jayas (2010) point out that the rapid heating, volumetric heating, is an environmentally clean process and low operating costs are advantages of using microwaves in drying processes.

Many investigations have been conducted on the food products changes in quality characteristics due to the variation in the microwave power in microwave drying process. The variation in the microwave drying power of pumpkin slices from 100 W to 250 W resulted in the bioactive compounds degradation, such as polyphenols, carotenoids and chlorophyll a, in addition to reducing the antioxidant capacity (NAWIRSKA-OLSZANSKA; STEPIEN; BIESIADA, 2017). Different results were observed in the apples slices microwave drying, when increasing application power from 180 W to 540 W improved the retention of phenolic compounds and antioxidant activity (AL JUHAIMI et al., 2016). It is believed, however, that nutrient degradation is related to the sample exposure temperature and time, and not directly to microwave

power. High microwave potentials can shorten the drying process duration, improving the retention of thermo sensitive compounds (AL JUHAIMI et al., 2016), this effect is observed as long as the process time reduction is significant. Musielak and Kieca (2014) described the variation influence of microwave power, from 150 W until 300 W at four levels, during red beetroot and carrot microwave vacuum drying. The higher the power, the less time necessary to dry the material, however, this drying acceleration caused appearance damage, color change, β-carotene degradation to both of the dried materials.

The energy efficiency was related to the microwave energy use by several works (DARVISHI et al., 2013; HAN et al., 2016; ZAREIN; SAMADI; GHOBADIAN, 2015). The lower energy consumption was reported by Darvishi et al. (2013) (200 W to 500W) and Zarein, Samadi and Ghobadian (2015) (200 W to 600W) when they used higher microwave power in the sardines and apple slices drying, respectively. The authors related the reduction in process time as the factor that culminated in energy savings.

The texture, shrinkage and rehydration capacity of microwave dried products are improved by the use of lower microwave potencies due to the minimization of damage to cellular tissues (HORUZ; MASKAN, 2015; SARIMESELI, 2011). In the MWD of slices of pumpkin, Nawirska-Olszanska, Stepien and Biesiada (2017) reported that the hardness of the product was reduced with the use of higher microwave power (comparing the range of 100 W to 250 W), due to the partial dissolution of the middle lamella during the application of the microwaves. In the drying of eggplant and pomegranate seeds

(AYDOGDU; SUMNU; SAHIN, 2015; HORUZ; MASKAN, 2015), the shrinkage was reduced and the rehydration increased by the use of microwave, comparing with the convective drying.

2.3.3. Microwave vacuum food drying (MWVD)

The pressure reduction inside the drying chamber (vacuum establishment) is used in order to minimize the product quality (BÓRQUEZ; MELO; SAAVEDRA, 2015) degradation. The product dried in vacuum systems quality is maintained by two routes: increase drying rates and oxidative processes reduction.

In vacuum drying, the vaporization occurs with lower energy demand, since the vacuum reduces the boiling water point, facilitating the vaporization inside the product. In addition, reducing the pressure in the chamber causes water vapor molecules to migrate faster to the product surface, due to the lower surface vapor pressure. This condition creates a large vapor pressure gradient between the interior the surface of the product, resulting in higher drying rates. Thus, the vacuum application in drying systems promotes drying at a lower temperature than under atmospheric pressure for the same drying rate. Control under oxidative degradation processes during vacuum drying is due to the absence of oxygen in contact with the product. Consequently, this condition contributes to the maintenance of color, texture and taste of dry products. Vacuum drying is especially suitable for products that are heat sensitive, such as fruits and vegetables, whose composition is abundant in bioactive molecules (PU; SUN, 2017).

The main disadvantage to the use of vacuum in drying processes is the large operational cost, due to the need to promote the vacuum in the chamber for a long period of time. However, the vacuum association to microwave energy can promote rapid drying processes under reduced temperatures, ensuring the highest quality of the final product in terms of taste, aroma, texture, appearance and nutritional components.

As for the inherent advantages of dried products in MWVD systems, Setiady et al. (2009) evaluated several methods of potatoes drying, and observed a smaller shrinkage and the development of porous structure due to the application of vacuum and the vapor high internal pressure. In addition, the porous structure resulted in more complete and faster rehydration. Therdthai and Northongkom (2011) in addition to these characteristics, also observed a reduction of 90 % in drying time and greater preservation of b^* (yellowness) in vacuum-drying of *Boesenbergia pandurata* rhizomes than in convective dried samples.

In MWVD of sweet potato with lychee snacks, Qiao, Huang and Xia (2012) observed that the higher potencies use reduced drying time and nutrient degradation. Huang et al. (2011) reported the reduction in time and energy consumption for MWVD of apples and potatoes, compared to drying by freeze-drying. The antioxidant capacity and retention of anthocyanins were higher in vacuum-dried blueberries compared to convective processes and microwave drying associated with convection (ZIELINSKA; MICHALSKA, 2016).

Kwok et al. (2004) observed that the MWVD of species *Amelanchieraln ifoliale* species berries increased the content of anthocynanins and phenolic compounds, which are associated with

antioxidant capacity, comparing with convective dried seeds. MWVD was shown to be as advantageous as freeze-drying in carotenoid retention at carrot slices and vitamin C retention from apples slices, and more efficient than convective drying (CUI et al., 2008). Drying of gooseberry pulp sheets in MWVD, the microwave power has a higher effect to increase the drying rates than the vacuum pressure, however, both contributed with the drying rate of the process, producing high quality snacks (ZHENG et al., 2013).

The green tea leaves MWVD analysis showed that there was no significant effect under the color and polyphenols content during drying at various microwave potencies. Drying under reduced microwave potencies was significant in minimizing antioxidant activity and catechin content losses (HIRUN et al., 2014).

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SECOND SECTION
ARTICLE 1

MICROWAVE AND MICROWAVE-VACUUM DRYING OF PERUVIAN CARROTS (*ARRACACIA XANTHORRHIZA* BANCROFT) ROOTS: DRYING KINETICS, PHENOLIC COMPOUNDS, β-CAROTENE, SHRINKAGE, REHYDRATION, COLOR AND TEXTURE.

Running title: Microwave drying of Peruvian carrots roots.

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Abstract - Peruvian carrot is a root from South America. Despite its nice taste and health-promoting effects, commercialization of Peruvian carrot is restricted due to its short shelf life and post-harvest losses. The goal of this work was to analyze the influences of the variation of microwave power level and pressure in the quality attributes of Peruvian carrot chips obtained by microwave (MW) and microwave vacuum (MWV) drying. The comparison with convective drying at 70 ºC (CD-70) showed that the MW and MWV technologies substantially improved quality of the chips. It was found that a shortening in the drying time caused by the microwave power level controlled partially the textural collapse, increased rehydration and crispness, besides reduced hardness and shrinkage characteristics and preserved β-carotene content. However, it also promoted phenolic compounds degradation and color changes. The vacuum application (MWV) preserved phenolic compounds, β-carotene and color changes. However, it did not influence the physical characteristics. The results suggested that MWV drying at higher power level of Peruvian carrot chips were preferable to produce chips with acceptable physical and nutritional quality, because the carotenoids and phenolic compounds were satisfactory retained, rehydration and textural parameters were great and there were minimal shrinkage and color changes.

Keywords Microwave power level; catechin; chips.

1. INTRODUCTION

The Peruvian carrot (*Arracacia xanthorrhiza* Bancroft) also known as arracacha or "little cassava", is a root vegetable from South American. The Peruvian carrot root is essentially energetic food. Besides, it presents significant levels of vitamin A, carotenoids, minerals and may be characterized as a nutraceutical food. Peruvian carrots present numerous health benefits. It is recommended for diets of babies and young children, convalescing patients and elderly (Albano et al., 2014) due the high digestibility of its starch (Rocha et al., 2011). Despite the high agronomic yield, the major problem for storing Peruvian carrot is it short shelf life due to its high moisture content (Albano et al., 2014). Therefore, Peruvian carrots can be conserved by drying, producing ready to eat healthy snacks or ingredients for soups, puree and children foods. The most popular drying method applied to an industrial scale is the convective drying (CD). Although the simplicity of the convective process, it has many limitations with regard to quality of dried product. The high temperature of air drying and exposure to oxygen contribute to the degradation of bioactive compounds, changes in volume, texture and color, besides the process present low energy efficiency and very long drying time (Junqueira et al., 2017; Zielinska et al., 2017). The quality loss during drying can limit the market value and the demand for dried foods.

Due to several limitations of CD, the implementation of alternative drying method, as microwave drying (MW) (Junqueira et al., 2016; Junqueira et al., 2017) and microwave-vacuum drying (MWV) (Corrêa et al., 2011; Zielinska et al., 2017), has been highlighted.

Microwave drying (MW) is a drying method that preserves heat sensitive compounds and saves energy and time, due the microwave heating mechanism (volumetric heating). The microwaves generate an oscillating

electric field when it incident on wet point into the food matrix. The high frequency of the microwaves causes internal friction of molecules, mainly due to dipole characteristics of water molecules, causing an instantly vaporization of them (Chandrasekaran et al, 2013). The high amount of vapor inside the material leads to a gradient between the surface and internal part of the material and speeds up moisture transfer (Roknul et al, 2014). The intense mass transfer rate shorten the drying time, improving several quality attributes, as shrinkage (Song et al., 2015; Junqueira et al., 2017), color changes (Esan et al., 2015), rehydration (Zielinska et al., 2016) and preserving vitamins and antioxidants compounds. Vacuum drying is considered a useful procedure for food drying. The low pressure reduces the water boiling point, making the water to vaporize at a lower temperature than in atmospheric condition. The use of vacuum in the microwave vacuum (MWV) drying facilitates the vaporization, reinforcing the pressure gradient observed at microwave drying (MW), which causes an even faster evaporation of water at a relatively low processing temperature (Qing-guo et al., 2006). Moreover, the absence of oxygen step down the oxidation reactions and it allowing to significantly color, texture, and flavor quality improvement.

To ensure the quality of dried food products, parameters as shape, color, texture, flavor and nutritional characteristics may be preserved (Link et al., 2017). The collapse of the structure is a main alteration in dried quality products, but it must be controlled. The collapse can reduces the porosity of dried materials, influencing flavor retention, shrinkage, crispness, hardening and rehydration capacity (Yi et al., 2016). The nutritional compounds losses also can be evaluated. The significantly heat sensitivity of pigments and nutrients of most fruits and vegetables, causing significant loss of the original color and content of vitamins, antioxidants and other nutrients (Esan et al., 2015).

The objective of this study was to analyze the quality of Peruvian carrots chips submitted to microwave (MW), microwave vacuum (MWV) and convective drying (CD) observing the influences of the variation of microwave power level and the vacuum application with respect to drying time, color, β-carotene retention, phenolic compounds, shrinkage and rehydration.

