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Research Article

Mathematical Modelling of the Rehydration Kinetics of Yam (*Dioscorea rotundata*) Chips in a Microwave Oven

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Abstract: Aim of study was to model rehydration of yam chips dried in a microwave oven at different power levels. We used a completely randomized3^2 factorial design corresponding to the numeric variables of power (420, 560 and 700 W) and mass (50, 60 and 70 g) in 1 cm thick×3 cm-diameter yam chips. 3 repetitions were made for a total of 27 experimental units. 2, 5 g yam chips were rehydrated using a 2.5 g/100 mL NaCl solution at 25°C. Power and mass variables showed significant differences ($p<0.05$). The maximum water absorption is given under the conditions of 700 W power and 70 g mass. Data obtained were evaluated through the following empirical models: Exponential Model, Peleg Model, First-order Kinetics, Weibull Distribution and Normalized Weibull Distribution. The results showed that Peleg model fitted much better (R^2>97,9% and 0,001<SSE<0,01), which suggests that this is the model that best describes the rehydration characteristics of yam.

Keywords: Empirical models, model fitting, moisture, power, water adsorption

INTRODUCTION

Yam is a staple food in many tropical regions, mainly Western Africa, Asia, the Pacific and the Caribbean (Martínez and Ortiz, 2009). The Caribbean region of Colombia is the main producer of yams in the Caribbean area accounting for more than 90% of the national yam production compared to other regions such as Antioquia, Chocó, Casanare and Vaupés, where yam production is given on a smaller scale. Colombia produced about 365,396 tons of yam in 2014 with a yield of 33,88 tons per hectare planted (Agronet, 2014). In the Caribbean region of Colombia yam dishes range from salty to sweet and from traditional recipes such as *mote de queso* to sweet yam, which is usually prepared for Easter (Reina Aranza, 2012). When dehydrated in the form of flour, yam can be used in the production of soups, cookies, bread, drinks and desserts (Espinosa, 2009).

Drying is a traditional method of food preservation as well as a very useful tool to prolong the shelf life of tubers by reducing the weight for transportation and storage space (Darvishi *et al*., 2014). Microwave dehydration helps prevent related to the heating of the surrounding environment as it provides a more effective and uniform heating as well as a homogeneous drying (Darvishi *et al*., 2013; Zarein *et al*., 2015). Some foods that are dehydrated, whether whole, in pieces or powdered, must be rehydrated for consumption or later use in different processes. Hence the importance of studying the transfer of matter associated with rehydration (Hogekamp and Schubert, 2003). Several authors suggest that rehydration can be considered as a measure of the damage caused to foods during dehydration (Doymaz and Ismail, 2013; Farahnaky and Kamali, 2015; García *et al*., 2016), since it is a complex process that helps restore the properties of fresh, previously dehydrated foods with or without pre-drying treatments (Hogekamp and Schubert, 2003).

The most widely used food rehydration methods include immersion in water (perhaps the most common), sugary solutions, milk, yogurt and fruit and vegetable juices, among others. The immersion times must be short-lived so that the rehydration method results in a product with characteristics similar to those of a fresh product (Rastogi *et al*., 2004). Regarding the transfer of matter associated with rehydration, it could be said that water absorption occurs faster at the beginning of the process and then it gradually decreases until the moisture content reaches equilibrium, that is, when all intercellular or intracellular spaces become saturated with either water or a moisturizing solution

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(Krokida and Marinos-Kouris, 2003). Numerous empirical and semi-empirical models have been used to describe rehydration of porous foods (Wallach *et al*., 2011; Van der Sman *et al*., 2013; Ho *et al*., 2013; Van der Sman *et al*., 2014). These models include the Peleg Model (Peleg, 1988), the Weibull distribution (Marquas *et al*., 2009), the normalized Weibull distribution (Marabi *et al*., 2003) and diffusion models based on Fick's second law (Cunningham *et al*., 2008; Falade and Abbo, 2007).

