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## Impact of different drying methods on the drying kinetics, color, total phenolic content and antioxidant capacity of pineapple

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### ABSTRACT

In this study, the effects of convective (60, 70, 80 and 90°C), microwave (120 and 350 W) and freeze-drying methods on the drying kinetics, color, total phenolic (TP) content and antioxidant capacity of pineapples were examined. The statistic tests proved that the Midilli *et al.*, Two Term, Wang and Singh and Page models were superior to the other models and yielded the closest predictions to the experimental values. The lowest change in the color parameter ( $\Delta E$ ) value (4.83) was obtained by freeze-drying the pineapples. The dried samples demonstrated a decrease in the TP content compared to the fresh samples and a decrease in the antioxidant capacity. The best antioxidant capacity and TP content values were obtained via freeze drying and microwave drying at 350 W, respectively. According to the results obtained from this study, convective, freeze drying and microwave methods are suitable for drying pineapple.

### Impacto de diferentes métodos de secado en la cinética de secado, el color, el contenido fenólico total y la capacidad antioxidante de la piña

### RESUMEN

Para el presente estudio se examinaron los efectos de la aplicación de métodos convectivos (60, 70, 80 y 90°C), de microondas (120 y 350 W) y de liofilización en la cinética de secado, el color, el contenido fenólico total y la capacidad antioxidante de la piña. Las pruebas estadísticas confirmaron que los modelos de Midilli *et al.*, Two Term, Wang y Singh, y Page resultan superiores a los otros modelos, produciendo pronósticos más cercanos a los valores experimentales. El menor cambio en el valor (4.83) del parámetro de color ( $\Delta E$ ) se obtuvo a partir de la liofilización de la piña. En comparación con las muestras frescas, las muestras secas acusaron descenso del contenido fenólico total y de su capacidad antioxidante. Los mejores valores asociados a la capacidad antioxidante y al contenido fenólico total se obtuvieron con la aplicación de la liofilización y el secado con microondas de 350 W, respectivamente. De acuerdo a los resultados de este estudio, los métodos convectivos, de liofilización y el secado con microondas constituyen métodos aptos para el secado de la piña.

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### PALABRAS CLAVE

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## Introduction

Pineapple (*Ananas comosus* L.), originally from the American tropics, is a member of the botanical family *Bromeliaceae*. It is rich in nutrients, including ascorbic acid, minerals, fibers, and antioxidants, and it has sensorial properties (mechanical properties, water, flavor, acidity/sweetness ratio, color) (Ramallo & Mascheroni, 2012). Pineapple fruit is a good way to increase the nutritive value of poor people's diets and to reduce dietary deficiencies (Da Silva, Nogueira, Duzzioni, & Barrozo, 2013). The total worldwide pineapple production in 2013 was estimated to be between 24 and 25 million tons (FAO, 2015). Pineapple fruit can be consumed fresh and/or processed as juice or canned (Kingsly, Balasubramaniam, & Rastogi, 2007). Additionally, drying pineapple slices and rings can be used as an alternative processing technology with the ability to enrich this raw material and expand consumption methods (Cortellino, Pani, & Torreggiani, 2011).

Drying is a very simple and old method to preserve fruits. Convection drying is one of the most popular drying methods with a low-cost application. However, it has

disadvantages. The process is time consuming (Nawirska, Figiel, Kucharska, Sokoł-Łetowska, & Biesiada, 2009) and may result in a significant change in the quality in the dried products (Qing-Guo, Min, Mujumdar, Wei-Hua, & Jin-Cai, 2006). Microwave drying has been on the rise in popularity as an alternative method. In principal, electromagnetic energy is directly converted to kinetic energy in the water molecules, and the product itself produces the heat (Motevali, Minaei, Khoshtaghaza, & Amirnejat, 2011). The high drying rate, reduced process time and lower energy requirement are some of the advantages of microwave drying. However, microwave drying may result in non-uniform heating and/or surface overheating (Ahrne, Pereira, Staack, & Floberg, 2007). The alternative process of freeze drying dehydrates food via sublimation. Freeze drying preserves a high amount of the aroma and allows for good rehydration, which are indicators of yielding high-quality products. However, this drying method costs more in capital and operation (Qing-Guo *et al.*, 2006). A range of drying methods can be used to obtain high-quality, dried pineapple products.

This study was mainly conducted with the purpose of determining the thin layer drying kinetics of pineapples in convective, microwave and freeze dryers, choosing the best viable drying models and examining the differences in color, total phenolic (TP) content and antioxidant capacity between fresh and dried pineapple products.