2. MATERIAL AND METHODS

2.1. Sample preparation

Fresh Peruvian carrots roots (*Arracacia xanthorrhiza* Bancroft), were purchased in the local market (Lavras, Minas Gerais state, Brazil). The roots were whole, healthy and free of any strange odor. The whole Peruvian carrots were stored in a refrigerator at 4 ± 1 ºC prior to use. After peeling, the Peruvian carrots were cut in to disk shaped (30.10 ± 0.11 mm diameter, 2.35 ± 0.34 mm thickness) with the aid of a stainless steel mold. The Peruvian carrots slices received a blanching pretreatment (100 ºC; 30 s), before the drying, in order to reduce the initial enzymatic activity (Pedreschi et al., 2011), followed by an ice bath (60 s). After treatment, excess water on the product surface was removed by gently blotting with absorbent paper and samples were immediately dried. The physical and chemical characterization of fresh and blanched Peruvian carrots are presented in Table 1.

2.2. Drying treatments

The Peruvian carrots slices were subjected to convective drying at 70 °C (CD-70), microwave (MW) drying at three microwave power levels and atmospheric pressure and microwave vacuum (MWV) drying at three microwave power levels and absolute pressure of 26.5 kPa, totally seven treatments (Table 2). The experiments were performed until an average final

moisture content of 0.08 ± 0.02 kg H_2O kg^{-1} dry basis (d.b) was reached, which was suitable for safe storage. In each batch, 50 ± 1 g of blanched slices were dried. Each experiment was performed in triplicate and the average values were reported.

2.2.1 Microwave and microwave vacuum dryer

The microwave vacuum dryer, which operates under vacuum and atmospheric pressure, consists in a modified domestic microwave oven (Electrolux, Model MEC41, Joinville, Brazil) with internal capacity of 31 L, maximum microwave power output of 1000 W at a frequency of 2450 MHz. A container of polypropylene was used as the vacuum chamber due its mechanical resistance and low dieletric constant (Monteiro et al., 2015) in the interior of the oven. Peruvian carrots sliced were placed in the vacuum chamber on a teflon tray, that is also transparent to microwave.

The vacuum chamber was connected to a vacuum pump (DVP, model - LC.305, Rome, Italy) and to a semi analytic balance (accuracy ± 0.001 g) (Ohaus, model Adventure ARC120, Nanikon, Switzerland). A computer recorded changes in the weight of the samples each 10 s. The vapor from the samples was condensed and collected in a glass trap, helping to protect the vacuum pump. After adaptations, the domestic microwave oven was tested with a microwave oven survey meter (Icel, MW 2020, Manaus, Brazil).

2.2.2. Convective dryer

The samples were submitted to convective drying (CD) in a tunnel dryer (Eco Engenharia Educacional, model MD018, Brazil) with the parallel flow at 70 °C and 2 m s^{-1}. During the convective drying, the mass of the samples was monitored using a digital balance (accuracy ± 0.01 g) (Marte Científica, AD 33000 model, Brazil) coupled to the sample holder.

The experimental conditions were performed at the microwave power levels of 428.09 ± 33.95 W (MW-400); 259.80 ± 31.63 W (MW-250) and 105.16 ± 23.85 W (MW-100). These microwave power settings were measured according "IMPI 2-Liter" (Buffler, 1993). The microwave vacuum experiments were carried out at absolutely pressure of 26.5 kPa, at the same microwave power levels (MWV-400; MWV-250 and MWV-100). Before each trial at MWV batches, the weighing system was set to zero under absolute pressure of 26.5 kPa. After drying, the Peruvian carrot chips were cooled in a desiccator at room temperature and divided in two groups. One of them was immediately analyzed about moisture, color, shrinkage, rehydration and texture characteristics; and the other group was packed in opaque polyethylene pouches and stored at -18 °C before analysis of β-carotene content and phenolic compounds.

2.3. Quality characteristics of the dried product

2.3.1. Moisture content

The moisture content of the fresh, blanched and dried samples was measured by applying the standard method 934.06 proposed by Association of Official Analytical Chemist [AOAC] (2010).

2.3.2. Identification and quantification of phenolic compounds

The phenolic compounds extracts of Peruvian carrots were prepared according to Ramaiya et al. (2013). 2.5 g of sample were homogenized with 20 mL of methanol (70 %, v/v) HPLC grade (JP Baker) for 1 h at ultrasound bath (Unique, model USC 2850A, Indaiatuba, Brazil), at room temperature. Then, the extract was centrifuged for 15 min at 25000 *g* at 4 °C (centrifugal SP Labor

SP701, Presidente Prudente, Brazil). Subsequently the extracts were filtered through filter paper (Quanty, Brazil) and before injection the samples were filtered in polyethylene 0.45 μm porosity Millex HV filtering units (Millipore, Brazil).

The identification and quantification of phenolic compounds were analyzed using a HPLC system (Shimadzu, Prominence model, Japan) comprised of a high-pressure pump (Shimadzu, LC-20 AD model, Japan), an auto sampler (Shimadzu, SIL-M 20A model, Japan) and a diode array detector (DAD) (Shimadzu, SPD-M20A model, Japan). The following chromatographic conditions were used: HPLC system, DAD; Shim-pack VP-ODS (250 × 4.6 mm 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 of 2 % (v/v) acetic acid in deionised water and mobile phase B consisted of methanol 70 % (v/v), deionised water 28 % (v/v) and acetic acid 2 % (v/v). The flow-rate of the mobile phase was 1 mL min^{-1} at 15 °C and gradient elution method. The injection was conducted with a volume of 20 μL and the detection was performed at 280 nm. Phenolic compounds were identified and quantified by comparing their retention time to known previously injected standards (chlorogenic acid, catechin, p-coumaric acid and caffeic acid). The results of triplicates were expressed as milligrams per kilograms (mg kg^{-1} d.b.)

2.3.3. β-carotene retention

Total carotenoids were assessed according to the methodology described by Rodriguez-Amaya (2001) with adaptations in which 1 g of Peruvian carrot chips was used. The carotenoids were exhaustively extracted with cold acetone, partitioned into petroleum ether and washed with distilled water. The determination of β-carotene retention considered the initial β-carotene content variations in different batches of samples after blanching process.

Determination of total carotenoid content was performed by measuring the absorbance of β-carotene, which is the predominant Peruvian carrot carotenoid (Pedreschi et al., 2011) in a UV/Vis spectrophotometer (Varian, model Cary 50 Probe, Australia) at 450 nm, which correspond to β-carotene determination. β-carotene content was calculated according the Equation 1.

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

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 of β-carotene $(100\ g)^{-1}$ (d. b.) and the β-carotene retention was expressed in percentage related with each batch.

2.3.4. Color parameters

A colorimeter (Konica Minolta Co., Model CR-400, Osaka, Japan) was used to determine the color parameters of fresh, blanched and dried samples. The color was expressed by the CIE L^* a^* b^* space for the 10º standard observer and the D 65 standard illuminant. L^* values, which determine how dark or light the color is, ranged from zero (black) to 100 (white) and a^* (green to red) and b^* (yellow to blue), as defined by CIE (Commission Internationale de L'Éclairage). These color parameters were used to calculate the Chroma (C^*) and hue angle (h°), according to Equations 2 and 3. The chroma (C^*) indicates color saturation, which is proportional to its intensity, ranging from an opaque to vivid from 0 to 60. Hue angle represents the color tone by identifying the red (h° = 0º), yellow (h° = 90º), green (h° = 180º) and blue (h° = 270º) colors. One reading was

performed per chips surface by placing the colorimeter head directly above the slice. Five samples were evaluated for each treatment.

$$C^* = \left(a^{*2} + b^{*2}\right)^{1/2} \quad (2)$$

$$h(°) = \tan^{-1}\left(b^*/a^*\right), \text{ when } a^*>0 \quad (3a)$$

$$h(°) = 180 + \tan^{-1}\left(b^*/a^*\right), \text{ when } a^*<0 \quad (3b)$$

2.3.5. Volumetric shrinkage

The volumetric shrinkage was determined by measuring the area and the thickness of the samples. Measurements of the area were obtained by analysis of images with the free software Image J® 1.47t, which provides the sample area by converting the pixels in the image in real dimensions, from a known scale (Mendonça et al., 2017). The images were captured with a digital camera (Sony DSC-WX50/B model, Manaus, Brazil) and transferred to a computer to be processed with Image J software. For each sample, the thickness was observed at five different points with the aid of a digital caliper (Western, DC-6 model, Beijing, China). The percentage of shrinkage of dried Peruvian carrot chips was calculated as follows (Equation 4):

$$\%\text{Shrinkage} = \frac{V_0 - V_d}{V_0} \times 100 \quad (4)$$

where V_0 is the volume of the blanched Peruvian carrot chip (cm^3) and V_d the volume of the dried Peruvian carrot chip (cm^3). Four samples were evaluated for each treatment.

2.3.6. Texture

A compression test was performed to evaluate hardness and crispness of Peruvian carrot chips, which was determined using a texturometer (Stable Micro Systems, TA-X2T, Surrey, UK) which was equipped with a 5 mm spherical probe (P/5S) (Stable Micro System). The samples were placed on a hollow planar base, and the force was applied to the sample using the probe at a constant speed of 2 mm s^{-1} until the sample was cracked. The maximum compression force and the number of peaks in the force-deformation curve of each sample were considered as an indication of hardness and crispness of sample, respectively (Zielinska et al., 2015). Data were analyzed by the software of Texture Exponent 32 (StableMicro System Ltd., Surrey, UK). From the force curve, the following parameters were extracted: maximum force/hardness (N) and number of force peaks (counted when the peak had a value higher than the threshold value of 0.049 newton). All the tests were performed at room temperature. Ten replications were performed for each treatment.

2.3.7. Rehydration

The rehydration capacity of dried Peruvian carrots chips was quantified using the coefficient of rehydration (COR) and the rehydration ratio (RR) (Ramallo & Mascheroni, 2012). The determinations were conducted with immersion in deionised water at 100 °C for 2 h (Mendonça et al., 2017) because a probable application of the Peruvian carrots rehydrated in instantaneous soup or child food, added to boiling water, is expected, where the rehydration process takes place at high temperatures and short times. The rehydration ratio (RR) is defined as the mass ratio of rehydrated sample to that of dry sample (Equation 5).

$$RR = \frac{m_{rh}}{m_{dh}} \quad (5)$$

The coefficient of rehydration (COR), which indicates the degree of weight recovery with respect to the fresh product, is calculated according to Equation 6:

$$COR = \frac{m_{rh}(100 - X_0)}{m_{dh}(100 - X_{dh})} \quad (6)$$

Where m_{rh} is the mass of rehydrated sample (g); m_{dh} is the mass of dehydrated sample (before rehydration); X_{dh} is the moisture content (% wet basis: g water per 100 g of matter) of sample after drying; X_0 is the moisture content (% wet basis) of fresh sample, previous to drying. The measurements were carried out in triplicates.

