Ready-to-eat snacks from microwave dried red radishes: Quality parameters and drying kinetics

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ABSTRACT The microwave drying (MWD) of red radish slices was investigated from 90-450 W. Experimental drying curves were simulated using the Midilli–Kucuk model by means of a generalized curve. Quality of final product (color, antioxidant capacity, total polyphenols, flavonoids and ascorbic acid contents) were evaluated. High power level increased the mass transfer and the effective moisture diffusivities and shortened the drying time up to 70.73 %. Antioxidant capacity, total phenolic and total flavonoids content were found to be in the range of 0.559-1.475 mg/ g DW, 1.88-3.00 mg/g DW and 13.44-20.68 mg/g DW, respectively. Energy consumption and drying efficiency of the drying process were found to be in the range of 3.20-5.25 kWh/kg and 11.62-18.47 %, respectively.

KEYWORDS Dehydration technology; Drying kinetics modelling; Antioxidants; Functional food

1. Introduction

Radish (*Raphanus sativus L.*), a cruciferous vegetable, is a good source of natural antioxidants (phenolic compounds, carotenoids, tocopherols, and ascorbic acid) (Goyeneche et al., 2015). Due to its seasonality, dehydration technologies are used to improve the shelf life of vegetables to reduce their moisture content to such extent that microorganisms cannot grow.

Moreover, the market of dehydrated products named snacks obtained after a drying process has grown significantly in recent years to accomplish the new trends related to health care (Chacón-Orduz et al., 2017). Chips obtained from conventional hot air drying presented poor quality associated with shrinkage, dark color and hard texture. Instead, MWD showed to be a more efficient option producing higher quality dried products (Figiel, 2009). Microwaves can penetrate the foodstuff quickly and deeply, heating the entire food product from the inside to the outside and leading to a dehydrated healthy snack with a desirable texture (Jing et al., 2010; Joshi et al., 2016).

Mathematical models are useful tools to describe the behavior of drying curves and predicting drying time at various experimental conditions (Ruiz Celma et al., 2009; Akpinar, 2006; Motta Lima et al., 2000). To our knowledge, this is the first report on the process modeling and the quality features of red radish subjected to different MWD process conditions.

Therefore, the aim of this work was to evaluate the effect of different MWD conditions in red radish slices, in order to obtain healthy innovative snacks. For this purpose, drying kinetics as well as relevant quality characteristics of the final product were experimentally determined. In addition, mathematical modelling was performed to discuss the drying curve and energy consumption of the processes.

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2. Materials and methods

2.1 Plant material

Field grown red radishes (*Raphanus sativus var. sativus L.*) “Colorado Redondo” (Cherry Belle, Hazera) were obtained from a local farm in Buenos Aires Province, Argentina. They were stored at 5 ± 1 °C in the darkness prior to processing. Radish roots were separated from leaves, washed, and cut in slices (3.90 ± 0.11 mm) with a vegetable cutter. The initial moisture content (IMC) was determined gravimetrically (AOAC, 1990). The IMC was 21.39 ± 0.01 kg water/kg of dry matter.

2.2 Drying process

Microwave drying was performed with a domestic microwave oven (brand ATMA, model Easy Cook, maximum power 900 W and frequency 2450 MHz), with the following inner dimensions: height 285 mm; width 511 mm, and depth 410 mm. The oven was operated at different microwave output power levels. Based on preliminary tests, it was observed that charring and sample boiling occurred above 450W. Therefore, three power levels (90 W, 27 0W and 450 W) were selected.

In order to obtain the drying curves, radish slices were uniformly distributed on the turntable of the microwave. The charge density was 2.083 kg·m^{-2}. Slices weight was monitored using a balance (Denver, APX-1502) and drying was performed until reaching constant weight (equilibrium condition). At the end of each drying process, samples were cooled for five minutes at 25 °C and kept in hermetic polyethylene bags at -80 °C prior analysis. All measurements were carried out in triplicate.