## Materials and methods

### Drying equipment and drying procedure

In all the experiments in this study, wholly matured and healthy pineapples were used. Fresh fruits were purchased from a farmer's market in Bursa, Turkey. The fruits were then stored until analysis at a temperature of  $4 \pm 0.5^\circ\text{C}$ . The initial moisture content of the fresh samples was  $6.69$  (g water.g dry matter<sup>-1</sup>) based on oven drying (ED115 Binder, Tuttlingen, Germany) at  $105^\circ\text{C}$  (Celen & Kahveci, 2013). The average diameter of the samples was  $30 \pm 0.04$  mm. Using a food slicer, the samples were sliced into pieces  $3 \pm 0.06$  mm thick (Nicer Dicer, China). Three different drying methods were used in the drying experiments: convective, microwave and freeze drying. All experiments were performed three times each, and the experiments continued until the moisture content of the samples dropped to  $0.1$  (g water.g dry matter<sup>-1</sup>).

### Convective drying

A rotating round plate of glass material with a 400 mm diameter was used to place the pineapple slices in a thin layer, and the slices were dried using a laboratory convective oven (Whirlpool AMW 545, Italy). The air velocity was set to  $1.5 \text{ m s}^{-1}$ , and air temperatures of  $60$ ,  $70$ ,  $80$  and  $90^\circ\text{C}$  were used for the drying process. Under the oven, a digital balance (Shimadzu UX-6200H, Tokyo, Japan) with a  $0.01$  g precision was used to measure the mass (Izli & Isik, 2014). Moisture losses were checked every 5 min during the drying process.

### Microwave drying

A microwave oven (Arçelik MD574, Istanbul, Turkey) with output power levels of  $120$  and  $350$  W was used for the drying treatment. The pineapple slices were placed in a thin layer on a rotating round plate of glass material with  $245$  mm diameter. Every 2 min, the moisture loss in the sample was checked by removing the sample with the glass plate and placing it on the digital balance (Radwag, Radom, Poland) with a  $0.01$  g precision.

### Freeze drying

A laboratory-type freeze dryer (Alpha 1–2 LD Plus, Osterode am Harz, Germany) with a processing temperature of  $-50^\circ\text{C}$  and a constant pressure in the drying chamber of  $52$  Pa was utilized in this experiment. The moisture loss in the sample was checked every 2 h with an accuracy of  $\pm 0.01$  g (Radwag, Radom, Poland) during the drying process.

### Mathematical modeling of the drying data

The moisture ratio data were adapted to the nine thin-layer models that are typically used to model drying curves (Table 1). The moisture ratio (MR) values were calculated using Equations (1) and (2):

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where  $M_t$  corresponds to the moisture content at a given time (g water.g dry matter<sup>-1</sup>),  $M_o$  corresponds to the initial moisture content (g water.g dry matter<sup>-1</sup>) and  $M_e$  corresponds to the equilibrium moisture content (g water.g dry matter<sup>-1</sup>). When compared to  $M_t$  or  $M_o$ , the values of  $M_e$  are relatively small. Consequently, the moisture ratio was simplified to the following as described by some analysts (Midilli, Kucuk, & Yapar, 2002):

$$MR = \frac{M_t}{M_o} \quad (2)$$

### Color measurement

Using a colorimeter, the L (lightness), a (redness/greenness) and b values (yellowness/blueness) of the fresh and dried pineapple samples were graded using 10 readings at random locations on the surfaces of the samples (MSEZ-4500L, HunterLab, Virginia, USA). Moreover, the chroma, C [Equation (3)], hue angle,  $\alpha$  [Equation (4)] and total color differences,  $\Delta E$  [Equation (5)], were calculated using the following equations (Vega-Gálvez et al., 2009):

$$C = \sqrt{(a^*^2 + b^*^2)} \quad (3)$$

$$\alpha = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (4)$$

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (5)$$

### Preparation of the sample extracts

The method of Turkmen, Sari, and Velioglu (2005) was applied to obtain pineapple fruit extracts to measure the TP content and antioxidant capacity. Homogenized pineapple samples

**Table 1.** Selected thin layer drying models used to mathematically model the pineapple drying kinetics.

**Tabla 1.** Modelos seleccionados de secado de capas finas utilizados para modelar matemáticamente la cinética de secado de la piña.

