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A N I N T E R N A T I O N A L J O U R N A L

Mathematical Modeling of Convective Air Drying of Quinoa-Supplemented Feed for Laboratory Rats

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ABSTRACT

Drying kinetics of quinoa-supplemented feed for laboratory rats during processing at 50, 60, 70, 80 and 90ºC was studied and modeled in this work. Desorption isotherm was obtained at 60ºC giving a monolayer moisture content of 0.04 g water/g d.m. The experimental drying curves showed that drying process took place only in the falling rate period. Several thin-layer drying equations available in the literature were evaluated based on determination coefficient (r^2), sum squared errors (SSE) and Chi-square (χ^2) statisticals. In comparison to the experimental moisture values, the values estimated with the Logarithmic model gave the best fit quality (r^2 >0.994, SSE < 0.00015 and χ^2 < 0.00018), showing this equation could predict very accurately the drying time of rat feed under the operative conditions applied.

Key words: rat feed, quinoa, drying kinetics, modeling, statistical test

INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is a native plant of the Andean region and is a member of the subsection Cellulata, genus *Chenopodium* (Bhargava et al., 2006). The agricultural potential of this crop is its adaptability, always providing high yield under any adverse climatological conditions (Tolaba et al., 2004; Gely and Santalla, 2007). Quinoa is not a true cereal but rather a fruit, thus, it has been called a pseudo-cereal and even a pseudo-oilseed. Quinoa seeds were used by the pre-Colombian Andean people as a stable food component and sometimes to replace the animal protein in their diet due to its unusual composition and exceptional balance between oil, protein and fat (Tolaba et al., 2004; Brady et al., 2007). The protein content, lysine, fat and fiber of quinoa are superior to those of wheat and other cereals like barley, corn and rice (Coulter and Lorenz, 1991; Koziol, 1992; Tolaba et al., 2004; Gely and Santalla, 2007). In addition, quinoa is a good source of vitamin E and several vitamins of group B. It also has desirable fatty acid composition and high levels of calcium, iron and phosphorous (Doğan and Karwe, 2003). These characteristics of

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quinoa make this cereal a perfect supplement not only for human diets but also for animal feeding (Amekbungwan, 2007).
The laboratory rat has become the most widely studied experimental animal model for biomedical research. Since 1966, the scientific literature has more than 300,000 research articles reporting the use of rats. More than 140 inbred strains of rats are currently available, mostly developed for specific disease characteristics, such as cancer, diabetes, hypertension, nutrition, cavity formation, alcohol preference and various inmunological responses. Rats have also been the model of choice for neurobiology, behavioral biology, toxicology and many other areas of biomedical research (Howard et al. 1995).
In particular, for rats whose diet consists of natural ingredients, possible changes in the formulation of these diets may be appropriate to generate improvements in ingredient availability and nutrient composition (Benevenga et al., 1995). Several authors have reported the beneficial effect of supplementing the rat's diet (Van Dam et al., 1999; Rashad and Moharib, 2003; Hanczakowski and Skraba, 2006; Rivera et al., 1978; Taylor et al., 2005). In addition, quinoa provides the diet formulation antioxidant components like vitamin E and phenolic compounds, and constitutes an important energy source (Jørgensen and Lindberg, 2006; Miranda et al., 2010).
In order to extend the shelf-life of food products, drying can be used as an effective method of preservation (Toğrul and Pehlivan, 2003). The basic objective of food dehydration is to remove the water to a level at which microbial spoilage is minimized. In addition to this increase in stability, there is a significant reduction in weight and volume that also contributes to reduce the cost of packaging, handling, storing and distribution of foodstuffs (Crapiste, 2000; Akpinar et al., 2003). Prior to studying the drying characteristics of any food, it is necessary to evaluate its moisture sorption behavior. Sorption behavior, represented by the food isotherms, describes the relationship between the water activity and the equilibrium moisture content of the product under study at a given temperature (Vega-Gálvez et al., 2008; Di Scala and Crapiste, 2008). An understanding of sorption parameters is, therefore, valuable in describing the intrinsic processing- and storage-induced changes in food quality (Sharma et al., 2009).
The mathematical modeling is a very useful tool for quickly and inexpensively ascertaining the effect of different system and process parameters on the outcome of a process (Sandeep and Irudayaraj, 2001). Mathematical modeling is an important tool to predict and simulate the drying experimental data. It also contributes to the design of the dryer equipment regarding to optimum drying times as well as a better understanding of the drying mechanism (Sacilik, 2007; Di Scala and Crapiste, 2008). In this regard, it is fundamental to control the air-drying temperature which is the operational condition affecting mainly the process kinetics (Di Scala and Crapiste, 2008; Vega-Gálvez et al., 2008, 2009).
Therefore, the aim of the present study was to determine experimentally the drying curves of quinoa-supplemented rat feed under different drying temperatures, to simulate experimental data with selected mathematical models and to evaluate the influence of temperature on the kinetic parameters of these models.