2.3 Diffusional coefficients and models

2.3.1 Moisture diffusivity

Fick's second diffusion law (Eq. 1) was used to estimate moisture diffusion (Vega-Gálvez et al., 2012).

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4L^2}\right) \tag{1}$$

where MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m^2/s), t is drying time (s) and L is thickness (here half) of layer (m). MR of radish slices was calculated using Eq. 2:

$$MR = \frac{X_{wt} - X_{eq}}{X_{w0} - X_{eq}} \tag{2}$$

where X_{w0} is the initial moisture content (g water/g dry matter), X_{wt} is the moisture content at time t (g water/g dry matter) and X_{eq} equilibrium moisture content (g water/g dry matter).

2.3.2 Midilli-Kucuk model

The Midilli-Kucuk model (Eq. 3) was satisfactorily applied in previous work to mathematically model characteristics of agricultural products during dehydration. In addition, this selected model can be an important tool not only to improve drying processes but also minimize products damages (Lemus-Mondaca et al., 2015).

$$MR = a\exp(-ktn) + bt \tag{3}$$

2.3.3 Drying Curves Generalization

The proposed methodology of generalized drying curves is applied to the experimental drying curves (Lemus-Mondaca et al., 2015). This kind of approach is very interesting because it permits comparison of the results of different experiments by reducing them to only one set. In this case, MR is correlated to a dimensionless time variable (Eq. 4).

$$\tau = \frac{N_c t}{MR_o} \tag{4}$$

where τ is dimensionless drying time (dimensionless), t is drying time (min), MR_o is initial moisture content (dimensionless), N_c is constant rate of drying (1/min).

2.4 Energy consumption and efficiency

During microwave dehydration, specific energy consumption required (E_t) for drying a kilogram of radishes is calculated using Eq. 5 according to the work of Motevali et al. (2011).

$$E_t = \frac{P \times t}{W_0} \tag{5}$$

where E_t is the specific energy consumption required (kWh·kg^{-1}), P microwave output power (kW), t drying time (h) and W_0, the initial weight of sample (kg).

The microwave drying efficiency was calculated as the ratio of heat energy utilized for evaporating water from the sample to the heat supplied by the dryer (Soysal et al., 2006).

$$\eta_d = \frac{m_w \lambda_w}{Pa\, t} \tag{6}$$

with η_d microwave drying efficiency in %; m_w mass of evaporated water in kg; λ_w latent heat of vaporization of water (J·kg^{-1}); Pa average microwave power in W; and t time in s.

2.5 Quality parameters

2.5.1 Determination of color parameters

Color was measured by a tristimulus colorimeter (MINOLTA, CR-300), calibrated with a white standard ($Y = 92.0$, $x = 0.3133$, $y = 0.3199$). The measurements were made using a CIE $L^*a^*b^*$ color space (Lab), with L^* lightness (whiteness or brightness/darkness), a^* chromaticity on a green $(-)$ to red $(+)$ axis, b^* chromaticity on a blue $(-)$ to yellow $(+)$ axis [CIE]. Numerical values L^*, a^*, b^* were converted into total color difference (ΔE), according to Eq. 7:

$$\Delta E = \sqrt{(a_s^* - a_o^*)^2 + (b_s^* - b_o^*)^2 + (L_s^* - L_o^*)^2} \tag{7}$$

with a_s^*, b_s^* and L_s^* values of the samples and a_o^*, b_o^* and L_o^* values of the fresh slices (Goyeneche et al., 2014).

2.5.2 Determination of vitamin C content

Vitamin C (Vit C) content was determined by a titrimetric assay in triplicate. Relative content of $VITC_R$ was expressed as Eq. 8 (Goyeneche et al., 2016).

$$VITC_R = \frac{VITC}{VITC_0} \tag{8}$$

with $VITC$ content after the treatment and $VITC_0$ content in fresh samples.