No	Model name	Model	References
1	Henderson and Pabis	$MR = a \exp(-kt)$	Zhu and Shen (2014)
2	Newton	$MR = \exp(-kt)$	Izli and Isik (2014)
3	Page	$MR = \exp(-kt^n)$	Doymaz and Ismail (2011)
4	Logarithmic	$MR = a \exp(-kt) + c$	Bhattacharya et al. (2015)
5	Two Term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Sacilik et al. (2006)
6	Two Term Exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	Izli and Isik (2014)
7	Wang and Singh	$MR = 1 + at + bt^2$	Manikantan et al. (2014)
8	Diffusion Approach	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	Celen, Kahveci, Akyol, and Haksever (2010)
9	Midilli et al.	$MR = a \exp(-kt^n) + bt$	Midilli et al. (2002)

(1 g) were extracted via shaking at 140 rpm (Biosan OS-20, Latvia) for 120 min at room temperature with 4.5 mL of methanol/water (80/20 v/v). Following centrifugation for 15 min at 10,000 g (Sigma 3K30, UK), the collected supernatants were put into falcon tubes. Then, the residues of the mixtures were re-extracted under identical conditions and the supernatants were combined and passed through a 0.45- $\mu$ m polytetrafluoroethylene membrane filter. Extraction procedures were carried out three times on same sample.

### Determination of the total phenolic content

With a few alterations, the method of Igual, García-Martínez, Martín-Esparza, and Martínez-Navarrete (2012) was applied to measure the TP content of the extracts. The pineapple extract (0.25 mL), 15 mL of distilled water and 1.25 mL of Folin–Ciocalteu reagent (Sigma-Aldrich, Germany) were mixed together for 15 s (WiseMix VM-10, Daihan, Korea), and the mixture was left to sit for 8 min for the assay. Following this step, 3.75 mL of 7.5% Na<sub>2</sub>CO<sub>3</sub> was added to the mixture, and the volume was brought to 25 mL with distilled water. The blue color absorbance was analyzed at 765 nm after 120 min of incubation in the dark at room temperature (Optizen 3220 UV, Mecasys, Korea). A gallic acid standard calibration curve was utilized to calculate the TP content present in the fresh and dried samples and was expressed as mg GAE/100 g of dry weight (d.w.). Each sample was analyzed three times.

### Determination of the antioxidant capacity

Following the method of Allothman, Bhat, and Karim (2009), the DPPH (2,2-diphenyl-1-picrylhydrazyl)-free radical scavenging activity of the pineapple extracts was spectrophotometrically evaluated (Optizen 3220 UV, Mecasys, Korea). To 3.9 mL of a 25 mM methanolic solution of the DPPH radical (Sigma-Aldrich, Germany), 0.1 mL of the appropriately diluted extract was added, and the mixture was vortexed (WiseMix VM-10, Daihan, Korea) for 15–30 s. The reaction of the mixture was allowed to proceed in the dark at room temperature for 30 min. After this, the absorbance was measured at 515 nm (Optizen 3220 UV, Mecasys, Korea). The results were expressed as  $\mu$ mol Trolox equivalents (TE)/g d.w. Three sets of each sample were analyzed.

### Statistical analysis

The research was conducted using randomized plot factorial designs for the experiments. In the process of measuring the investigated components, three replicates were used. To analyze the results, MATLAB (MathWorks Inc., Natick, MA) and JMP (Version 7.0, SAS Institute Inc., Cary, NC, USA) were used. The mean differences were used for the significance test, and the least significant difference test gave a 5% level of significance. The model with the lowest reduced chi-squared ( $\chi^2$ ) and root mean square error (RMSE) values and the highest coefficient of determination ( $R^2$ ) was confirmed as the best model to describe the drying characteristics of the pineapples in a thin layer (Arumuganathan, Manikantan, Rai, Anandakumar, & Khare, 2009). The description of these statistical values is as follows:

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})}{N}} \quad (7)$$

where

$MR_{exp,i}$  corresponds to the experimental moisture ratio in test number  $i$ ,

$MR_{pre,i}$  corresponds to the estimated moisture ratio in test number  $i$ ,

$N$  corresponds to the observation number and

$n$  represents the number of constants in the drying model (Doymaz & Ismail, 2011).

## Results and discussion

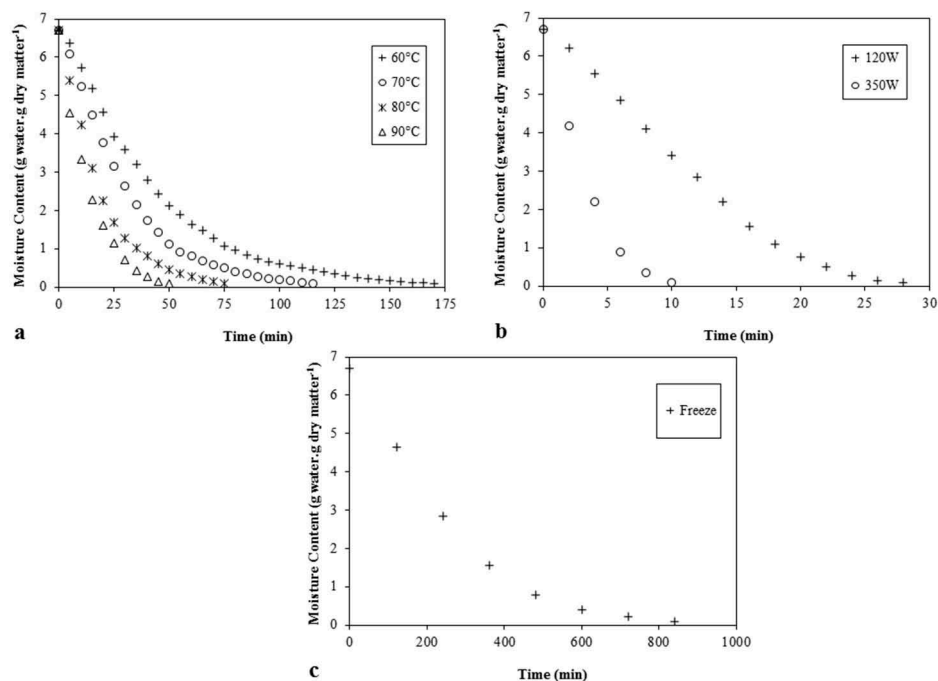
### Drying kinetics of the dried pineapple