Rehydration is not the opposite process to dehydration since the latter not only causes irreversible changes in the food but also alters its texture resulting in the migration of solutes and the loss of volatile substances. Dehydration also reduces the elasticity of cell walls and can cause protein coagulation thereby reducing their water retention capacity. The rate and intensity of rehydration are used to measure the quality of the dehydrated product (Vega and Lemus, 2006; Vergeldt *et al*., 2014). The purpose of this study is to determine the applicability of rehydration models in order to describe and predict the rehydration kinetics of yam chips.

MATERIALS AND METHODS

Samples of yam (*D. rotundata*) were collected in the municipality of Ciénaga de Oro, Córdoba, Colombia. The samples were cut into 3 cm-diameter×1 cm thick chips. A domestic microwave oven (Haceb HM-1.1) with a frequency of 2.450 MHz and internal dimensions 354 mm×228 mm×373 mm was used to dry the chips. The sample mass (50, 60 and 70 g) was taken and distributed uniformlyon the turntable plate. Different power levels (420 W, 560 W and 700 W) were evaluated.

Methods:

Rehydration: Method 88-04 (AACC, 1983) was used to determine the rehydration technique. Tests were conducted using yam chips (2.5 g) which were rehydrated at room temperature using 25 mL of distilled water or a 2.5 g/100/mL solution. Changes in weight during rehydration were recorded every 5 min until reaching a constant weight. The rate of rehydration (Zambrano *et al*., 2007) is represented by the slope of the curve according to the equation below:

$$X = X_{e-}(X_e - X_i)e^{-K_{reh}t}$$

In the above equation X represents the chips moisture content during rehydration (kg water/kg dry solid), while X_e accounts for the moisture content when reaching equilibrium, K_{reh} represents the rehydration rate in min^{-1} and t accounts for the time of rehydration (min).

Table 1: Mathematical models of rehydration

Model	Equation
Exponential model	(X_t-X_e)/(X_i-X_e) = e^(-P1*t^P2)
Peleg model	X_t = X_i+t/(P3+(P4*t))
First-order kinetics	(X_t-X_e)/(X_i-X_e) = e^(-P5*t)
Weibull distribution	X_t/X_e = 1-e^(-(t/∝)^β)
Normalized Weibull distribution	(X_t-X_i)/(X_e-X_i) = 1-e^-((t*Deff*Rg)/L^2)^β

Ertekin and Yaldiz (2005)

Rehydration capacity or RC (g rehydrated yam/g dry yam) which expresses the material's rehydration ability, can be calculated as follows:

$$RC = Wr/Wd$$

where,

Wr = The total weight at the end of the rehydration process

Wd = Corresponds to the weight of the dry material

Mathematical modelling: Models such as the Exponential model, Peleg model, First-order Kinetics, Weibull Distribution and Normalized Weibull Distribution (Table 1) were used to determine the model that best describes the kinetic behavior of yam rehydration. The Sum of Squares for Error (SSE) and the coefficient of determination (R^2) were also estimated in order to evaluate lack of fit. Low SSE values and high R2 values were used in order to determine which model provides the best fit.

Statistical analysis: Data analysis involved the use of a completely randomized 3^2factorial design corresponding to the numeric variables of power (420, 560 and 700 W) and mass (50, 60 and 70 g). 3 repetitions were made for a total of 27 experimental units. Data analysis was carried out using Statgraphics Centurion XVI.I software.

RESULTS AND DISCUSSION

Rehydration: Rehydration Capacity (RC) was affected by power and mass (p<0.05), while interaction did not show any difference. The numerical index of rehydration capacity (Sanjuán *et al*., 2001) was used to show structural changes in the final quality of rehydrated yam. Table 2 shows RC values for the different treatments to which the samples were subjected.