2.5.3 Determination of total phenolic content (TPC)

The TPC was determined colorimetrically by the Folin-Ciocalteau method (Goyeneche et al., 2015). Results were expressed as mg Gallic Acid Equivalent (GAE)/100 g of dry weight (DW).

2.5.4 Determination of total flavonoids content (TFC)

TFC was determined according to Goyeneche et al. (2015), calculated from a calibration curve (510 nm) using Quercetin as standard, and expressed as mg Quercetin/100 g DW.

2.5.5 Determination of antioxidant capacity (AC)

AC was determined by the scavenging activity of the stable 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical following the procedure described by Goyeneche et al. (2015). Results were expressed as mmol TE (Trolox equivalent)/100 g DW.

Table 1: Empirical and kinetic parameters values and statistical tests for each MWD treatment for Midilli-Kucuk model.

Treatment	Parameters				*SSE*	*RMSE*	χ^2
	a	*k*	*b*	*N*			
90 W	0.993233	0.004267	-0.000367	1.411433	0.000058	0.007301	0.000064
270 W	0.999300	0.022800	0.000287	1.345800	0.000043	0.006483	0.000052
450 W	1.004733	0.038367	0.000267	1.369633	0.000114	0.010251	0.000140

2.6 Statistical analysis

Quality of fit of the proposed models for the drying kinetics data was evaluated by statistical tests including the determination coefficient (r^2), sum squared error (SSE) and Chi-square (χ^2) (Lemus-Mondaca et al., 2015). For the quality analysis, a randomized experimental design with a factor of MWP at three levels (90, 270 and 450 W) was applied. All determinations were performed in triplicate. The results were expressed as average ± standard deviation. ANOVA was performed (at a significance level $P < 0.05$) to determine the significance of the means. Differences among means were evaluated using the Tukey test.

3. Results and discussion

3.1 Mathematical modelling of drying kinetics

3.1.1 Effect of power level on D_{eff}

Figure 1 shows the experimental drying curves for the three working MWD power settings. All curves showed a clear exponential tendency with MR decreasing rapidly as the MWD power increased. As expected, it was observed that the drying time to reach similar moisture content decreased as MWD power levels increased.

The D_{eff} values obtained for 90, 270 and 450 W were 2.36±0.27, 5.67±1.83 and 7.98±1.77$\times10^{-10}$ $m^2 \cdot s^{-1}$, respectively. Values of D_{eff} increased with MWP. Similar results were reported by Lee et al. (2018) in radish strips dried under similar condition. Izli et al. (2021) obtained values in the order of 10^{-9} for pepino fruit slices dried under 90 to 160 W, and also reported that the lowest effective moisture diffusivity was at 90 W. Differences were statistically significant only between 90 and 450 W. This should be based on the fact that vapor pressure diminished with the decline in MWP and moisture encountered less resistance when evaporating (Izli et al., 2021). Similar values of D_{eff} were reported for garlic and onion slices (Sharma and Prasad, 2004; Sharma et al., 2005).

3.1.2 Midilli-Kucuk model

Table 1 presents the kinetics and empirical values of parameters k, n, a, and b as well as the quality of the model as affected by the different MWD power levels. In particular, k showed a positive correlation with the power level and should be assumed to be directly proportional to it. Instead, the n, a, and b values remained relatively unchanged or showed a non-clear trend, suggesting their dependence on other characteristics of the drying process. Some authors have suggested that the values of kinetics parameters were related to the moisture diffusion coefficient during drying process, which could be associated with the facility to moisture removal from the radish slices (Akpinar, 2006; Dadalı et al., 2007).

It can be observed in Fig. 1 that the Midilli–Kucuk model provided a good fit to all the experimental drying curves. Similar results were reported in previous works (Doymaz et al., 2006; Dadalı et al., 2007; Lemus-Mondaca et al., 2015).