The drying curves for the pineapple samples under all the drying conditions are shown in Figure 1. The drying conditions determined the total time required to reach the final moisture content. The time was highest at  $-50^\circ\text{C}$  with freeze drying (840 min) and lowest at 350 W with microwave drying (10 min). These results showed that compared to freeze drying, the drying time decreased by 98.81% for the pineapple samples dried at a microwave power of 350 W. Moreover, the drying time decreased as the microwave power level increased. The moisture equilibrium content for the pineapple samples was achieved by microwave method applications of 120 W for 28 min or 350 W for 10 min. This pattern, a decrease in the drying time with an increase in the microwave power level, was documented by Celen and Kahveci (2013) for tomatoes, Omolola, Jideani, and Kapila (2014) for bananas and Duan, Huang, Wang, Qiao, and Fang for lychees. As expected, the convective method achieved drying in 50 min at  $90^\circ\text{C}$ . Using the same method at 60, 70 and  $80^\circ\text{C}$ , the drying process was completed in 170, 115 and 75 min, respectively. These results indicated that increasing the drying temperature caused an important decrease in the drying time. Similar results in terms of a temperature effect on the drying time for tomato (Purkayastha, Nath, Deka, & Mahanta, 2013), peach (Doymaz & Bilici, 2014) and cornelian cherry fruits (Ozgen, 2015) have been documented in the literature.

### Fitting of the drying curves

Tables 2 and 3 show the model constants, i.e. the  $R^2$ , RMSE and  $\chi^2$  values, calculated from the curve fitting calculations on the moisture ratio with the drying time and the selected drying conditions on the nine drying processes. In all cases, the values of  $R^2$ , RMSE and  $\chi^2$  varied from 0.9439 to 0.9998, 0.0048 to 0.0822 and  $0.3035 \times 10^{-4}$  to  $66.6356 \times 10^{-4}$ , respectively, indicating good fit results. The statistical value results show that the drying curves of the pineapple were best described by the models from Midilli et al. ( $60^\circ\text{C}$ ,  $90^\circ\text{C}$  and 120 W), Two Term (70 and  $80^\circ\text{C}$ ), Wang and Singh (350 W) and Page (Freeze). The best  $R^2$ , RMSE and  $\chi^2$  values from the Midilli et al., Two Term, Wang and Singh and Page models were 0.9997, 0.0052 and  $0.3511 \times 10^{-4}$ ; 0.9998, 0.0048 and  $0.3035 \times 10^{-4}$ ; 0.9995, 0.0088 and  $28.4487 \times 10^{-4}$ ; and 0.9997, 0.0062 and  $0.4313 \times 10^{-4}$ , respectively.

The variations in the experimental and predicted moisture ratios using the most appropriate models in terms of the



**Figure 1.** Drying curves of pineapple samples using (a) different convective temperatures; (b) two microwave power levels; and (c) one freeze condition.

**Figura 1.** Curvas de secado de muestras de piña obtenidas a partir de la aplicación de a) distintas temperaturas convectivas; b) dos niveles de potencia de microondas; y c) una condición de congelamiento.

drying time at selected temperatures, microwave power applications and freeze-drying conditions for the dried pineapple are presented in Figure 2. The models were satisfactory for describing the drying characteristics of the pineapples in a thin layer under the experimental conditions, but they did not exactly match the experimental data. These findings confirmed the results of Motavali, Najafi, Abbasi, Minaei, and Ghaderi (2013) and Bhattacharya, Srivastav, and Mishra (2015) for the Midilli et al. model, Lahsasni, Kouhila, Mahrouz, and Jaouhari (2004) and Sacilik, Elicin, and Unal (2006) for the Two Term model, Arumuganathan et al. (2009) and Manikantan, Barnwal, and Goyal (2014) for the Wang and Singh model and Doymaz and Ismail (2011) and Zhu and Shen (2014) for the Page model.