2.4. Statistical analyses

Experimental data were statistically analyzed using one-way variance analysis carried out in order to assess differences amongst dried sample measurements under specific conditions. Disparities between means were compared using the Tukey's test. Statistical significance was expressed at the 0.95 probability level ($p \leq 0.05$). These analyses were performed using the software Statistica 8.0 (StatSoft Inc., Tulsa, USA).

3. RESULTS AND DISCUSSION

3.1. Blanched and fresh samples characteristics

Physical and chemical characteristics of fresh and blanched Peruvian carrots slices are presented in Table 1. Similar characteristics for fresh sample were observed for Matsuguma et al. (2009), Pedreschi et al. (2011) and Carmo and Leonel (2012). After blanching the average moisture increase due the water

absorption that occurs during immersion in hot water, despite it was not significantly ($p > 0.05$). A slightly quality parameters change, as color, β-carotene and phenolic compounds content was notice, it was also previously descripted by Pedreschi et al. (2011). The variation of chemical compounds can be due to the oxidation, thermal degradation or lixiviation of soluble molecules, as acid caffeic.

Table 1 – Physical and chemical characteristics of fresh and blanched Peruvian carrot slices.

Parameter	Fresh	Blanched
Moisture content [g (100 g)$^{-1}$] w.b.	73.25±4.04^{a}	76.92±3.75^{a}
Color parameters		
L*	71.60±2.03^{a}	59.08±2.57^{b}
a*	-2.57±1.01^{a}	-4.86±0.88^{a}
b*	32.23±2.76^{a}	36.01±4.92^{a}
hue	93.85±2.01^{b}	97.75±1.42^{a}
C*	32.33±3.58^{a}	36.35±4.92^{a}
β-carotene [mg (100 g)$^{-1}$d. b.]	887.49±9.00^{a}	619.57±8.05^{b}
Phenolic compounds [mg kg^{-1}d. b.]		
Catechin	498.40±7.06^{b}	583.92±5.56^{a}
Chlorogenic acid	1319.58±131.19^{a}	1049.00±73.48^{b}
p-Coumaric acid	191.25±0.58^{a}	190.12±2.03^{a}
Caffeic acid	148.93±35.36^{a}	35.05±1.41^{b}

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

3.2. Drying characteristics of Peruvian carrots chips

The changes in moisture content of Peruvian carrots chips dehydrated by (a) convective drying at 70 °C (CD-70) and (b) microwave (MW) and microwave vacuum (MWV) at different microwave power level are show by Figure 1. Similarly to early studies (Lin et al., 2010; Roknul et al., 2014; Apinyavisit et al., 2017), MW and MWV drying reduced the drying time (Table 2) when compared to CD-70. The duration of the drying process was reduced

twenty times, from 120 minutes at CD-70, to approximately six minutes, at MWV-400 treatment.

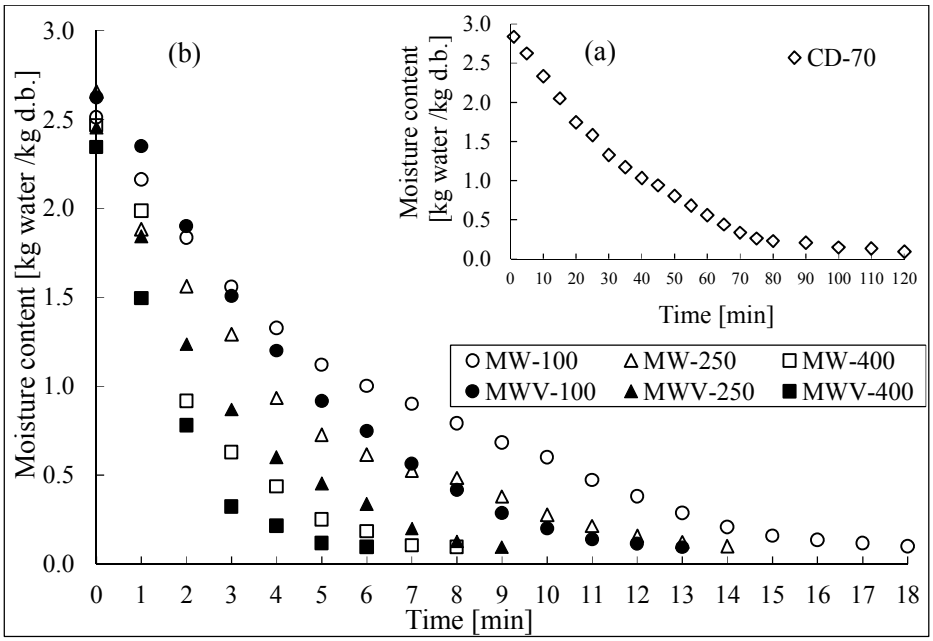

Figure 1 – Drying kinetics of Peruvian carrots chips dehydrated by (a) convective drying at 70 °C (CD-70) and (b) microwave (MW) and microwave vacuum (MWV) at different microwave power level.

Table 2 - Drying times of Peruvian carrots chips subjected to different drying methods.

Code	Drying method	Drying time [min]
CD-70	Convective drying at 70 °C 2.5 m s^{-1}	120.00±14.14
MW-400	Microwave at 428.09±33.95W	8.00±0.94
MW-250	Microwave at 259.80±31.63W	14.58±0.35
MW-100	Microwave at 105.16±23.85W	18.08±0.36
MWV-400	Microwave vacuum at 428.09±33.95W and 26.5 kPa	6.00±0.23
MWV-250	Microwave vacuum at 259.80±31.63W and 26.5 kPa	9.17±0.47
MWV-100	Microwave vacuum at 105.16±23.85W and 26.5 kPa	13.00±0.95

Average value ± standard deviation (n = 3). CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

The faster drying observed at microwave involved the heating mechanisms promoted to the microwaves application. The microwaves penetrate into the moist inner core water molecules, causing the quick internal vaporization due the selectively heated, named volumetric heating. The internal vaporization create a vapor pressure gradient between the superficies which cause an intense flux of water out of the inner of the sample (Chandrasekaran et al., 2013; Roknul et al., 2014). Thus, the high moisture content allow a greater volumetric heating, making the microwave drying a rapid drying process. Therefore, microwave power level increasing, greater amount of microwave energy being absorbed causing volumetric heating, which increase the amount of the internal vapor generation, decreasing the drying time. Similar results have previously reported for longan (Apinyavisit et al., 2017), durian (Bai-Ngew et al., 2011) and mushroom (Giri et al., 2007) in MW drying.

The result also showed that the MWV treatment presented shorter drying time than MW treatment, at the same microwave power level. This result shows the vacuum effect to reducing drying time. At low pressure, the boiling pointing of water is reduced (approximated 66 ºC at 26.5 kPa), accelerating the evaporation rate, consequently increasing the mass transfer and drying rates while decreasing the drying time (Apinyavisit et al., 2017). In Figure 1, it can be observed that the samples drying at microwave vacuum method (MWV-400; MWV-250 and MWV-100) had a large extent of high drying rate period, comparing MWV and MW kinetics in each microwave power level. At the end of the drying, the local moisture content is reduced, so the microwave volumetric heating was not able to maintain the high drying rates, because the low moisture content with in the wet slices (Yan et al., 2013). Thus, the vacuum application at microwave drying (MWV) increase the drying rate at low local moisture content, when the drying is usually slowly.

3.3. Color

One of the most important criteria for consumer acceptance and the success of the product is color. Undesirable changes in the color of a food may lead to a decrease in its quality and marketing value. A decrease in lightness (L^* value) or in hue (hue° value) is considered as an indicator of color degradation for carotenoids as they relate the heat sensitivity of pigments (Aral and Beşe, 2016). Table 3 presents the mean values and standard deviations of the lightness (L^*), Chroma (C^*), hue angle (hue°) of surface color measurements of different dried method.

Table 3 - Values of color parameters (L^*, $C^*$and hue°) and β-carotene retention obtained for Peruvian carrot chips in different drying methods

Drying method	L^*	C^*	Hue [°]	β-carotene retention [%]
CD-70	62.37 ± 0.81^{d}	30.57 ± 1.53^{d}	84.59 ± 1.80^{cd}	57.38 ± 0.24^{e}
MW-400	61.76 ± 0.20^{d}	37.35 ± 0.9^{c}	82.49 ± 1.85^{d}	68.95 ± 1.44^{c}
MW-250	68.63 ± 0.50^{bc}	36.59 ± 1.50^{c}	85.40 ± 1.11^{bc}	63.29 ± 0.58^{d}
MW-100	67.88 ± 1.07^{c}	50.04 ± 1.44^{ab}	87.85 ± 0.54^{b}	79.78 ± 1.37^{b}
MWV-400	66.96 ± 0.94^{c}	47.77 ± 0.47^{b}	87.59 ± 0.24^{b}	81.41 ± 1.38^{b}
MWV-250	71.09 ± 1.57^{a}	37.74 ± 1.31^{c}	90.54 ± 0.54^{a}	67.09 ± 1.00^{c}
MWV-100	70.35 ± 1.39^{ab}	50.83 ± 1.54^{a}	90.51 ± 0.25^{a}	88.87 ± 1.16^{a}

Average value ± standard deviation (n = 4 for β-carotene retention and n = 5 for color parameters). Mean followed by different superscript letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test. CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

MWV samples at lower levels of microwave power were lighter (higher L^* value), presented more vivid color (high C^* value) and yellowness (hue ≈ 90°) than those obtained by CD-70 and high microwave power level, with or without vacuum. The vacuum use at low microwave power developed dried chips with a higher degree of lightness ($p \leq 0.05$). This is probably because the low chips temperature (associate with low microwave power and vacuum drying) and lower amount of oxygen in MWV, which prevent formation of

brown pigment during the drying process. Higher microwave power level, consequently higher sample temperature, caused reduction of the L^* values ($p \leq 0.05$), which is indicative of a darkening due to degradative oxidation reactions of carotenoids and Maillard reaction that might occur at the high product temperature and oxygen presence (Qing-guo et al., 2006) and promote darker samples.

The microwave use at low power provided higher vividness chips color (high C^*value). Except at the MWV-400 sample, in this case, although the high microwave power, and consequently high sample temperature, the relatively short-term duration of the treatment, produced chips with high quality than MWV-250 treatment. Clearly, samples exposed to oxygen and high temperature for a long time (CD-70 and MW samples) presented lower values of Chroma.