3.1.3 Generalized Drying Curves

The possibility of fitting all the drying data to only one curve for only one generalization was evaluated. Thus, a generalized drying curve was applied to study the influence of the operational variables on the MWD behavior. The Midilli–Kucuk model was used to model the generalized drying curve as this model showed very good results, as can be seen in Fig. 2. Parameters in the Midilli–Kucuk equation are presented in Eq. 9, which also obtained a high value of $r^2 = 0.9951$. This allowed establishing a generalized Midilli–Kucuk model for estimating drying curves for any value of MWP within the range of the performed experiments (90 to 450 W), which opens new doors for further research on the application of the Midilli–Kucuk model for describing MWD of radish slices.

$$MR = 0.984 \exp\left(-2.008\tau^{1.460}\right) + 0.005\tau \quad (9)$$

Figures 1 and 2 show the experimental MR of the radish slices as function of drying times during MWD at 90, 270 and 450 W. At the beginning of the drying process the moisture content of the slices was quickly reduced. Increasing the power level from 90 to 450 W enhanced the moisture loss. Similar results were obtained in radish strips (Lee et al., 2018) and potato chips (Joshi et al., 2016). The increase in MWP from 90 to 450 W

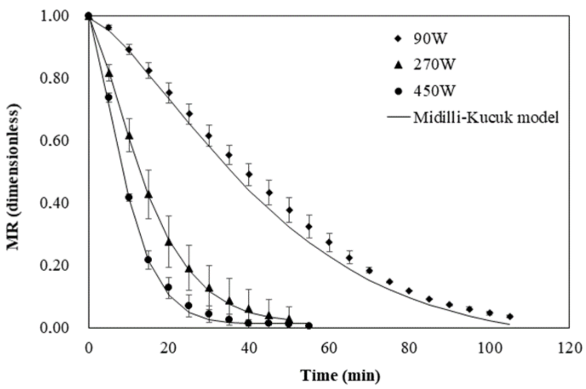

Figure 1: Experimental and simulated drying curves by Midilli–Kucuk model.

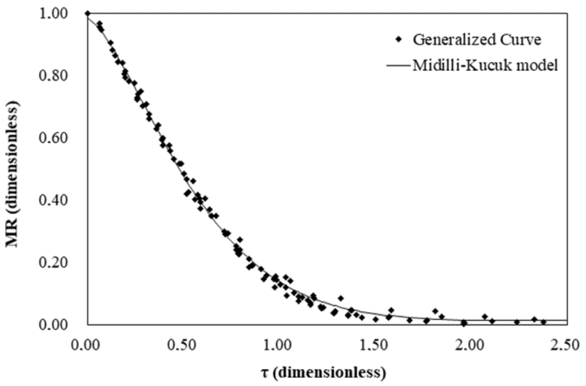

Figure 2: Generalized drying curve modeled by Midilli–Kucuk equation.

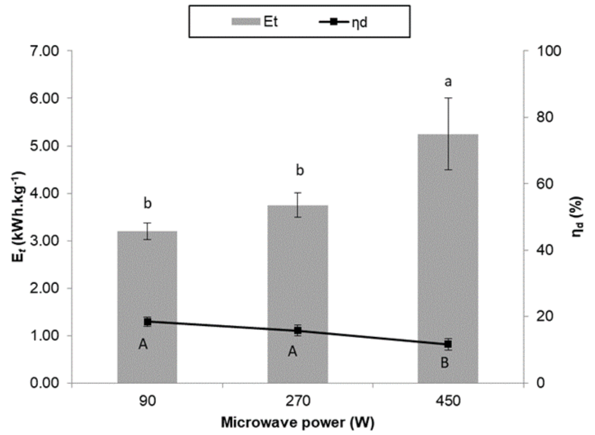

Figure 3: Specific consumption (E_t) and drying efficiency (η_d) of radish slices exposed to different microwave power levels. Values are means ± standard deviation ($n = 3$). Different letters above the bars indicate significant differences ($P \leq 0.05$).

shortened the drying time up to 70.73 %. Drying times required to reach the constant weight were 102.5, 41.6 and 30 min for MWD at 90 W, 270 W, and 450 W MWP, respectively.