### Color analysis

As seen in Table 4, the different drying methods affected the color parameters of the dried pineapple fruits. With the exception of the freeze-dried sample, which had a significantly ( $P < 0.05$ ) higher  $L^*$  value (74.53), the  $L^*$  values in all the dried samples decreased compared with the fresh fruit (69.28). On the other hand, the fresh sample (0.48) contained significantly ( $P < 0.05$ ) lower  $a^*$  values than that of any other drying method, except for freeze drying (0.23). The  $b^*$  value was ( $P < 0.05$ ) the highest for the sample convectively dried at 60°C (49.56) and the lowest for the sample microwave dried at 350 W. The C values of the dried fruits closely followed the  $b^*$  values. The highest C values (49.81 and 49.06, respectively) were in the fruits convectively dried at 60 and 70°C, and the samples were significantly ( $P < 0.05$ ) more vivid in color than any of the other dried and fresh samples. Compared to the fresh sample, a significant ( $P < 0.05$ ) decrease was observed in the  $a$  values for the convective and microwave-dried samples. This clearly indicated that more browning occurred, which is probably a

result of the higher  $a^*$  values of the dried samples ( $P < 0.05$ ). Freeze-dried pineapple slices presented the lowest  $\Delta E$  value of 4.83. As the  $L^*$  value of the samples decreased, their  $\Delta E$  values increased. Compared to the microwave-dried samples, the pineapple samples dried at 80 and 90°C using convective drying were significantly ( $P < 0.05$ ) darker in color. Similar effects from microwave drying were previously recorded by Sumnu, Turabi, and Oztop (2005). Color changes in the pineapple slices caused by thermal treatment may be strongly related to pigment degradation, which is enhanced by the drying temperature and microwave power, especially that of carotenoids, and the formation of brown pigments via non-enzymatic (Maillard reaction) and enzymatic reactions (Dueik, Marzullo, & Bouchon, 2013).

### Total phenolic content

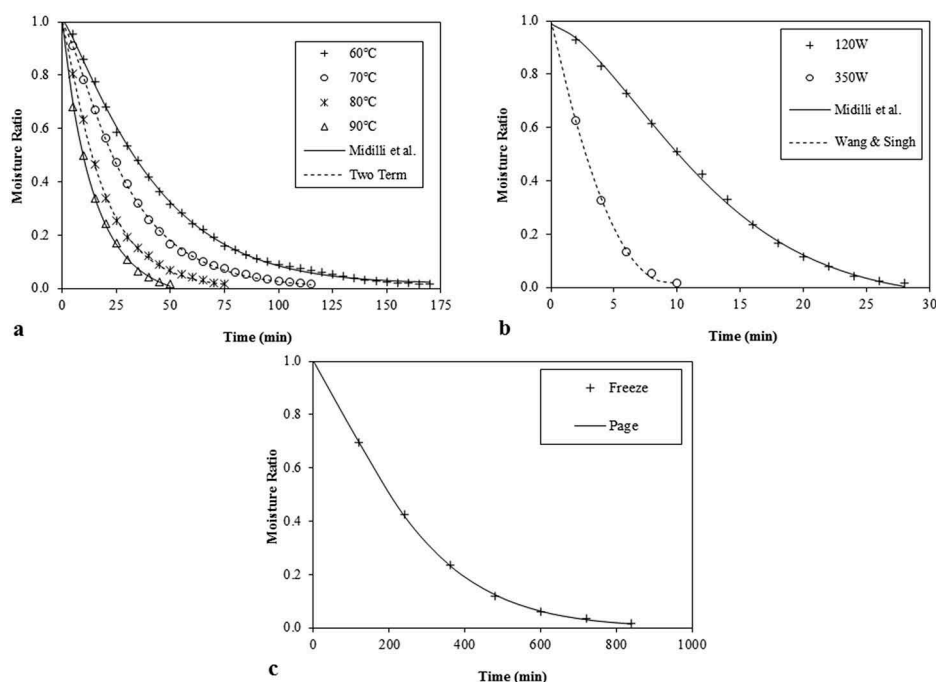
Figure 3 presents the TP contents of the pineapple slices dried using different methods. The drying treatments greatly influenced the TP content. The fresh sample was initially measured at 467.44 mg GAE/100 g d.w. for the TP content. With the exception of the microwave-dried slices at 350 W (514.85 mg GAE/100 g d.w.), the TP content in the fresh sample was significantly ( $P < 0.05$ ) higher than that in the dried samples. Convective drying at 60°C resulted in the lowest TP content in the pineapple (269.89 mg GAE/100 g d.w.). The TP content of the microwave-dried pineapple slices was 1.10 times higher than that of the fresh sample and 1.17 times higher than that of the freeze-dried sample (439.50 mg GAE/100 g d.w.). The results showed no statistically significant changes ( $P > 0.05$ ) between the TP content values of the microwave (120 and 350 W) and freeze-dried pineapple samples. The same trend was observed by Chang, Lin, Chang, and Liu (2006) and Da Silva et al. (2013) when they evaluated the content of phenolic compounds in tomatoes and pineapples after drying, and they also obtained