MWV and MW at low power showed higher hue angle value (h°), close to yellow. The yellowness is absolutely desirable for Peruvian carrot chips because the high content of β-carotene, that are naturally present in the Peruvian carrot. CD-70 and MW samples at high power level decreased the angle value ($p \leq 0.05$), distancing from yellow and tending to red. This may be due to the degradative reactions of β-carotene pigment, mentioned above, which yielded a more opaque and less intense yellow color, resulted of the long-term of high temperature reached to the sample and the presence of oxygen. According to Apinyavisit et al. (2017) high temperatures causes a darker and yellow color. However, in this study, was observed a decreased in the yellowness (decrease of hue angle). This is probably because the thermal degradation of pigment β-carotene associated to yellow color of Peruvian carrot chips that might decrease the amount of this color on the dried product.

Several studies have shown that MWV drying conditions, the low microwave power, related to low sample temperature, and oxygen restriction in the microwave vacuum chamber decreased the auto-oxidation of the pigments

resulting in increased lightness and hue angle (Therdthai and Zhou, 2009; Bai-Ngew et al., 2011; Zhang et al., 2011; Hirun et al., 2014) supporting the results observed in the present study. Consequently, coupling a low microwave power with vacuum could be a good alternative for improving the color of Peruvian carrots chips, as observed at MWV-100 treatment.

3.4. β-carotene

Carotenoid is an important nutrient in the human diet because β-carotene is a precursor of vitamin A. Furthermore, β-carotene is a group of carotenoid responsible for the yellow colors of several vegetable and animal tissues. It is well-know that heat, oxidation and other conditions can promote the carotene degradation (Saini et al., 2015). Therefore, carotene content was an important quality index for evaluating the effect of MW-related drying.

The β-carotene retention of Peruvian carrot chips dried using different methods is shown in Table 3. It can be seen that the β-carotene retention in MWV Peruvian carrot chips were greater than that using MW, at the same microwave power level ($p \leq 0.05$). For CD-70 products, the lowest retention of β-carotene is observed. As expected, the carotenoids degradation diminished by drying time reduction, as MW and MWV employee.

Although the use of vacuum, with the same microwave power, apparently results in samples with higher carotenoid content, considering that the samples were previously blanched, the lower carotenoid degradation is due to the short drying time associated to MWV treatments, since that the oxidative enzymes were considerable inactive.

An intense reduction in the β-carotene retention was reported when increase microwave power level ($p \leq 0.05$) of 100 W to 250 W. It is due of the increasing microwave power cause increase in temperature, that might

degradation of heat sensitive molecules as β-carotene. Similar results were reported by Al Juhaimi et al. (2016) in apple microwave drying.

However, comparing microwave power only in the high and intermediate level (range of 250 to 400 W), an opposite effect of the power increase was observed. This result can be explained such that the higher microwave power could shorten the drying process duration, if the drying time reduction is expressive, thus improving the retention heat sensitive compounds (Wojdyło et al., 2013). High-drying temperature and long-drying time, besides oxygen exposure, have significant effects on β-carotene degradation (Yan et al., 2013), these results are in accordance with hue angle color parameter (yellowness) (Table 3).

3.5. Phenolic compounds

HPLC - DAD/UV-Vis analysis identified the presence of the chlorogenic acid, catechin, p-coumaric acid and caffeic acid in fresh and blanched Peruvian carrots (Table 1). Similarly to previously published data of fresh Peruvian carrots cream variety (Pedreschi et al., 2011), chlorogenic acid was the main phenolic acid. However, the presence of catechin was not previously described for cream variety, but it was identified at the present work for roots of the cultivar Amarela de Senador Amaral. The variations of these chemical properties may depend upon the climate, season, horticultural practices and variety. In potatoes, catechin was reported, reaching 2040 mg kg^{-1} d.b. (Valcarcel et al., 2015; Akyol et al., 2016). In general, values of each phenolic compound are within the range reported for Peruvian carrots (Pedreschi et al., 2011) and others roots as sweet potato (Lebot et al., 2016) and black carrots (Akhtar et al., 2017).

Table 4 shows the content of each phenolic compound of chips dried by different methods. The chips dried by CD-70 presented lower content of

chlorogenic acid and catechin ($p \leq 0.05$), which might be due to the longer drying time, resulting in greater loss of heat sensitive molecules, as phenolic and as also described for carotenoids. The p-coumaric content was not significative influenced to drying method ($p > 0.05$), with a slightly higher content at MW-400 samples. For all drying method, the caffeic acid was completely degraded and was not reported for chips (data not shown).

Table 4 - The content of phenolic compounds by HPLC in Peruvian carrot chips obtained after different drying methods (mg kg^{-1} d.b.)

Compounds	Chlorogenic acid	Catechin	*p*-Coumaric acid
CD-70	225.01±33.78^{c}	101.06±0.26^{f}	53.39±0.41^{b}
MW-400	344.82±9.94^{bc}	181.46±5.34^{c}	62.46±2.89^{a}
MW-250	445.68±1.68^{b}	137.36±3.93^{de}	55.85±0.40^{b}
MW-100	444.44±2.99^{b}	148.85±7.23^{d}	53.71±0.32^{b}
MWV-400	412.12±14.54^{b}	119.68±15.38^{ef}	54.01±1.52^{b}
MWV-250	582.64±36.13^{a}	335.32±0.39^{b}	52.98±0.60^{b}
MWV-100	689.40±72.27^{a}	367.66±3.77^{a}	54.85±0.71^{b}

Average value ± standard deviation (n = 3). Mean followed by different superscript letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test. CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

In general, the chlorogenic acid and catechin content of samples dried by MWV at lower microwave power level was slightly higher than that of MV. The highest content of chlorogenic acid and catechin was found in Peruvian carrot slices dried at MWV-100 and MWV-250 drying method. Despite the blanching, which also contributed to reduce the peroxidase enzyme action, and, consequently the intense oxidative degradation of these molecules, the vacuum use and the low microwave power level presented effects on the preservation of phenolic compounds ($p \leq 0.05$). It can be explained by the fact that those factors contribute both to reduce Peruvian carrots chips temperature during drying, lower microwave energy and water boiling point, lower the drying temperature of chips. The greater preservative effect of phenolic compounds due the use

MWV at lower power level was also reported to potato and apple restructured chips (Liu et al., 2016).

3.6. Texture

Texture is considered one of the most important quality attribute of ready-to-eat snack foods and criteria concerning consumer acceptance of snack chips (Yan et al., 2013). Figure 2 shows the texture properties of Peruvian carrot chips in each drying treatment. The texture was considered in terms of hardness and crispness as indicators of quality of the dried Peruvian carrot chips. The crispness was presented with a number of peaks. The higher number of peaks the higher crispness.

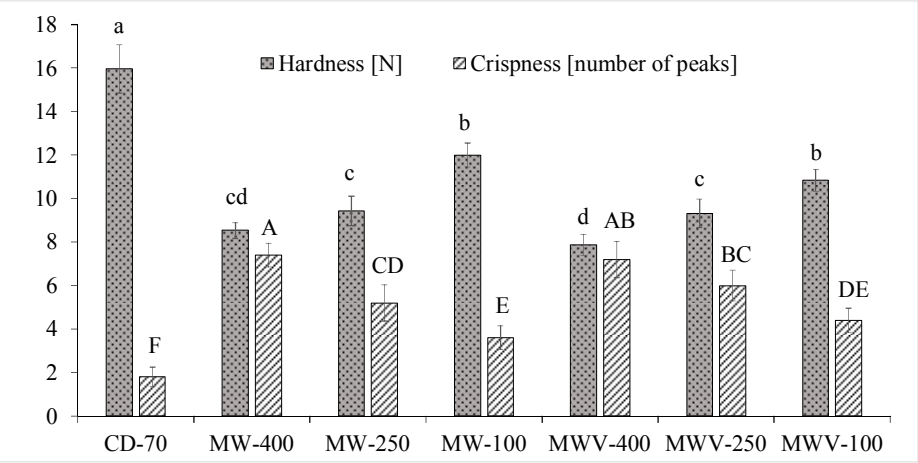

Figure 2 – Effect of different drying methods on the texture of Peruvian carrots chips. Different upper-case letters indicate a significant difference ($p \leq 0.05$) in the crispness data; different lowercase letters indicate a significant difference ($p \leq 0.05$) in the hardness data) according to Tukey's test (n = 10). CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

The results show that Peruvian carrot chips subjected to MW or MWV presented a significant decrease in hardness ($p \leq 0.05$) compared to CD method, while the number of peaks were higher (Figure 2), indicating that less case

hardening occurred with MW and MWV dried Peruvian carrot chips. Moreover, the results also showed that increasing microwave power level decrease the hardness and increase the crispness of chips from MW and MWV methods (Figure 2) ($p \leq 0.05$). Besides the literature describe that firmness of dehydrated chips increase linearly with temperature (Gulati et al., 2015), higher microwave power level application at MW and MWV drying results in a porous structure, causing lower hardness and higher crispness of Peruvian carrot chips.

Similarly, durian chips from MWV presented a significant decrease in hardness and increase in crispness comparing with CD, the increase in the MW power level intensified this behavior (Paengkanya et al., 2015). MW and MWV drying could developed a puffed structure at dried products (Yan et al., 2013), as microwave energy is applied volumetrically, the intense internal vapor flux generated for the pressure differential between food matrix and drier chamber, and for rapid increase in the temperature by microwave application (Therdthai et al., 2011) will cause greater puffing. This mechanism results in crispier and softer chips structure. However, in the current study, vacuum application at MWV did not have a significant effect on texture of the dried Peruvian carrot chips ($p > 0.05$). Other researchers who studied the MW and MWV at restructured potato and apple chips (Huang et al. 2011) and potato (Yan et al., 2013) have also reported similar results. MW and MWV at higher microwave power level have lower hardness and higher crispness, which suggest that the taste of these chips would be somewhat more desirable as compared to the CD and to the lower microwave power chips.

3.7. Volumetric Shrinkage

Table 5 shows the volumetric shrinkage of Peruvian carrots chips microwave and convectively dried. MW and MWV dried samples decreased the shrinkage ($p \leq 0.05$) comparing with CD-70 method. The shrinkage during

convective drying is associated with a low transport rate of water and prolonged drying time, causing collapsed and tough texture (Song et al., 2009; 2015).