Differences in vapor pressure between the center and the surface of the products generated by the higher microwave heating (MWH) power produced a faster mass transfer process. According to Bai-Ngew et al. (2011), the increased drying rate observed in durian slices exposed to MWH might have been due to a rapid process resulting in a faster rise in the sample's temperature to reach water boiling point when compared to radish results. A similar effect with MWH conditions on the rate of moisture changes was found in the drying process of potato slices (Joshi et al., 2016).

3.2 Energy consumed and process efficiency

Foodstuffs like vegetables contain polar molecules like water. Bipolar rotation is an important phenomenon which explains the heat production in a radish slice placed inside a microwave field. Water molecules generally have a random direction but inside a microwave field, they adapt themselves to the polarity of the field. The polarity changes rapidly in a microwave field. According to Motevali et al. (2011), the required specific energy increases with the microwave output power.

According to our results, at the highest microwave level, drying time decreased and the highest drying rate was achieved. Motevali et al. (2011) proposed that the increase of bipolar water molecules adapted to the polarity of the field should result in more energy being absorbed from microwaves thus generating heat and consequently increasing the sample temperature.

Figure 3 shows the energy consumed in MWD for drying a kilogram of radish slice as well as the drying efficiency of the processes. Average energy consumption and efficiency during drying of radish samples ranged from 3.20 to 5.25 kWh/kg of fresh product and 11.62 to 18.47 % for the output microwave power ($P < 0.05$). The drying efficiency (%) decreased with the increased power, however the difference was statistically significant only for 450 W. Similar results have been reported for mushrooms and apples (Motevali et al., 2011; Zarein et al., 2015). Differences could be attributed to several factors such as equipment structure, drying conditions (microwave power, frequency, temperature), material properties, or food matrix, among others.

3.3 Quality characteristics

3.3.1 Effect of the MWD on surface color

Color parameters (L^*, a^* and b^*) are presented in Table 2. The L^* value did not statistically change when compared to the fresh radish, except for 450 W where the treatment showed a significantly lower L^* value indicating a loss of luminosity. This highest power employed was more aggressive, affecting the L^* parameter at the end of the process. Conversely, durian chips exposed to vacuum MWH showed a non-significant change in L^* value (Bai-Ngew et al., 2011). Joshi et al. (2016) argued that MWD did not induce browning, as it rapidly inhibited the enzymatic action responsible for browning. As MWP increased, a^* value changed from -0.14 to 1.64 (90 W), 3.76 (270 W) and 4.15 (450 W), showing an overall shift of slices' color towards redness. The observed increase was only statistically significant for the highest power. This might be caused by non-enzymatic browning or other thermal damages (Joshi et al., 2016). A statistically significant increase in the b^* value with time was also observed for each MWP during MWD with a change in color towards yellowness. Pimpaporn et al. (2007) reported that the values of L^* remained almost constant whereas a^* and b^* values continuously increased during the MWD.

Total color difference (ΔE), a combination of L^*, a^* and b^* values, is a colorimetric parameter extensively used to characterize the variation of color in food during processing (Maskan, 2001). ΔE was calculated from Eq. 7 using data obtained from MWD of the radish slices at the three MWP evaluated (Table 3). Regarding the power employed for MWD, the most remarkable color changes in the final product were found for 450 W. At every power employed, the final product showed ΔE higher than 12,

Table 2: Color parameters (L^*, a^* and b^*) and total color difference (ΔE) of surface and $VITC_R$ of microwave drying radish slices. Values are means ± standard deviation ($n = 3$). Values with same letter are not significantly different ($P \geq 0.05$).