Table 2. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of pineapple at different temperatures.  
 Tabla 2. Valores estimados de los coeficientes y de pruebas estadísticas obtenidos a partir de la aplicación de

No.	60°C					70°C					80°C					90°C				
	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )
1	a = 1.062 k = 0.02389	0.9970	0.0159	2.4066	a = 1.06 k = 0.03424	0.9953	0.0207	4.6269	a = 1.024 k = 0.05385	0.9980	0.0135	2.0483	a = 0.9998 k = 0.07287	0.9983	0.0131	1.4695				
2	k = 0.02253	0.9935	0.0236	5.4824	k = 0.03239	0.9920	0.0271	7.9185	k = 0.05265	0.9975	0.0151	2.5732	k = 0.07288	0.9985	0.0124	1.3226				
3	k = 0.01237 n = 1.151	0.9988	0.0099	1.0315	k = 0.01663 n = 1.185	0.9993	0.0081	0.7915	k = 0.04083 n = 1.081	0.9989	0.0099	1.1347	k = 0.06841 n = 1.022	0.9984	0.0126	1.3669				
4	a = 1.068 k = 0.02298	0.9973	0.0151	2.1346	a = 1.072 k = 0.03203	0.9962	0.0186	3.8115	a = 1.027 k = 0.0529	0.9980	0.0137	2.1033	a = 1.014 k = 0.06849	0.9990	0.0101	0.7902				
5	c = -0.01305 a = -3.054 k <sub>0</sub> = 0.02057 b = 4.141	0.9965	0.0174	2.8880	c = -0.02335 a = -0.2463 k <sub>0</sub> = 0.144 b = 1.247	0.9998	0.0048	0.3035	c = -0.005917 a = 1.09 k <sub>0</sub> = 0.05703 b = -0.09075	0.9993	0.0081	0.7571	c = -0.02159 a = 2.301 k <sub>0</sub> = 0.08304 b = -1.301	0.9982	0.0135	1.5501				
6	k <sub>1</sub> = 0.02149 a = 0.0001227 k = 183.6	0.9932	0.0240	5.6613	k <sub>1</sub> = 0.03885 a = 1.747 k = 0.04398	0.9994	0.0075	0.6540	k <sub>1</sub> = 0.3602 a = 1.545 k = 0.06394	0.9988	0.0107	1.3126	k <sub>1</sub> = 0.09258 a = 1.37 k = 0.08073	0.9986	0.0120	1.2247				
7	a = -0.01553 b = 0.0000603	0.9792	0.0421	18.5833	a = -0.02254 b = 0.0001272	0.9846	0.0375	14.2511	a = -0.03544 b = 0.0003123	0.9695	0.0531	28.4487	a = -0.05003 b = 0.0006295	0.9757	0.0497	25.6049				
8	a = 1.388 k = 0.02188 b = 0.9287	0.9932	0.0241	5.5519	a = 1.873 k = 0.02979 b = 0.9108	0.9919	0.0273	7.6803	a = 20.87 k = 0.05259 b = 1	0.9972	0.0162	2.7554	a = -1.081 k = 0.0941 b = 0.8802	0.9984	0.0127	1.2105				
9	a = 1.015 k = 0.01227 n = 1.163	0.9994	0.0070	0.5956	a = 1.005 k = 0.01555 n = 1.212	0.9997	0.0052	0.3511	a = 1.003 k = 0.03818 n = 1.111	0.9992	0.0087	0.9409	a = 0.9976 k = 0.076 n = 0.969	0.9991	0.0093	0.7260				
	b = -0.0000893				b = 0.0001331				b = 0.0001942				b = -0.0005432							

Table 3. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of pineapple using microwave (120 and 350 W) and freeze conditions.