MATERIALS AND METHODS

Raw material and formulation

The quinoa-supplemented rat feed formulation was carried out mixing rat feed and quinoa (*Chenopodium quinoa* Willd.). The quinoa seed was obtained from a crop grown in 2008, Cahuil, VI Region, Chile. The rat feed was purchased from the local market of the city of La Serena, Chile. Before preparing the mixture, quinoa seeds were washed with agitated water during one hour to extract the highest amount of saponin, changing the water every 10 minutes. Then, 125 g of quinoa were blanched in 250 mL of water at 80ºC for 15 min. Subsequently, quinoa was drained and cooled at 10ºC. Finally, quinoa was mixed with 125 g of rat feed (Champion S.A.®, Chile) and 300 mL of water; this mixture was homogenized in a Meat Mincer (Brice meat Mince,TJ12 model, Sydney, Australia). This mixture was molded into a semisphere with a diameter 31.4 $\pm$ 0.30 mm and drying experiments were carried out.

Physico-chemical analysis

The moisture content was determined by AOAC method n◦ 934.06 (AOAC, 1990) employing a vacuum oven (Gallenkamp, OVL570, Leicester, UK) and an analytical balance with an accuracy of ± 0.0001 g (CHYO, Jex120, Kyoto, Japan). Crude protein content was determined using the Kjeldahl method with a conversion factor of 6.25 (AOAC no. 960.52). Lipid content was analyzed gravimetrically following Soxhlet extraction (AOAC no. 960.39). Crude fiber was estimated by acid/alkaline hydrolysis of insoluble residues (AOAC no. 962.09). Crude ash was estimated by incineration in a muffle furnace (Felisa, 360D) at 550°C (AOAC no. 923.03). All methodologies followed the recommendations of Official Method of Analysis (AOAC, 1990), and all the analyses were made in triplicate.

Moisture desorption isotherm

The desorption isotherm of the rat feed was determined at 60ºC. The methodology consisted in taking a known mass of sample (in triplicate) and allowing it come into equilibrium with an atmosphere produced by a saturated salt solution having a known relative humidity within a sealed container. This method was recommended by the European Project COST 90 (Spiess and Wolf, 1983). The weight of the samples was taken every 15 days until reaching constant weight (equilibrium condition). The salts used to obtain a range of water activity between 0.10 and 0.95 included LiCl, $KC_2H_3O_2$, $MgCl_2$, K_2CO_3, $NaNO_2$, KI, NaCl and KNO_2 (Labuza et al., 1985). All containers with solutions producing relative humidity greater than 75% were added separately a Thymol solution which inhibited the development of fungi in the system (Vega-Gálvez et al., 2008). The model used for the prediction of the equilibrium moisture content of rat feed was the equation proposed by Guggenheim, Anderson and de Boer, commonly termed GAB (equation 1) (Tolaba et al., 2004; Ait Mohamed et al., 2005).

$$X_{we} = \frac{X_m \cdot C \cdot k \cdot a_w}{(1 - k \cdot a_w) \cdot (1 + (C - 1) \cdot k \cdot a_w)} \quad (1)$$

where X_{we} is the equilibrium moisture content (g water/g dm,), a_w is the water activity (dimensionless) and X_m monolayer moisture content (g water/g dm,).