Table 5 - Values of volumetric shrinkage [%] obtained for Peruvian carrot chips in different drying methods

Drying method	Volumetric shrinkage [%]
CD-70	64.38 ± 4.78^{a}
MW-400	35.32 ± 2.93^{d}
MW-250	46.15 ± 2.36^{b}
MW-100	42.32 ± 1.59^{bc}
MWV-400	26.02 ± 3.40^{e}
MWV-250	37.60 ± 1.22^{cd}
MWV-100	44.52 ± 1.43^{b}

Average value ± standard deviation (n = 4). Mean followed by different superscript letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test. CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

Moreover, microwave power level and vacuum decreased volumetric shrinkage ($p \leq 0.05$). A drying study on green peas also indicated that microwave power and vacuum both were significant to reduce shrinkage (Chauhan and Srivastava, 2009).

High microwave power help to intensify the mass transfer within the chips matrix, because microwave heating create a large vapor pressure gradient between the center and the surface of the products (Chandrasekaran et al, 2013). The high internal vapor pressure causes greater puffing, as mentioned above. Yan et al (2013) also reported the effect of microwave power reducing shrinkage in sweet potato dices. Those authors suggested that the vapor formed cannot escape fast enough through the lower porosity tissue structure of food, leading in a low percentage of shrinkage.

The vacuum application improved drying rate at MWV, resulting in a less shrunk structure. It could be attributed to the fact that the lower pressure, the lower is the boiling point of water, resulting in a greater driving force for mass

transfer, which could help to prevent tissue shrinkage. This is also consistent with the results of Lyu et al. (2017) and Paengkanya et al. (2015).

As mentioned earlier, microwave power level has been the same effect to decrease the hardness and the shrinkage of dried chips. It was possible to relate the increase in hardness (Table 4) and the shrinkage of Peruvian carrot chips (Table 5). According to Huang et al. (2011), there are an effect of shrinkage of tissue structure increasing the hardness, due the collapse structure.

3.8. Rehydration

The rehydration characteristics of the dried product is related to physical and chemical changes of samples during drying. Rehydration is an important step in the utilization of dried food, an optimal rehydration condition can be used as a quality index of dehydrated product (Link et al., 2017). Experimental measures of the moisture content in fresh Peruvian carrot roots ranged between 0.75 and 0.82 g water g^{-1} (wet basis, w.b.). In the experimental conditions of the present study, samples reached high moisture values after rehydration ranged from 0.49 to 0.66 g water g^{-1} w.b., if the moisture was calculated with the assumption that the dry matter remains constant during the rehydration process. The overall high rehydration may be that the samples were in the form of thin slices and water permeated through the surface into the interior of the samples easily because of large contact areas and thinness of slices.

Rehydration ratio (RR) values for Peruvian carrot chips during 2 h of rehydration are detailed in Figure 3, these coefficients are expressed as the average of results of three drying-rehydration tests. It was observed that rehydration ratio (RR) increases with the rehydration time. The water uptake took place in the first hour of immersion, then reached to the equilibrium. Moreover, RR increase faster (high rehydration rates) in the first 20 min than in the end of the process. Similar rehydration kinetics behaviour was reported for

pitaya chips (Yi et al., 2016). At the beginning of the rehydration curve, MWV dried chips presents higher rehydration rates then MW and CD dried chips, which could be partially due to well expanded structure attributed to vacuum and microwave application, which reduce the internal resistance to water absorption.

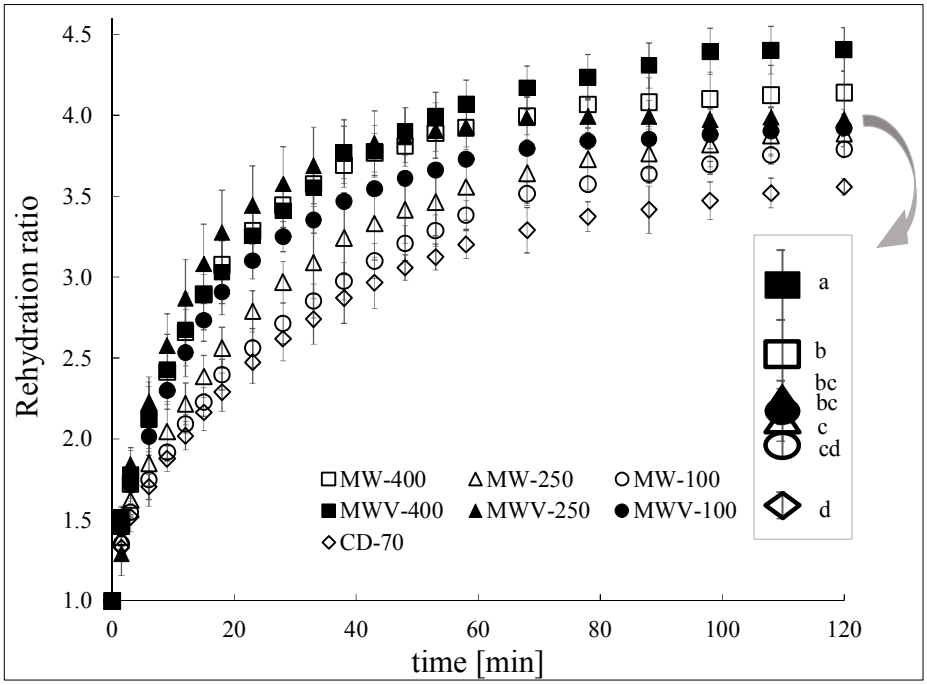

Figure 3 – Rehydration ratio of Peruvian carrot chips dried by different drying method. CD: convective drying. MW: microwave. MWV: microwave-vacuum drying. Mean followed by different letters indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

The rehydration properties (COR and RR) of the MW and MWV samples are bigger than those of CD-70 ($p \leq 0.05$) (Table 6 and Figure 3). The possible reason for it can be attributed to the fast drying process, to the development of pores opening during the intense flux of vapour through the matrix of Peruvian carrot (Kumar et al., 2017; Yan et al., 2010), and the less shrinkage in the structure of the samples (MW and MWV), which in favors of

the rehydration of products. According to Ramalho and Mascheroni (2012) at severe drying conditions, as observed at CD-70, irreversible structural collapse have taken place in vegetal tissue during drying, leading to a loss of rehydration capacity.

Table 6 - Coefficient of rehydration (COR) of Peruvian carrot chips in different drying methods. These values were calculated with experimental data obtained towards the end of 2 h of rehydration.

Drying method	COR
CD-70	0.61 ± 0.05^{d}
MW-400	0.78 ± 0.02^{ab}
MW-250	0.74 ± 0.05^{abc}
MW-100	0.69 ± 0.03^{bc}
MWV-400	0.80 ± 0.03^{a}
MWV-250	0.74 ± 0.02^{abc}
MWV-100	0.68 ± 0.02^{c}

Average value ± standard deviation (n = 3). Mean followed by different superscript letters in the same column indicate a significant difference ($p \leq 0.05$), according to Tukey's test. CD: convective drying. MW: microwave. MWV: microwave-vacuum drying.

In regard to microwave power level effect, it can be noted that the average values of RR and COR parameters indicate that the extent of rehydration also increased with increasing power level. However, there were no statistical differences ($p > 0.05$) among COR and RR values related to microwave power level, except between MWV400 and MWV-100. However, at low and intermediate power levels (MWV-250; MW-250; MWV-100; MW-100) significative shrinkage was also observed (Table 5). These results indicated that changes in the rehydration properties could be such explained by an interaction between less shrinkage and better rehydration characteristics, explained by the fact that the preservation of the internal tissue structure reduces the internal resistance to water penetration during rehydration. Similar results were obtained in mango chips using explosion puffing drying. Zou et al. (2013) reported that the rehydration ratio of mango chips is affected by the shrinkage of the samples.

Regarding to vacuum, it was observed significant effect of MWV comparing MW samples only in the RR values, at maximum microwave power level (MWV-400 and MW-400), even though the average values indicate a tendency to vacuum improve rehydration properties. This result is in accordance with Chauhan and Srivastava (2009); Kumar et al. (2014) and Kumar et al. (2017).

4. CONCLUSION

MW and MWV allows fast moisture removal that result in short drying times comparing with CD-70, moreover improving the quality of chips. From the viewpoint of physical changes the increase in the microwave power level affected positively the dried Peruvian carrot chips, promoting great rehydration and crispness characteristics and controlled shrinkage and hardness. The shorten in the drying time caused for microwave power level preserves β-carotene content. On the other hand, the microwave power level, that is associated with the heating of the product, degraded the phenolic compounds and promote color changes. The vacuum application at MWV preserves phenolic compounds, β-carotene and color, however it did not significantly to the physical characteristics. The MWV at low and intermediate power level results in nutritional preservation of Peruvian carrots, except for β-carotene, and using high microwave power level the chips presents more favorable physical characteristics, higher β-carotene retention and slight color change. Thus results suggested that the use of the higher microwave power level and vacuum at MWV process for Peruvian carrot chips were preferable to produce chips with acceptable physical and nutritional quality. At this condition the carotenoids and phenolic compounds are satisfactory retained, rehydration and textural coefficients were great and there were minimal shrinkage and color changes.

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ARTICLE 2

MICROWAVE-VACUUM DRYING OF RESTRUCTURED PERUVIAN CARROTS CHIPS: EFFECT OF TWO-STAGE POWER LEVEL ON THE KINETICS AND QUALITY PARAMETERS

Running title: Microwave-vacuum drying of restructured Peruvian carrots chips

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Abstract - Peruvian carrot is a root rich in bioactive compounds, whose commerce and consume is restricted due its short shelf life. The objective of the present work was to evaluate the microwave-vacuum drying (MWV) of restructured Peruvian carrot chips, by constant and two-stage power level, about the influence of microwave power level at drying time, kinetic parameters, energy consumption and preservation of carotenoids and phenolic compounds. The power level increases the drying rate, sample temperature, energy consumption and reduces the drying time at constant microwave power level treatments. However, the drying rate at the end of the drying was not influenced by microwave power level. At two-stage power level treatments, the drying time was similar to that observed at constant power level trials. The temperature and the energy consumption was lower and they was not affected by power level. Better preservation of nutritional compounds was provided by two-stage at higher power level (MWV-5-1) and at lower and constant power level (MWV-1). Page's and Fick's models presented both good fit to experimental data. The use of two-stage at higher power level (MWV-5-1) saved energy, reduces the drying duration and contributes to preserves bioactive molecules of restructured Peruvian carrots chips.

Keywords - *Arracacia xanthorrhiza*; β-carotene; Mathematical model; Energy consumption.