The average RC obtained shows that power (700 W) has a greater RC value than the other treatment intensities. This indicates that yam chips suffer greater tissue damage (cell membrane and cell wall) when subjected to this power level, resulting in an increase in water absorption capacity. On the other hand, the chips subjected to a 560 W power level showed less damage to their cellular structure and also remained denser and more rigid. Garcia *et al*. (2016) obtained similar results

Table 2: Rehydration capacity

	Mass (g)		
	50	60	70
Power (W)	Rehydration capacity (g water/g dry matter)		
420	1.67±0.30a[1]	1.67±0.32a	1.58±0.24a
560	1.58±0.31a	1.55±0.31a	1.53±0.21a
700	1.81±0.36b[2]	1.70±0.30b	1.74±0.36b

1, 2: different letters mean a significant difference in values

Table 3: Peleg model rehydration parameters

		Peleg's model		
Power	Mass	Parameters	SSE	R^2
420W				
	50 g	P3 = 0.910462457; P4 = 0.603351756	0.00531591	0.99826369
	60 g	P3 = 1.395629595; P4 = 0.507832512	0.06609218	0.98497636
	70 g	P3 = 2.323671831; P4 = 0.600402735	0.08869859	0.97921669
560W				
	50 g	P3 = 2.100422992; P4 = 0.264402247	0.07296679	0.98250296
	60 g	P3 = 1.717257455; P4 = 0.32973978	0.0410936	0.9864115
	70 g	P3 = 2.123184434; P4 = 0.788787799	0.04684806	0.98503709
700W				
	50 g	P3 = 1.224730917; P4 = 0.439693835	0.02903118	0.99569064
	60 g	P3 = 1.219592347; P4 = 0.556832417	0.04716357	0.9889896
	70 g	P3 = 1.466975554; P4 = 0.362496118	0.06113222	0.98960098

in rehydrated cassava chips. RC values show that drying damages plant tissues, which implies a greater rehydration capacity as well as a reduction in water retention capacity. Therefore, the more damaged the tissues are, the more capable they become to absorb water, however, they are not able to retain it. In addition, starch gelatinization prevents water from flowing within the matrix (Ogawa and Adachi, 2014).

Microwave dehydration is a heating technology that involves heating a product from its center to its surface. This not only affects the release of water vapor but also breaks the cell structure reducing the product's ability to retain rehydration (Doymaz and Ismail, 2013; Zura *et al*., 2013). Unlike the results obtained, previous studies have reported different RC values as follows: 1,947 g water/g dry matter in cassava dehydrated with a microwave (20 g/280 W) (Garcia *et al*., 2016); 0.927 g water/g dry matter in chestnuts dehydrated by hot air (Moreira *et al*., 2008); 1.2 g water/g dry matter in meat (Muñoz *et al*., 2012); and 5.28 g water/g dry matter in carrots (Melquíades *et al*., 2009).

Mathematical modelling: Data adjustment involved the use of (5) rehydration models: Exponential model, Peleg model, First-order kinetics, Weibull distribution and Normalized Weibull distribution. All models had R^2 values greater than 90%, except for the Weibull distribution, which had an R^2 value below 90%. The Peleg model (R^2>97.9% and 0.01 <SSE<0.001) was found to be the most suitable for describing the characteristics of yam rehydration as shown in Table 3. Previous research has shown that Peleg model also provides the best description of rehydration experimental data for products such as potato flour (Al-muhtaseb *et al*., 2004), beans (Ulloa *et al*., 2016), cured meat (Delgado and Sun, 2002) and yam chips (Montes *et al*., 2008).

Power and mass variables ($p<0.05$) have a significant effect on the Peleg model constants. The lowest P3 and P4 values were obtained by using a 700W power level, that is, an increase in power results in a decrease in the values of the constants. The P3 constant is a kinetic parameter that will depend on the rehydration temperature, while P4 is a constant characteristic of each food which is used to determine the moisture content when reaching equilibrium. The higher P4 value the lower the water absorption capacity, which confirms that chips dried at 700W have a higher RC.

CONCLUSION

Rehydration capacity was affected by the intensity of the treatments. The 700 W power level was responsible for most of the damage caused to the cell structure of the chips, resulting in greater water absorption as well as significant differences between power levels of 420W-700W and 560 W-700 W.

The results showed that Peleg model fitted much better (R^2>97.9% and 0.001<SSE<0.01), which suggests that this is the model that best describes the rehydration characteristics of yam.

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