Experimental determination of drying curves

The drying experiments were carried out using a convective dryer designed and built in the Department of Food Engineering of Universidad de La Serena (Fig. 1). Five temperatures were used in the study of the drying kinetics (50, 60, 70, 80 and 90ºC). The drying air flow rate was held constant at 2.0 ± 0.2 m/s and measured with an omnidirectional anemometer (Extech Instrument Inc., 451112, Waltham, USA). The inlet relative humidity was 67.6 ± 5.6%, measured by an ambient digital hygro-thermometer (Extech Instrument Inc., 445703, Waltham, USA). All the drying experiments were carried out in triplicate, using a sample mass of 9.4 ± 0.49 g and a load density of 1.9 ± 0.09 kg/m^2. The mass was measured on an analytical balance (Ohaus, SP402, New Jersey, USA) with an accuracy of ± 0.01 g at defined time intervals, connected by a system interface (Ohaus, RS232, New Jersey, USA) to a PC, which recorded and stored the data. The experiments were finished at the point of reaching constant weight (equilibrium condition). The dried samples were packaged in polypropylene bags.

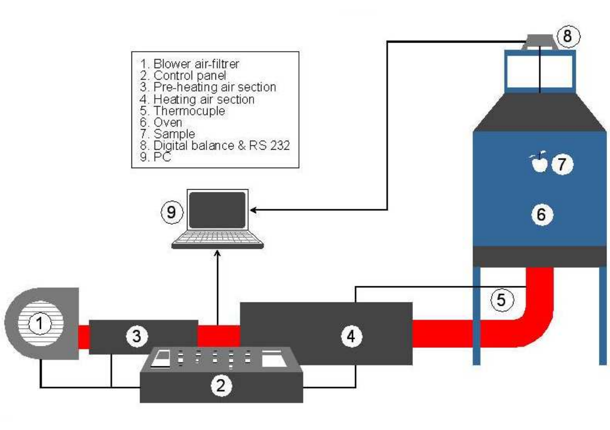

Figure 1-Schematic diagram of drying equipment.

Mathematical modeling

To simulate the experimental drying curves, some mathematical models were used (Table 1). All these equations used the moisture ratio (MR) as dependent variable (equation 2), which related the gradient of the sample moisture content in real time with the initial moisture content and the equilibrium moisture content (Akpinar et al., 2003; Babalis and Belessiotis, 2004; Simal et al., 2005).

$$MR = \frac{X_{wt} - X_{we}}{X_{wo} - X_{we}} \quad (2)$$

where X_{wt} is the moisture content (g water/g dm,), X_{wo} is the initial moisture content (g water/g dm,) and X_{we} is the equilibrium moisture content (g water/g dm,)

The Arrhenius-type equation was used to evaluate the dependence with the temperature on the empirical parameters k_i (i = 1, 2,…,11), n_i (i = 1, 2, …, 10), c, α and β, from which the activation energy (E_a) was determined.

$$Y = Y_o \cdot \exp\left[{-E_a}/{RT} \right] \quad (12)$$

where Y is the parameter to be studied, Y_o is the Arrhenius factor, R is the universal gas constant (8.314 J/mol K) and T is the absolute temperature (K).

Statistical tests

The fit quality of the experimental data to all models was evaluated using determination coefficient (r^2, equation 13), sum square errors (SSE, equation 14) and Chi-square (χ^2, equation 15) (Akpinar, 2006; Hayaloglu et al., 2007). The Statgraphics Plus® 5.1 software (Statistical Graphics Corp., Herndon, USA) was used to estimate statistically significant differences among samples, applying analysis of variance (ANOVA) for a confidence level of 95% (P value < 0.05) (Vega- Gálvez et al., 2008). This analysis was carried out to estimate if there were least significant differences (LSD) among the means of the kinetic and empirical parameters of all the models. The multiple range test (MRT) was used to determine if there were possible homogeneous groups among the parameters.

$$r^2 = \frac{\sum_{j=1}^{N} \left(MR_{ci} - \overline{MR}_{ei} \right)^2}{\sum_{j=1}^{N} \left(MR_{ei} - \overline{MR}_{ei} \right)^2} \quad (13)$$

$$SSE = \frac{1}{N} \sum_{j=1}^{N} \left(MR_{ei} - MR_{ci} \right)^2 \quad (14)$$

$$\chi^2 = \frac{\sum_{j=1}^{N} \left(MR_{ei} - MR_{ci} \right)^2}{N - z} \quad (15)$$

where MR_{ei} is the experimental moisture ratio (g water/g dm,), MR_{ci} is the calculated moisture ratio (g water/g dm,), $\overline{MR}_{ei}$ is the average experimental moisture ratio (g water/g dm,), N is the number of data values, z is the number of constants and j is the number of terms.