1. INTRODUCTION

Peruvian carrot (*Arracacia xanthorrhiza*, Bancroft), also known as arracacha, is a root vegetable originally from the Andean South America. One of their nutritional interest is related to their very amount of high resistant starch (Lovera et al., 2017). Furthermore, Peruvian carrot roots are source of carotenoids (pro-vitamin A) and phenolic compounds (Pedreschi et al., 2011), significant levels of minerals such as calcium, phosphorous and iron. Due to this set of attributes, it may be characterized as a nutraceutical food (Albano et al., 2014).

Its harvesting time is limited as well as its storage life due to high respiration rate and fast enzymatic and oxidative degradation process. It can be directly consumed as soups, purées and stews or processed in to starch (Lovera et al., 2017). Also, it 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 protection technique especially used for preserving of fruits and vegetables. It contributes to inhibit enzymatic and microbial activity, extending the shelf life of products. Also, it provides a reduction in size and transportation costs (Sahin; Doymaz, 2017). However, drying process are related to the degradation of heat sensible compounds, due the long-term exposition to high temperatures (Link et al., 2017). Therefore, the parameters of drying implementation must be controlled. Microwave vacuum (MWV) drying is rapid, more uniform and energy efficient compared to conventional convective drying. The advantages of this technique is connected to the combination of both microwave heating and vacuum drying. The microwave heating generating a rapid energy transfer and the pressure decrease conferee a low process temperature and fast mass transfer (Apinyavisit et al., 2017), resulting in a very rapid, low temperature drying process, and thus it has the potential to improve

energy efficiency and reduces chemical and physical changes in dried products (Bórquez et al., 2015). Several fruits and vegetables have been successfully dried my MWV drying, include with satisfactory thermo sensitive molecules preservation, such as plum (Michalska et al., 2016); blueberries (Zielinska; Michalska, 2016), banana, grape, tomato and carrot (Monteiro et al., 2015). Several drying studies have tested the variation of drying conditions throughout the process (Kowalski; Pawlowski, 2010; Kowalski; Mierzwa, 2011; Schossler et al., 2012; Rosa et al., 2013). All of them reported improvement of product quality and energy efficiency. These advantages were confirmed for MWV when the variation in the microwave power throughout the drying was reported for beetroot and carrots (Musielak; Kieca 2014) and banana, grape, tomato and carrot (Monteiro et al., 2015).

Theoretical, semi-theoretical and empirical mathematical modeling of the drying processes can help in improving drying systems or even for the control of the drying process (Doymaz, 2017). Researchers have used theoretical and semi-theoretical models to identify the drying behavior of agricultural products, as Page's model and that derived from direct solution of Fick's second law, respectively.

Therefore, the aim of the present work was to study the influence of the power level at constant and two-stage microwave power level during microwave vacuum (MWV) drying of restructured Peruvian carrot chips, in regard to drying time, kinetic curves, energy consumption and preservation of carotenoids and phenolic compounds.

2. MATERIALS AND METHODS

2.1 Sample preparation

Peruvian carrots roots (*Arracacia xanthorrhiza* Bancroft), was purchased in a local market (Lavras, Minas Gerais, Brazil). The roots were selected according to the absence of injuries and any strange odor. The whole Peruvian carrots were washed, dried with absorbent paper for removal of excess water, and stored in a refrigerator at 8 ± 1 ºC prior the experiments. The roots were peeled, cut into cylinders (2 mm thickness and 30 mm diameter) and blanched (30 s at 100 °C) to reduce the peroxidase activity (Pedreschi et al., 2011).

2.2. Processing of restructured Peruvian carrot chips

The blanched roots were ground for 3 min using a blender (Philips Walita model RI2087) until the paste became smooth. The paste was pressed and shaped into a plate sheet (3 mm thick, 150 mm × 100 mm) inside a Teflon plate for de MWV drying trials.

2.3. Microwave vacuum (MWV) dryer

The MWV dryer consists in a modified domestic microwave oven (Electrolux, Model MEC41, Joinville, Brazil) with internal capacity of 31 L, maximum microwave power output of 1000 W at a frequency of 2450 MHz. A container of polypropylene was used as the vacuum chamber (Monteiro et al., 2015) in the interior of the oven. The vacuum chamber was connected to a vacuum pump (DVP, model - LC.305, Rome, Italy) and to a semi analytic balance (3000 g ± 0.001 g) (Ohaus, model Adventure ARC120, Nanikon, Switzerland). A computer recorded changes in the sample mass each 10

seconds, allowing the control of the process. The vapor from the samples was condensed and collected in a buffering bottle, helping to protect the vacuum pump in case of water spilling from the buffering bottle. After adaptations, the domestic microwave oven was tested with a microwave oven survey meter (Icel, MW 2020, Brazil).

2.3.1. Drying procedure

The paste sheets of Peruvian carrots were subjected to MWV dryer at five power levels and absolute pressure of 26.5 kPa. The experiments were conducted until the achievement of 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 according to the method "IMPI 2—Liter" (Buffler, 1993) and summarized in Table 1. Prior to each trial at MWV, the weighing system was set to zero under absolute pressure of 26.5 kPa. Each experiment was performed in triplicate and the average values are reported. The initial mass of sample used in each experiment was determined at 50.0 ± 0.5 g.

Surface temperature of restructured Peruvian carrot chips was measured with an infrared sensor thermometer (Fluke, 62 MAX model, Eindhoven, Holand), immediately after taking them out of the vacuum chamber at MWV dryer. The external temperature of ten points of each trial was recorded and assumed that the temperature measured with this method reflected the changes in mean temperature during MWV, as also considered for Michalska et al. (2016) and Bai-Ngew et al. (2015).

After drying, the restructured chips of Peruvian carrot were cooled in a desiccator at room temperature. Immediately it was analyzed about moisture. The β-carotene content and phenolic compounds samples were sealed in opaque polyethylene bags and stored at -18 °C for further analysis.

2.4. Analysis of drying experiments

Drying kinetics were analyzed as function of moisture ratio (MR). The dimensionless moisture content (MR) is given by Equation 1

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

where M is the moisture content (g H_2O g^{-1} dry basis), 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.]. The equilibrium moisture content (M_{eq}) value was much lower than initial moisture content and moisture content at time t (min). Therefore, its value was assumed to be zero for the drying conditions (Esturk; Soysal, 2010).

The drying rate (DR) of restructured Peruvian carrots chips during MWV drying experiments was calculated from the change in moisture ratio over drying time using the 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), t is the drying time (min).

2.4.1. Mathematical modeling of drying curves

Two exponential mathematical models were performed to determine and evaluate the mass transfer parameters of restructured Peruvian carrots chips: the empirical Page's model (Doymaz, 2012) and the semi-theoretical unidirectional diffusion model based on the second law of Fick (Crank, 1975). In these models, the moisture ratio (MR) is defined by Equation 1.

Page's model

The empirical Page equation is presented by Equation 3.

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

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

Fick's model

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

As a result, Fick's unidirectional diffusion equation (Crank, 1975) becomes, Equation 4:

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

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

The effective diffusivities were obtained using the non-linear regression (Quasi-Newton) from software STATISTICA 8.0® (Statsoft, Tulsa, USA), considering the expansion of the equation with five terms.

2.4.2. Energy consumption (EC)

The energy consumption (EC) is defined as the energy required to evaporate unit mass of water from the sample, is given by the Equation 5 (Kumar et al., 2017). It was expressed in terms of MJ $kg^{-1}$of water removed.

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

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

2.5. Quality characteristics of the dried product

2.5.1. Moisture content

The moisture content of the samples was measured by applying the standard method 934.06 proposed by Association of Official Analytical Chemist [AOAC] (2010).

2.5.2. β-carotene content

Total carotenoids were determined following methodology described by Rodrigues-Amaya (2001) with adaptations. The dried samples were cooled to cryogenic temperature and then ground in an analytic mill (Ika, A11, Brazil). The powder (1.0 g) was placed in a flask (250 mL) and the carotenoids were exhaustively extracted with cold acetone, partitioned into petroleum ether and washed with distilled water. Determination of total carotenoid content was performed by measuring the absorbance of β-carotene, which is the predominant Peruvian carrot carotenoid (Pedreschi et al., 2011) in a UV/Vis spectrophotometer (Varian, model Cary 50 Probe, Australia) at 450 nm, which correspond to β-carotene determination. β-carotene content was calculated according the Equation 6.

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

where Abs is the absorbance and 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.).

2.5.3. Quantification of phenolic compounds

The dried samples were cooled to cryogenic temperature and then ground in an analytic mill (Ika, A11, Brazil). The powder (2.5 g) was placed in a flask (250 mL) and 20 mL of methanol (70 %, v/v) HPLC grade (JP Baker) was added, the solution was homogenized. The extraction flask was then placed in the ultrasound bath (Unique, model USC 2850A, Indaiatuba, Brazil), at room temperature for 1 hour. Then, the extract was centrifuged for 15 min at 25000 *g* at 4 °C (centrifugal SP Labor SP701, Presidente Prudente, Brazil), and filtered through HV Millex filter units, in polyethylene, with 0.45 μm of porosity (Millipore, Brazil) (Ramaiya et al., 2013).

The quantification of phenolic compounds were analyzed using a HPLC system (Shimadzu, Prominece model, Japan) comprised of a high-pressure pump (Shimadzu, LC-20 AD model, Japan), an autosampler (Shimadzu, SIL-M 20A model, Japan) and a diode array detector (DAD) (Shimadzu, SPD-M20A model, Japan). 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 of 2 % (v/v) acetic acid in deionised water and mobile phase B consisted of methanol 70 % (v/v), deionised water 28 % (v/v) and acetic acid 2 % (v/v). The flow-rate of the mobile phase was 1 mL min^{-1} at 15 °C and gradient elution method. The injection was conducted with a volume of 20 μL and the detection was performed at 280 nm. Phenolic compounds were identified and quantified by comparing their retention time to known previously injected standards

(chlorogenic acid and catechin). The results were expressed as milligrams per kilograms of dry basis (mg kg^{-1} d.b.).

2.6. Statistical analyses

2.6.1. Statistical evaluation of the mathematical models

Data were analyzed using Statistica software (Statistica 8.0®, Statsoft Inc., Tulsa, OK). The parameters of equations were estimated using a non-linear regression procedure. The higher the value of R-square (R^2) and the lower the value of sum square error (SSE) were chosen as the criteria for goodness of fit (Junqueira et al., 2017). This statistical parameter is calculated according to equation 7.

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

2.6.2. Statistical evaluation of the quality analysis

Data were subjected to analysis of variance (ANOVA) using software STATISTICA 8.0® (Statsoft, Tulsa, USA). Disparities between means were compared using the Tukey's test. Statistical significance was expressed at the 0.95 probability level ($p \leq 0.05$). All the experiments were carried out in triplicates.