Treatment (power/time)	L^*	a^*	b^*	ΔE	$VITC_R$
Control	76.68 ± 1.82 a	-0.14 ± 0.52 a	4.93 ± 1.18 a	0.00 ± 0.00 a	1.00 ± 0.00 a
90 W	78.83 ± 2.06 a	1.64 ± 2.01 a	16.39 ± 1.99 b	13.32 ± 2.08 b	0.33 ± 0.06 b
270 W	72.33 ± 4.80 a	3.76 ± 1.79 a	17.59 ± 6.1 b	16.23 ± 3.95 b	0.12 ± 0.05 b
450 W	60.1 ± 6.80 b	4.15 ± 1.77 b	24.25 ± 3.07 b	27.92 ± 6.67 b	0.05 ± 0.01 b

Table 3: TPC (mg eq Gallic Acid/g DW), TFC (mg eq. Quercetin/g DW) and AC (mg eq Trolox/g DW) of fresh radish slices (Control) and microwave dried radish slices at power level 90, 270 and 450 W. Values are means ± standard deviation ($n = 3$). Values with same letter are not significantly different ($P \geq 0.05$).

Treatment	TPC	TFC	AC
Control	5.06 ± 0.17 a	33.84 ± 0.51 a	2.610 ± 0.457 a
90 W	1.88 ± 0.20 c	13.44 ± 1.26 b	0.559 ± 0.427 c
270 W	2.47 ± 0.46 b	15.41 ± 1.91 b	0.720 ± 0.332 bc
450 W	3.00 ± 0.29 b	20.68 ± 2.82 b	1.475 ± 0.482 b

which indicated a ‘very obvious difference’ according to the scale employed by Goyeneche et al. (2016) for fresh radish. This difference might be a result from biochemical reactions in the tissues, such as caramelization or Maillard reaction and also charring. Joshi et al. (2016) also observed a rise in ΔE during MWD of potato chips. b^* parameter seemed to affect ΔE value in a higher proportion.

3.3.2 Effect of MWD on Vitamin C

The consumption of radish roots confers health promotion with natural medicinal value due to the presence of phytochemicals (among them $VITC$) with diverse beneficial properties (Goyeneche et al., 2015).

Vitamin C content found on fresh radish slices was 11.14 ± 0.74 mg/100 g of fresh weight. This value was in the same order of magnitude with those reported in radish by other authors (Goyeneche et al., 2015; Pushkala et al., 2013).

Vitamin C is the most heat-labile vitamin and the loss of this component during drying is influenced by temperature, presence of oxygen and drying time (Chen et al., 2018). The values of $VITC$ relative content ($VITC_R$) of radish during MWD are presented in Table 2. Reduction in $VITC$ levels of the samples subjected to MWD was recorded depending on the power applied.

Samples processed with the lowest power (90 W) presented a residual $VITC$ content of 32.3 % in comparison with the fresh product. However, in those processed with the highest power (450 W) it was reduced to 4.2 %. According to Farahnaky et al. (2018), ascorbic acid content of radish was reduced from 139 to 84 mg/kg after 2 min and 500 W of MWD, leaving a 60.43 % percentage in the product.

Although the $VITC$ content in the radish slices that were subjected to the lowest power was significantly reduced, it was still higher than that of sliced sweet potatoes dehydrated by microwaves at medium power (22.75 mg VITC/100 g DW) (Jing et al., 2010).

3.3.3 Effect of MWD on total polyphenolic content

Table 3 presents the TPC of radish as affected by MWD processes. TPC for fresh radish root was 506.23 ± 17.03 mg GAE/100 g DW. It was comparable with values reported in previous works for the same product: 341.45 ± 5.70mg GAE/100 g DW (Goyeneche et al., 2015), and 122 mg GAE/100 g DW (Pushkala et al., 2013).