RESULTS AND DISCUSSION

Raw material and Physico-chemical analysis

Proximate analysis of the mixture (quinoa and rats feed) presented an initial moisture content of 70.05 ± 0.02 g/ 100 g dm.; crude protein (nitrogen x 6.25) of 6.82 ± 0.01 g/ 100 g dm.; total lipids of 5.30 ± 0.01 g/ 100 g dm..; crude fiber of 3.36 ± 0.01 g/100 g dm; crude ash of 1.65 ± 0.03 g/100 g dm.; and available carbohydrates (by difference) of 11.81 ± 0.05 g/100 g dm. Proximate analysis of quinoa seeds can be found in previous work (Miranda et al., 2010).

Moisture desorption isotherm

The European Project COST 90 recommends that the GAB equation is the most appropriate model to satisfactorily describe moisture isotherms over a wide range of water activity in most foods (Sharma et al., 2009). For the five drying experiments, an average outlet air-drying temperature of 60.0 ± 2.5ºC was obtained; thus, desorption isotherm modeled by the GAB equation was determined at 60ºC. Figure 2 shows the desorption isotherm for rat feed for both experimental and GAB-calculated moisture content data as function of water activity at the mentioned temperature. The values of GAB-parameters were 0.04 (g water/g dm,), 0.89 and 60.94 for X_m, k and C, respectively. The parameter C was related to the upper and first sorption layers; and k could represent the interaction energies between multilayer properties with respect to bulk liquid (Erbas et al., 2005).

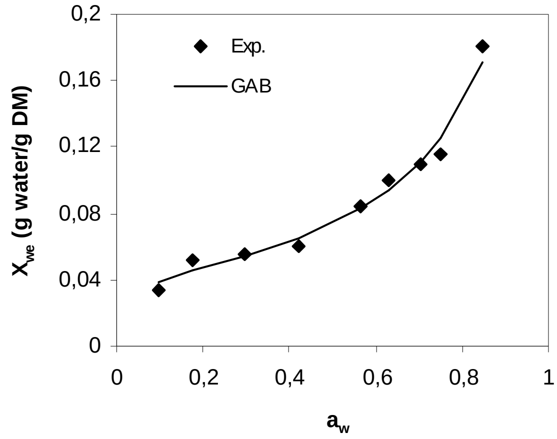

Figure 2 - Desorption isotherm of rats feed modeled by the GAB equation at 60 ºC.

The monolayer moisture content value was lower when comparing to those reported in other works for quinoa seeds (0.087-0.059 g water / g dm, 20-40ºC, Tolaba et al. ,2004); pea seeds (0.091-0.059 g water / g dm, 25-50ºC, Chen, 2003) and amaranth grains (0.063-0.049 g water / g dm., 40-70ºC, Calzetta et al., 2004).

Considering Figure 2 and the value obtained for parameter C, this isotherm could correspond to the type II according to Van der Waals classification (Erbas et al., 2005). According to the statistical tests, the GAB equation gave a good fit to the experimental moisture data (r^2= 0.94; SSE= $2.24x10^{-4}$ and χ^2= $3.20x10^{-4}$), demonstrating the ability of this model for predicting sorption data.

Mathematical modeling of drying curves

Figure 3 shows the experimental drying curves for the five working temperatures (50, 60, 70, 80 and 90ºC). All curves showed a clear exponential tendency and as the air-drying temperature increased, MR decreased rapidly. As expected, it was observed that the drying time decreased as temperature increased to reach similar moisture content. Similar drying behavior was reported by Vega-Gálvez et al. (2009) working with quinoa and Guiné et al. (2006) with chestnut.

For example, the time required to achieve a moisture content lower than 0.02 g water/g dm at 50ºC was 600 minutes, which was approximately twice the time necessary to reach the same moisture content at a temperature of 70ºC (300 minutes), and nearly three times for a temperature of 80ºC and 90ºC (240 minutes). These results were similar to those reported by Doymaz (2009) and Karabulut et al. (2007), working with spinach leaves and kurut, respectively. Likewise, only the presence of the falling rate period was observed explaining the use of the empirical models presented in Table 1. Table 2 shows the average values and standard errors of the parameters k_i (i = 1, 2, …, 11), n_i (i = 1, 2, …, 10), c, α and β, obtained for all proposed models. The parameters k_i increased as drying temperature increased. Similar relatively high values for k_i and n_i were reported by Vega-Galvez et al. (2009) working with quinoa when applying the same mathematical models of the present study and Duran et al. (2008) working with dried cereal.