3. RESULTS AND DISCUSSION

3.1. Drying kinetics at constants microwave power level (MPL)

Drying time (Dt) and sample surface temperature (SST) of the restructured chips of Peruvian carrots during the microwave-vacuum drying at constant power level are shown in Table 1. Drying time decreased and sample

surface temperature increased greatly when microwave power level (MPL) increased ($p \leq 0.05$). This result was expected, because the increase in the energy provision, with the increase in the microwave power level, causes faster evaporation of the moisture, resulting in a process time reduction (Chauhan; Srivastava, 2009) and an increase in the sample surface temperature (Michalska et al., 2016). The drying time required for reaching the final moisture content of samples ranged from 18.08 ± 1.06 to 47.83 ± 0.71 min, respectively from higher to lower power level. A similar effect in drying time decrease with a microwave power level increase has been reported for many products such as beetroot and carrots (Musielak and Kieca, 2014), mushrooms (Giri and Prasad, 2007) and bacterial culture (Ambros et al., 2018).

Table 1 - Drying time (Dt) and sample surface temperature (SST) for MWV restructured Peruvian carrots chips dried at constant microwave power level (MPL)

Code	MPL [W]	Dt [min]	SST [ºC]
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.

Drying rates curves for Peruvian carrots restructured chips at each MPL are shown in the Figure 1. The results showed that drying rate under higher power level was higher than under lower power level. These results corroborate the drying time (Table 1). The microwave heating happen due the phenomenon known as volumetric heating, which consists basically into the friction of permanent moment dipole molecules, as water, caused for the contact with the microwaves (Wray et al., 2015). The high kinetic energy acquired specifically

for water molecules causes the quick vaporization of then. The increase in the amount of energy dispensed to the sample increases the drying rate, reducing, consequently the duration of the drying process.

About the behavior of the drying rate during the drying process (Figure 1 (a)), it can be observed that in all experiments the drying rate curves had three defined periods. At the first period, the drying rate increases, at the second, it has a tendency to remain constant and, at the third period, the drying rate is reduced to levels close to zero, when finish the mass transfer. According to Zhang et al. (2006) the increasing drying rate period is resulted of the initial heating of the sample due the conversion of the microwave energy into thermal energy within the wet material, at this period, also known as heating period, the product temperature is rise to the boiling point of water (at the pressure used at present work, 26.5 kPa, the boiling point of the water is close to 66 ºC). Figure 1 (b) detailed report the heating period, which also show that the increase in the drying rate happen faster, higher the microwave power level.

The second period is the more relevant in terms of the moisture reduction. The high and relatively constant drying rates observed in this period are due the fact that microwave energy applied into the sample provides latent heat of vaporization of free water in the Peruvian carrots wet matrix. The moisture content maintain high the drying rate because of the volumetric heating which is related with sample moisture content (Yan et al., 2013). The constant drying rate period obtained from drying curves are illustrated in the Figure 1 (a). For MWV-1 and MWV-2, drying rate was evidently constant in the second period of drying. For higher power levels, a slight, but continuous decrease in drying rate was detected after the material reached the maximum. As in convective drying, the constant drying rate in microwave-vacuum drying is not easy to observe, due the complexity of the process. The microwave absorption is dependent of the dielectric loss factor, which in turn decrease with water

content. Then, the slight variation in the drying rate at the second drying period is due to the reduction in the dielectric loss factor (Rosa et al., 2013; Giri and Prasad, 2007). Considering that the moisture content is abundant in the food matrix at that period, increasing the microwave power (for different power level curves) the drying rate increased, and decreasing the moisture content (throughout the process) the drying rate was almost constant at each power level. It is an indication that the mass transfer probably is more influenced by microwave power level then by moisture content, at constant drying rate period. According to microwave heating theory, at high drying rates the sample temperature does not change (Zhang et al., 2006), what is a desirable attribute to drying process.

When the moisture content reaches a limier close to 0.8 g g^{-1} d.b., the drying rate is drastically reduced, beginning the reduced drying rate period, Figure 1 (c). At this period, the low water content does not favor the vapor generation, contributing to the internal resistance to mass transfer and causing reduced rates of drying and an increase in the product temperature (Zhang et al., 2006). As recovered at Figure 1 (c), it was also possible to note that, independently of the power level, all treatments presented similar low drying rates after reaches the critical moisture content. It can be used to confirm that the reduced drying rate at third drying period is due to the significance of the internal resistance to mass transfer (Giri; Prasad, 2007), but is not limited directly to moisture content, because it not reduces gradually as the moisture content in this period. Similar drastic reduction on drying rate was previously reported to Ambros et al. (2018) at microwave-vacuum drying of lactic acid bacteria.

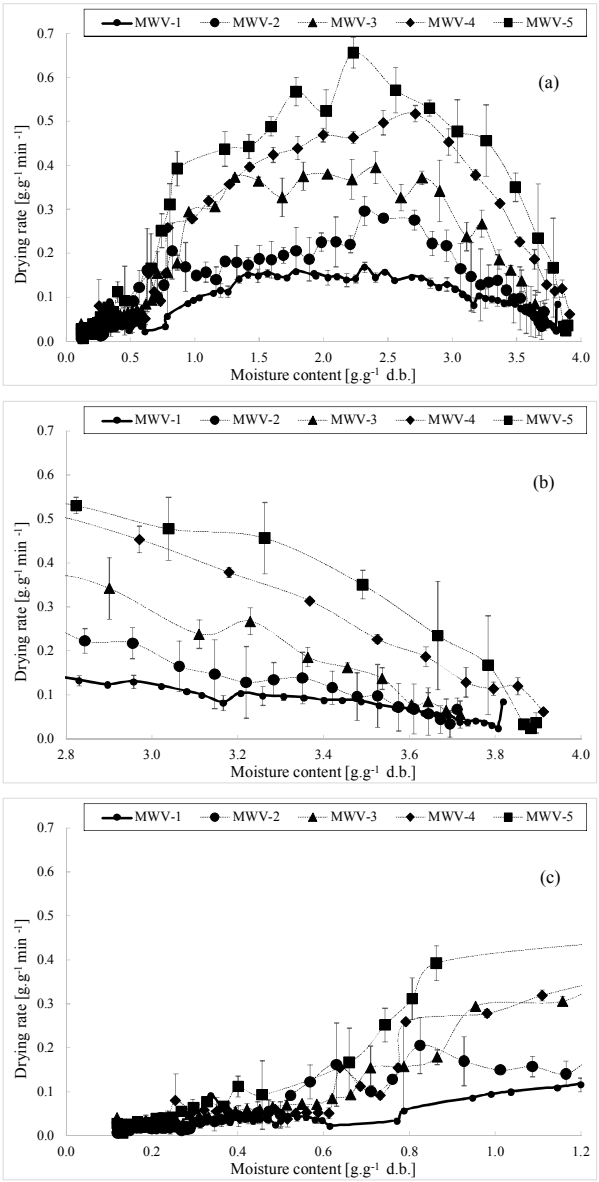

Figure 1 - Variation in drying rate with moisture content of restructured Peruvian carrots chips dehydrated under microwave vacuum at constant microwave power level. (a) All drying period. (b) Beginning of drying period. (c) Finishing of drying period.

Therefore, high MPL use is indicate to provide high drying rates at microwave drying of wet product. However, at the final stage of the drying, when the moisture reached a specific value (approximately 0.8 g g^{-1} for Peruvian carrots restructured chips), the drying rate was not influenced for the power level, probably it is influenced for the internal resistance of the food matrix, as the depletion of the dielectric loss factor. Then, the microwave power level should be reduced to save energy and prevent the possible heating of the sample (a more detailed analysis of the influence of the internal resistance of the material in the low microwave drying rate is not the objective of the present work).

3.2. Mathematical modeling of drying curves at constant MPL

The coefficients of drying models and the statistical criteria obtained by application of Page's and Fick's equation to the experimental drying data are given in Table 2.

The k coefficient of the Page's model increased from 0.1451 x 10^{-2} to 2.9216 x 10^{-2} s^{-1} with the MPL, respectively from lowest (MWV-1) to highest (MWV-5) power level. For the fitting parameter (n value), no trend was observed. The n values were more than one, similar to reported by Izli et al (2014) for carrots MWV dried and to Giri and Prasad (2007) for mushrooms MWV dried. It was observed $R^2 > 0.99$, lower SSE in all treatments when this model is employed.

Table 2 shows the results of effective diffusivity (D_{eff}) obtained with the unidirectional model of Fick (Crank, 1975). The values ranged from 1.5732 x 10^{-10} to 4.6982 x 10^{-10} m^2 s^{-1} and the R^2 higher than 0.92. It is possible to verify that the D_{eff} (from Fick's equation) and k coefficient (from Page's model) could represent clearly the effects of the microwave power level, increasing both D_{eff} and the k value with the energy microwave level used in the process.

Based on the statistical parameters of mathematical models, the highest R^2 and lowest SSE values, indicates the Page's model presented better fit than those obtained with Fick's equation. The lack of fit of the Fick's model can be due the fact that this model considers that drying rate is controlled only by internal water diffusion within solid materials, neglecting the external mass transfer resistance. However, as prior commented, the microwave power level is the major factor that limits the microwave drying rate until it reaches the critical moisture content (not the water diffusion as considered to Fick's equation). In this case, Page's model can be used to predict the drying kinetics of Peruvian carrot restructured chips obtained by microwave-vacuum drying at constant power level. The Page's equation represented properly the drying behavior of pumpkin microwave dried samples (Junqueira et al., 2017), MWV drying of leaves of *Anoectochilus roxburghii* (Zhang et al., 2014) and MWV drying of shiitake mushroom (Kantrong et al., 2014).

Table 2 - Modeling and statistical parameters of Peruvian carrot restructured chips obtained by different power level of MWV drying

Treatments				
Page's model	k x 10^2 [s^{-1}]	n	R^2	SSE x 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} x 10^{10} [m^2s^{-1}]		R^2	SSE x 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.

3.3. Drying kinetics at two-stage microwave power level

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

Drying duration and sample surface temperature of the restructured chips of Peruvian carrots at two-stage microwave power level vacuum drying are shown in Table 3. As expected, the drying time was inversely related to the power level applied at the first-stage of the process ($p \leq 0.05$), remaining at the range from 20.17 ± 0.94 to 37.92 ± 0.82 min. The drying times of two-stage treatments at the same MPL were statistically similar to those reported to constant microwave power level experiments ($p > 0.05$) (Table 1). The surface sample temperature was not influenced by microwave power level ($p > 0.05$) at two-stage treatments, because the final power level was the same for all trials.

Table 3 - Drying time (Dt) and sample surface temperature (SST) for microwave vacuum of restructured Peruvian carrots chips at two-stage microwave power level (MPL)

Code	MPL at first stage [W]	SST [ºC]	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]

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.