No.	120 W					350 W					Freeze				
	Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )		Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )		Model coefficients	R <sup>2</sup>	RMSE	χ <sup>2</sup> (10 <sup>-4</sup> )	
1	a = 1.115 k = 0.09158	0.9568	0.0721	51.3754		a = 1.025 k = 0.2995	0.9853	0.0468	22.1983		a = 1.031 k = 0.003994	0.9893	0.0370	13.7010	
2	k = 0.08251	0.9439	0.0822	66.6356		k = 0.2932	0.9873	0.0435	19.3215		k = 0.003887	0.9895	0.0367	13.5633	
3	k = 0.01705 n = 1.608	0.9978	0.0161	2.6984		k = 0.1865 n = 1.317	0.9993	0.0104	0.6084		k = 0.0008431 n = 1.266	0.9997	0.0062	0.1313	
4	a = 1.487 k = 0.04712	0.9898	0.0351	11.1814		a = 1.125 k = 0.2335	0.9938	0.0304	8.4255		a = 1.088 k = 0.003371	0.9941	0.0276	7.2286	
5	c = -0.4326 a = -56.89	0.9440	0.0822	66.5857		c = -0.1135 a = -2.961	0.9926	0.0332	9.9600		c = -0.07024 a = 0.5153	0.9840	0.0454	20.5593	
6	k <sub>0</sub> = 0.06599 b = 57.92					k <sub>0</sub> = 0.1368 b = 3.97					k <sub>0</sub> = 0.003973 b = 0.5188				
7	k <sub>1</sub> = 0.06631 a = 2.054	0.9917	0.0316	10.0785		k <sub>1</sub> = 0.1664 a = 1.882	0.9987	0.0141	1.4521		k <sub>1</sub> = 0.004025 a = 1.826	0.9995	0.0077	0.3173	
8	k = 0.1324 a = -0.05839	0.9906	0.0337	10.2732		k = 0.4238 a = -0.2133	0.9995	0.0088	0.2722		k = 0.005475 a = -0.002784	0.9970	0.0195	4.4752	
9	b = 0.0007802 a = 98.91	0.9864	0.0405	13.8749		b = 0.01159 a = 22.42	0.9948	0.0277	5.2764		b = 0.00000196 a = 0.0004692	0.9854	0.0434	15.8240	
	k = 0.02368 b = 0.9838					k = 0.1512 b = 0.9695					k = 0.004145 b = 0.9375				
	a = 0.9889 k = 0.01789	0.9988	0.0120	1.2457		a = 0.9989 k = 0.1894	0.9987	0.0137	1.2827		a = 0.9983 k = 0.0008045	0.9996	0.0074	0.2007	
	n = 1.558 b = -0.001308					n = 1.293 b = -0.0009443					n = 1.275 b = -0.00000285				



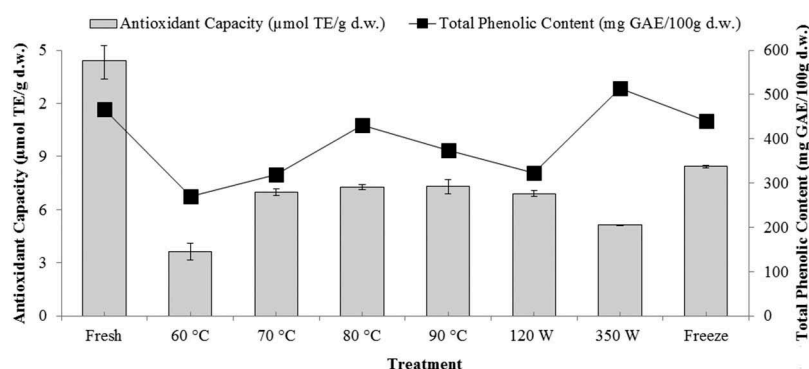
**Figure 2.** A comparison of the experimental and theoretical moisture ratios predicted by the Midilli *et al.*, Two Term, Wang and Singh and Page models at specific drying times under selected drying conditions (convective (a), microwave (b) and freeze (c)).

**Figura 2.** Comparación de las ratios de humedad obtenidas de manera experimental y teórica, pronosticadas por los modelos Midilli *et al.*, Two Term, Wang y Singh, y Page, empleando tiempos de secado específicos bajo condiciones de secado seleccionadas (convectiva (a), microondas (b), y congelamiento (c)).

**Table 4.** Color values of fresh and dried pineapple slices at different drying methods.

**Tabla 4.** Valores de color resultantes de la aplicación de distintos métodos de secado a rebanadas de piña fresca y seca.