From the ANOVA carried out to the parameters k_i (i = 1, 2, …, 11), n_i (i = 1, 2, …, 10), c, α and β of the proposed models for a confidence level of 95%, a P value < 0.05 was obtained for all of them, except for n_1, n_2, n_3, n_6, n_8 and α. This showed that there was statistically significant difference, and thus dependence on the drying temperature for most of these kinetic parameters, except for n_1, n_2, n_3, n_6, n_8 and α. The Arrhenius-type equation was applied to the parameters that showed dependence on temperature, resulting in an activation energy of 21.37 (k_1), 22.27 (k_2), 15.29 (k_3), 20.91 (k_4), 43.48 (n_4), 21.87 (k_5), 20.85 (β), 1.21 (n_5), 66.98 (k_6), 9.85 (c), 21.04 (k_7), 0.38 (n_7), 21.04 (k_8), 21.04 (k_9), 0.39 (n_9), 21.04 (k_{10}), 21.04 (n_{10}), 21.04 (k_{11}) kJ/mol. The parameters n_1, n_2, n_3, n_6, n_8 and α (P value >0.05) probably depended rather on the characteristics of the tissue and/or the drying air rate (Mwithiga and Olwal, 2004).

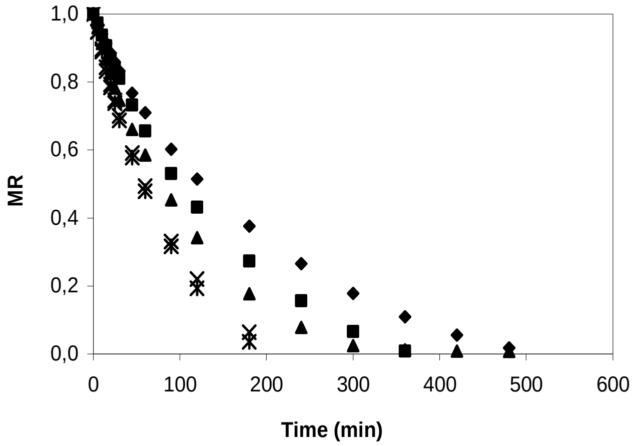

Figure 3 - Experimental drying curves of rats feed for the five working temperatures (ºC). ♦= 50 ºC; ■= 60 ºC; ▲=70ºC; X = 80ºC and ✳=90 ºC.

Table 1 - Mathematical models available in literature for simulating the experimental drying curves of rats feed

no.	Name	Model equation	References
3	Newton	$MR = \exp(-k_1 t)$	Simal et al. (2005)
4	Henderson and Pabis	$MR = n_1 \cdot \exp(-k_2 t)$	Doymaz (2009)
5	Page	$MR = \exp(-k_3 t^{n_2})$	Senadeera et al. (2003)
6	Modified page	$MR = \exp(-(k_4 t)^{n_3})$	Toğrul and Pehlivan (2003)
7	Wang-Singh	$MR = k_5 t^2 + n_4 t + 1$	Ertikin and Yaldiz (2004)
8	Logarithmic	$MR = n_5 \cdot \exp(-k_6 t) + c$	Midilli and Kucuk (2003)
9	Two term	$MR = n_6 \cdot \exp(-k_7 t) + n_7 \cdot \exp(-k_8 t)$	Doymaz (2004)
10	Modified Henderson and Pabis	$MR = n_8 \cdot \exp(-k_9 t) + n_9 \cdot \exp(-k_{10} t) + n_{10} \cdot \exp(-k_{11} t)$	Akpinar et al. (2003)
11	Weibull	$MR = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]$	Corzo et al. (2008)