Drying rates curves for Peruvian carrots restructured chips obtained for two-stage microwave power level vacuum drying are shown in the Figure 2 (a), (b) and (c). These results showed that the reduction of the microwave power level at the end of the second period of the drying (almost constant drying rate period) does not change the behavior of the kinetic curves, comparing with constant power level kinetic curves (Figure 1). It was also possible to define three distinct periods: increasing drying rate period, almost constant drying rate period and reduced drying rate period (Zhang et al., 2006).

The similarity between the constant and two-stage kinetic curves at third period of the microwave-vacuum drying (Figure 1 (c) and 2(c)) confirms which was previous observed, the drying rate at this period is determined to the internal resistance of the food matrix, and not influenced to the microwave power. For this reason, the reduction of the power level at the third period of the drying does not change the drying rates.

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

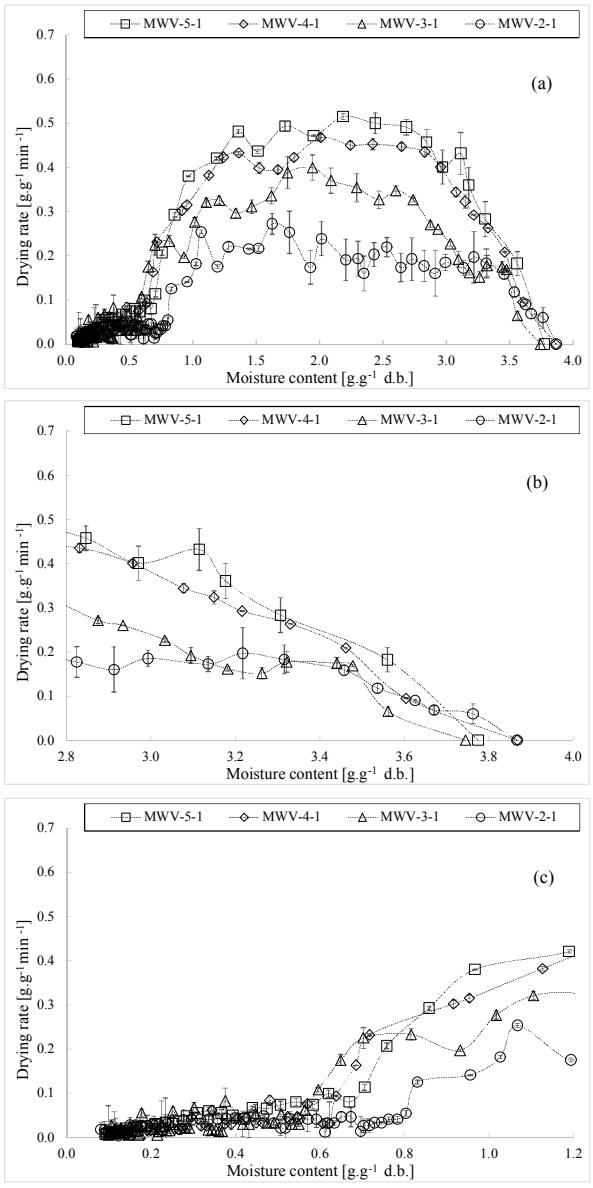

Figure 2 - Variation in drying rate with moisture content of restructured Peruvian carrots chips dehydrated under microwave vacuum at two-stage microwave power level. (a) All drying period. (b) Beginning of drying period (c) Finish of drying period.

Effective diffusivity (D_{eff}) values of Fick's model were between 2.83 x 10^{-10} and 4.31 x 10^{-10} m^2 s^{-1} (Table 4). These values are close than those observed at constant microwave power level trials (Tables 2), furthermore present the same tendency to increase with high power level. The Fick's model presented a good fit to the data when variable power level during microwave-vacuum drying was applied. The maintenance in the D_{eff} values, even with the reduction in the power level at the second-stage, was expected and are in accordance with the maintenance of the drying times and which was discussed about the no influence of the microwave power level at drying rate in the last drying period.

Table 4 - Modeling and statistical parameters of Peruvian carrot restructured chips obtained by variable power level during microwave-vacuum drying

Treatments				
Page's model	k x10^2 [s^{-1}]	n	R^2	SSE x10^4
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} x 10^{10} [m^2s^{-1}]		R^2	SSE x 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.

Although the maintenance of drying time by itself is not an advantage, it is imperative to check whether this causes a significant decrease in process energy and the influence of the reduced microwave power at the preservation of the bioactive compounds of the carrot chips restructured. Such evaluations would be other advantages in the two-stage drying process.

3.4. Energy Consumption (EC)

EC during the MWV drying at constant and two-stage power level processes was shown in Table 5. EC values ranged from 7.44 ± 0.16 to 13.11 ± 0.39 MJ kg^{-1} H_2O. In general, due the quality of the heating mechanism the drying methods employing MWV had lower EC (Jiang et al., 2017). MWV drying of green bell pepper reported the EC ranged from 6.25 to 17.04 MJ kg^{-1} H_2O (Kumar; Shrivastava, 2017).

Lowest EC were observed for the two-stage MPL treatments and MWV-1 treatment ($p \leq 0.05$). At constant MPL treatments, the lower MPL, the lower EC ($p \leq 0.05$). The use the higher microwave power, despite shorter the drying time (Table 1), increase the EC.

Table 5 - Energy consumption (EC) obtained for restructured Peruvian carrot chips in microwave-vacuum drying by constant and two-stage power level.

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.

When the two-stage power level was used, the variation at the MPL does not affected significantly the energy consumption ($p > 0.05$). The use of higher microwave power is restricted to a relatively short period from the beginning of the drying until reached 0.8 g g^{-1} (d.b.) (the critical moisture point for

restructured Peruvian carrot chips). Then, the two-stage power level can be used to save energy in microwave-vacuum drying of restructured Peruvian carrot chips, whatever the power level applied at the beginning of the process.

3.5. Carotenoid retention of restructured Peruvian carrot chips in MWV drying by constant and two-stage power level.

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 MWV-related drying. The β-carotene content of blanched Peruvian carrot was 635.32 ± 4.71 mg $(100\ g)^{-1}$ (d.b.). The β-carotene retention of restructured Peruvian carrot chips obtained at MWV drying by constant and two-stage power level is shown in Table 6.

Table 6 - Values of β-carotene retention obtained for restructured Peruvian carrot chips in MWV drying by constant and two-stage power level.

Treatments	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 indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

Great amounts of β-carotene was observed at MWV-5, MWV-1 and MWV-5-1 treatments ($p \leq 0.05$). At intermediate MPL treatments, was observed a negative effect of increase MPL at β-carotene retention ($p \leq 0.05$), especially at constant power level trials.

This result can be explained such that the expressive shorten on drying time, promoted by use of higher MPL can improve the retention of heat sensitive compounds (Wojdyło et al., 2013). While lower power level treatments, despite longer process duration, reduces its temperature, improving the carotenoid retention. Carotenoid molecule is degraded by exposure to heat for prolonged time (Al Juhaimi et al. 2016). The use of higher or lower microwave power, for both constant power level and higher power level at two-stage treatments contributed to preserve the β-carotene content.

3.6. Phenolic compounds content of restructured Peruvian carrot chips in MWV drying by constant and two-stage power level.

The major phenolic compounds at Peruvian carrots were catechin and chlorogenic acid. The amount of these compounds at blanched Peruvian carrot samples was respectively 583.92 ± 5.56 and 1049.00 ± 73.48 mg kg^{-1}(d.b). The phenolic compounds of restructured Peruvian carrot chips in microwave drying by constant and variable power level is shown in Table 7. It was found that the amount of each phenolic compound decrease with microwave drying.

The results (Table 7) also showed that restructured Peruvian carrot chips dried at lower and intermediate of constant microwave power level treatments (MWV-1; MWV-2; MWV-3) and the higher and lower power level at two-stage drying (MWV-5-1 and MWV-2-1) contained the highest amount of catechins ($p \leq 0.05$). The lowest level of catechins was found in the chips dried at MWV-5 ($p \leq 0.05$). The amount of chlorogenic acid was higher at MWV-1 and MWV-5-1 ($p \leq 0.05$). This data may be a consequence of reduction of the catechin and chlorogenic acid degradation when lower microwave power level was applied (Liu et al., 2016). High temperature induced by high microwave power might lead to faster degradation of catechins in the dried chips (Hirun at al., 2014). Increasing the power level of microwave, increase the sample temperature. The MWV-5-1 two-stage treatment presented great preservation of catechins and

chlorogenic acid. This result can be explained such that the higher microwave power at two-stage treatment could shorten expressively the drying process duration, improving the retention heat sensitive compounds even with high power exposition.

Table 7 - Values of phenolic compounds obtained for restructured Peruvian carrot chips in MWV drying by constant and two-stage power level (mg kg^{-1} d.b.)

Treatments	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 indicate a significant difference ($p \leq 0.05$), according to Tukey's test.

4. CONCLUSION

Constant MPL treatments showed that the power level affected directly the sample temperature and reduced drying time. The kinetic curves presented good fit to Page's model and kinetic parameters were influenced by MPL. The MWV drying process could be divided in three periods, and the third period of drying presents lower drying rates, independently of the microwave power level.

When two-stage power level was applied was observed that drying time decreased with the increase of power level, but it was similar to that observed at constant power level trials, at the same power level. About the sample

temperature, it was not affected by power level. Page's and Fick's model presented both good fit to experimental data.

The analyses of EC revealed that two-stage power level treatments consumed less energy per kg of evaporated water, and it was not influenced by power level at two-stage trials. For constant power level treatments, the power level increase the EC.

The use of two-stage at higher power level (MWV-5-1) and the constant power level at lower power (MWV-1) were the best treatments to preserve the amount of β-carotene, catechin and chlorogenic acid.

Therefore, the use of two-stage power level MWV drying promotes saving energy and time, and the preservation of quality attributes of restructured Peruvian carrots chips.

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THIRD SECTION

GENERAL CONCLUSION

The microwave drying of Peruvian carrots was achieved in different conditions. The microwave use results in short drying times comparing with convective process.

The use of the higher microwave power level and vacuum for production of Peruvian carrot chips were preferable to obtain chips with satisfactory retention of bioactive compounds (phenolic compounds and β-carotene) and great coefficients of rehydration and crispness, besides to minimize shrinkage and color changes.

The third period of microwave drying presents lower drying rates, regardless of the microwave power level. The reduction of the microwave power level after the critical moisture constitutes the two-stage power level MWV drying. It saves energy and time, and the preservation of amount of β-carotene, catechin and chlorogenic acid of restructured Peruvian carrots chips.