MWD statistically significant impacted TPC (Table 3). In processed products, TPC decreased when the power applied decreased, but the difference between 270 W and 450 W was not significant ($P \geq 0.05$). Similar results were reported by Farahnaky et al. (2018), where TPC of radish exposed to microwaves during 2 minutes was reduced from 1315.83 ± 2.95 to 998.34 ± 76.21 µg GAE/g extract. The degradation of phenolic compounds can be attributed either to the extent of drying time or to the drying temperature (Barroca et al., 2013). In this study, the degradation of phenolic compounds was due to the extension of drying time of the radish slices, because the lowest power applied showed the lowest level of TPC. Furthermore, at higher temperatures, the decrease of TPC in vegetables during drying could be explained by different mechanisms: the release of bound phenolic compounds; a partial degradation of lignin leading to the release of phenolic acid derivatives and the beginning of thermal degradation of the phenolic compounds (Maillard and Berset, 1995).

3.3.4 Effect of MWD on total flavonoids content

Flavonoids are phenolic compounds that exhibit high antioxidant activities. Their potential benefits for human health, such as prevention and protection of some cardiovascular diseases and treatment for some types of cancer and diabetes, are supported by epidemiological and in vitro evidence (Ballard and Maróstica, 2019).

Table 3 also presents the TFC of radish as affected by

MWD processes. TFC for fresh radish roots was higher than values reported by Goyeneche et al. (2015) for the same product (2.67 mg quercetin/g D.W.). Average TFC for the processed samples was 16.51 mg quercetin/g D.W. TFC did not show significant differences between microwave power levels of the drying process. Similar results were reported by Farahnaky et al. (2018), where TFC of radish exposed to microwaves during 2 minutes was reduced to 35.9 % after the complete process.

The stability and biological activity of flavonoids are dependent on temperature, and are more or less sensitive to heat treatment according to their structure.

3.3.5 Effect of MWD on Antioxidant Capacity

Table 3 shows the DPPH radical scavenging activity as affected by the MWD process. *R. sativus* extracts showed an effective DPPH radical scavenging activity. The AC of radish slices was reduced significantly when the MWD was applied. Losses of AC in radish dehydrated by microwaves could be attributed to the effect of heating caused by electromagnetic radiation during the drying process. The AC was reduced with the increasing power applied, the differences were significative between 90 and 450 W. Despite the reduction of AC observed in the samples, the power with the lowest AC (90 W) retained a 21.4 % from the fresh product.

In this study, the AC showed an inverse correlation with Vitamin C content. This index is more related to TPC, thus, López et al. (2010) found similar results in dried blueberries, and attribute this trend to the time of drying processes. Longer drying process due to low MWP applied, could produce a VITC degradation but also could induce polyphenols formation inside product tissues. Jing et al. (2010) found similar trends and correlation in VITC, TPC and AC in sweet potato exposed to MWD suggesting formation of new phenolic compounds during dehydration.

Regarding AC, the different nature of the food matrix exposed to MWD could be one of the more important causes of the differences found in literature for red pepper and mulberry leaves (Vega-Gálvez et al., 2009; Katsube et al., 2009).

4. Conclusion

Radish slices were dried by means of microwave technology and the process was effective to achieve an innovative snack-type-product. Influences of MWP on energy parameters and drying behavior of the samples were investigated. The Midilli–Kucuk model was satisfactorily applied to simulate the experimental drying data at each process condition. In addition, all drying curves were generalized, showing this equation can very accurately predict the drying time of radish under all the drying conditions studied. Higher MWP increased the mass transfer and the effective moisture diffusivities by reducing the drying times. It also showed the highest content of bioactive compounds as well as antioxidant capacity. However, as the power level increased the total energy consumption increased and the energy efficiency of the processes decreased. Therefore, working at high power level reduced drying times and showed acceptable bioactive compounds contents as well as functional property, but at the same time energy consumption presented higher values. Hence, as quality and energy consumption followed opposite trends during radishes dehydration, an optimization analysis is required which is our next step in this research.

Conflict of interest

The authors have declared no conflicts of interest for this article.

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