Table 2-Values of the kinetic and empirical parameters of the proposed mathematical models for simulating the experimental drying curves of rats feed

nº Eq.	Parameters	Air drying temperatures (ºC) ($x\ 10^{-2}$)				
		50	60	70	80	90
3	k_1 (min^{-1})	0.670 ± 0.075^{a}	0.930 ± 0.096^{a,b}	1.070 ± 0.180^{b}	1.403 ± 0.189^{c}	1.627 ± 0.259^{c}
4	n_1	108.521 ± 5.993	114.554 ± 7.444	106.824 ± 13.854	108.860 ± 4.712	115.984 ± 4.433
	k_2 (min^{-1})	0.693 ± 0.087^{a}	0.990 ± 0.123^{a,b}	1.103 ± 0.231^{b}	1.483 ± 0.234^{c}	1.770 ± 0.291^{c}
5	n_2	101.953 ± 4.504	110.227 ± 3.952	104.463 ± 6.598	107.733 ± 8.115	110.913 ± 2.706
	k_3(min^{-1})	0.562 ± 0.156^{a}	0.483 ± 0.081^{a,b}	0.823 ± 0.251^{a,b}	0.937 ± 0.290^{b}	0.882 ± 0.227^{b}
6	n_3	101.953 ± 4.504	110.227 ± 3.952	104.463 ± 6.598	107.733 ± 8.115	2.706 ± 2.706
	k_4(min^{-1})	0.608 ± 0.045^{a}	0.786 ± 0.024^{a}	1.006 ± 0.069^{b}	1.274 ± 0.128^{c}	1.388 ± 0.168^{c}
7	n_4	0.001 ± 0.045^{a}	0.001 ± 0.001^{a,b}	0.001 ± 0.001^{b}	0.003 ± 0.001^{c}	0.003 ± 0.001^{c}
	k_5(min^{-1})	-0.448 ± 0.036^{a}	-0.580 ± 0.017^{a}	-0.675 ± 0.045^{b}	-1.008 ± 0.063^{b}	-1.040 ± 0.103^{c}
8	n_5	106.629 ± 1.821^{a}	111.233 ± 0.420^{a,b}	102.907 ± 4.166^{b,c}	110.508 ± 2.589^{b,c}	114.008 ± 4.105^{c}
	k_6(min^{-1})	0.484 ± 0.036^{a}	0.598 ± 0.015^{a}	0.870 ± 0.102^{b}	1.138 ± 0.096^{b}	1.027 ± 0.158^{b}
	c	-7.933 ± 1.158^{a}	-11.339 ± 0.726^{a,b}	-3.349 ± 4.010^{a,b}	-10.447 ± 1.681^{b,c}	-14.145 ± 3.573^{c}
9	n_6	49.750 ± 0.586	50.723 ± 0.256	49.890 ± 0.710	50.294 ± 0.961	50.607 ± 0.436
	k_7(min^{-1})	0.577 ± 0.577^{a}	0.751 ± 0.009^{b}	0.935 ± 0.037^{c}	1.242 ± 0.115^{d}	1.315 ± 0.134^{d}
	n_7	50.177 ± 50.177^{a}	50.767 ± 0.167^{a,b}	50.310 ± 0.297^{b,c}	51.079 ± 0.343^{c}	51.013 ± 0.289^{c}
10	k_8(min^{-1})	0.577 ± 0.577^{a}	0.751 ± 0.009^{b}	0.934 ± 0.037^{c}	1.242 ± 0.115^{d}	1.315 ± 0.134^{d}
	n_8	33.017 ± 33.017	33.684 ± 0.175	33.100 ± 0.501	33.332 ± 0.690	33.573 ± 0.311
	k_9(min^{-1})	0.577 ± 0.577^{a}	0.751 ± 0.009^{b}	0.934 ± 0.037^{c}	1.242 ± 0.115^{d}	1.315 ± 0.134^{d}
	n_9	33.576 ± 33.576^{a}	34.065 ± 0.133^{a,b}	33.689 ± 0.296^{b,c}	34.142 ± 0.367^{b,c}	34.183 ± 0.207^{c}
	k_{10}(min^{-1})	0.577 ± 0.034^{a}	0.751 ± 0.009^{b}	0.934 ± 0.037^{c}	1.242 ± 0.115^{d}	1.315 ± 0.134^{d}
	n_{10}	33.335 ± 0.156^{a}	33.742 ± 0.115^{a,b}	33.411 ± 0.209^{b,c}	33.899 ± 0.244^{c}	33.864 ± 0.206^{c}
	k_{11}(min^{-1})	0.577 ± 0.034^{a}	0.751 ± 0.009^{b}	0.934 ± 0.037^{c}	1.242 ± 0.115^{d}	1.315 ± 0.134^{d}
11	α	101.953 ± 4.504	110.227 ± 3.952	103.970 ± 6.123	107.733 ± 8.115	110.913 ± 2.706
	β	16521.008 ± 1287.077^{a}	12728.340 ± 389.520^{a}	10261.100 ± 442.068^{b}	7898.385 ± 750.610^{c}	7231.801 ± 794.114^{d}

[a,b,c,d]Means with no common superscript differ significantly (P value< 0.0.