Drying method	Color parameters					
	$L^*$	$a^*$	$b^*$	$C$	$\alpha^\circ$	$\Delta E$
Fresh	69.28 ± 0.45	0.48 ± 0.03	41.86 ± 0.27	41.86 ± 0.27	89.38 ± 0.04	—
Convective drying						
60°C	68.17 ± 0.49	4.98 ± 0.31	49.56 ± 0.18	49.81 ± 0.17	84.31 ± 0.36	9.09 ± 0.17
70°C	67.80 ± 0.79	8.16 ± 0.10	48.38 ± 1.74	49.06 ± 1.72	80.46 ± 0.34	10.38 ± 1.13
80°C	48.70 ± 2.75	13.69 ± 0.58	39.77 ± 2.20	42.06 ± 2.27	71.03 ± 0.30	25.16 ± 2.20
90°C	40.08 ± 1.29	15.49 ± 0.69	30.34 ± 1.24	34.06 ± 1.42	62.99 ± 0.14	35.30 ± 1.18
Microwave drying						
120 W	65.37 ± 1.50	8.63 ± 0.35	35.62 ± 1.56	36.65 ± 1.53	76.40 ± 0.73	11.35 ± 0.95
350 W	54.63 ± 1.47	11.20 ± 0.58	30.90 ± 1.15	32.88 ± 0.99	70.09 ± 1.41	21.65 ± 0.97
Freeze drying	74.53 ± 0.60	0.23 ± 0.07	42.95 ± 0.29	42.95 ± 0.29	89.73 ± 0.10	4.83 ± 0.63



**Figure 3.** The effects of different drying conditions on the total phenolic content and antioxidant capacity of pineapple slices.

**Figura 3.** Efectos de las distintas condiciones de secado en el contenido fenólico total y la capacidad antioxidante de rebanadas de piña.

higher values in the dried samples than in the fresh samples. This result may possibly be due to the bound phenolic compounds disengaging from the cellular constituents (Chang *et al.*, 2006) and forming free phenolic compounds. In addition, the highest TP content in the slices microwave-

dried at 350 W can be explained by the wave penetrating directly into the material during microwave drying, causing greater cell disruption and rupture, which may result in more phenolic compounds being released. According to these observations, drying treatments have variable effects on

phenolic compounds. The intricate chemical interactions that influence the functional properties of food drying are still being researched.

### Antioxidant capacity

The change in the antioxidant capacity of the pineapple slices obtained using different drying methods is shown in Figure 3. The antioxidant capacity in the fresh sample was measured to be 14.39  $\mu\text{mol Trolox/g d.w.}$ . A significant ( $P < 0.05$ ) decrease was recorded in the antioxidant capacity of the samples for all the drying treatments, and this was also observed in strawberries (Wojdylo, Figiel, & Oszmianski, 2009) and apples (Sultana, Anwar, Ashraf, & Saari, 2012) by other researchers. The degradation of antioxidant compounds during drying is the cause of this decline. The highest antioxidant capacity in all the pineapple samples was observed in the freeze-dried samples (8.43  $\mu\text{mol Trolox/g d.w.}$ ), and the lowest antioxidant capacity value was observed in the slices convectively dried at 60°C (3.61  $\mu\text{mol Trolox/g d.w.}$ ). These results indicated that drying treatments at low temperature, which result in long drying times, may cause a decrease in the antioxidant capacity. Moreover, there was not a statistically significant ( $P > 0.05$ ) difference between the antioxidant capacity of the convective (70, 80 and 90°C) and microwave (120 and 350 W) dried samples (6.97, 7.26 and 7.29 and 6.90 and 6.79  $\mu\text{mol Trolox/g d.w.}$ , respectively). The antioxidant capacity of the samples was observed to be unrelated to the TP content of the samples. The correlation analysis conducted between the TP content and the antioxidant capacity for the pineapple slices provided a low correlation ( $R^2 = 0.1931$ ).

### Conclusions

This study examined the effect different drying methods had on the drying kinetics, color, TP content and antioxidant capacity of pineapple slices. The shortest drying time was achieved using the microwave drying method compared to the convective and freeze methods. Nine different thin-layer drying models were compared with regard to their  $R^2$ ,  $RMSE$  and  $\chi^2$  values to understand the drying characteristics of pineapple. According to the results, the Midilli et al., Two Term, Wang and Singh and Page models were the best models to explain the thin-layer drying of pineapple. Freeze drying had the best results for the color values as the values were the closest to the  $L^*$ ,  $a^*$  and  $b^*$  values of the fresh sample. Except for microwave drying at 350 W, the rest of the drying treatments reduced the TP content and antioxidant capacity of the dried pineapple samples. The results of the correlation analysis between the TP content and antioxidant capacity indicated a low correlation. During the drying process, there can be antagonistic or synergistic effects between the antioxidant compounds or other constituents. Overall, this study indicated that microwave drying shortens the drying time and can improve the overall quality of the dried pineapple slices in terms of the TP content, and freeze drying also had results that were close to that of the microwave drying. Lastly, the optimum TP content and antioxidant capacity were achieved using the convective drying method at 80°C. Taking into account the information that is available on this subject at present, we recommend

convective, freeze and microwave methods for drying pineapples. In further studies, it would be interesting to investigate combinations of drying methods with new modified dryers.

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### Disclosure statement

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