Statistical tests

Table 3 shows the results of statistical tests (r^2, SSE and χ^2) applied to the proposed equations. These statisticals evaluate the models fit quality of the experimental data and they have been used by other researchers in many food drying studies (Toğrul and Pehlivan, 2003; Doymaz, 2004; Akpinar, 2006). In general, all proposed models showed a good fit with high values of r^2 (r^2>0.93) and values close to zero for SSE and χ^2. According to the results, the model that best fitted the experimental data considering the regression coefficient ($r^2 \geq 0.99$) as the first criterion of selection, was the Logarithmic model, followed by Two-Term, Modified Henderson-Pabis and Weibull models. However, when evaluating the fit quality with the other two statisticals applied, the lowest values were obtained for SSE< 0.00015 and χ^2< 0.00018 for the Logarithmic model. Thus, if the three statisticals applied were considered, the equation that best fitted the experimental moisture data was the Logarithmic model. This good fit quality on experimental data could be explained because the Logarithmic model presents three terms, which provided a better mathematical approximation on the drying curves with exponential tendency. Several studies have also presented similar results for the Logarithmic model during the drying process of, e.g. apple, spinach leaves, tomate and chestnut (Velić et al., 2007; Doymaz, 2009; Sacilik, 2007; and Midilli and Kucuk, 2003).

Figure 4 presented the experimental and calculated MR values for the Logarithmic model, which showed the best fit quality on experimental data over the entire drying process. In the same figure, the Two-Term, Modified Henderson-Pabis and Weibull models are also plotted showing their goodness to the experimental curve fitting.

Table 3 - Statistical tests of the proposed model for each drying temperature

		Air drying temparatures				
Models	**Statistics**	**50 ºC**	**60 ºC**	**70 ºC**	**80 ºC**	**90 ºC**
Newton	r^2	0.96383	0.93807	0.96463	0.97613	0.94650
	SSE	0.00137	0.00317	0.00104	0.00158	0.00358
	χ^2	0.00144	0.00335	0.00110	0.00169	0.00383
Henderson-Pabis	r^2	0.96720	0.94633	0.96970	0.98230	0.95910
	SSE	0.00183	0.00462	0.00041	0.00060	0.00598
	χ^2	0.00203	0.00520	0.00165	0.00276	0.00690
Page	r^2	0.99603	0.99500	0.99547	0.99710	0.99377
	SSE	0.00066	0.00065	0.00041	0.00060	0.00071
	χ^2	0.00073	0.00073	0.00043	0.00064	0.00076
Modified Page	r^2	0.99603	0.99500	0.99547	0.99710	0.99377
	SSE	0.00057	0.00062	0.00031	0.00054	0.00065
	χ^2	0.00064	0.00069	0.00035	0.00062	0.00075
Wang-Singh	r^2	0.99183	0.99570	0.98287	0.99647	0.99603
	SSE	0.00164	0.00033	0.00170	0.00050	0.00049
	χ^2	0.00189	0.00038	0.00201	0.00059	0.00059
Logarithmic	r^2	0.99940	0.99970	0.99907	0.99973	0.99977
	SSE	0.00015	0.00003	0.00013	0.00001	0.00003
	χ^2	0.00018	0.00005	0.00015	0.00002	0.00003
Two term	r^2	0.99737	0.99627	0.99790	0.99740	0.99567
	SSE	0.00012	0.00046	0.00021	0.00025	0.00005
	χ^2	0.00016	0.00072	0.00031	0.00044	0.00009
Modified Henderson-Pabis	r^2	0.99737	0.99627	0.99790	0.99740	0.99567
	SSE	0.00012	0.00053	0.00023	0.00029	0.00051
	χ^2	0.00019	0.00088	0.00036	0.00059	0.00102
Weibull	r^2	0.99603	0.99500	0.99547	0.99710	0.99377
	SSE	0.00056	0.00061	0.00025	0.00054	0.00073
	χ^2	0.00062	0.00069	0.00028	0.00062	0.00084

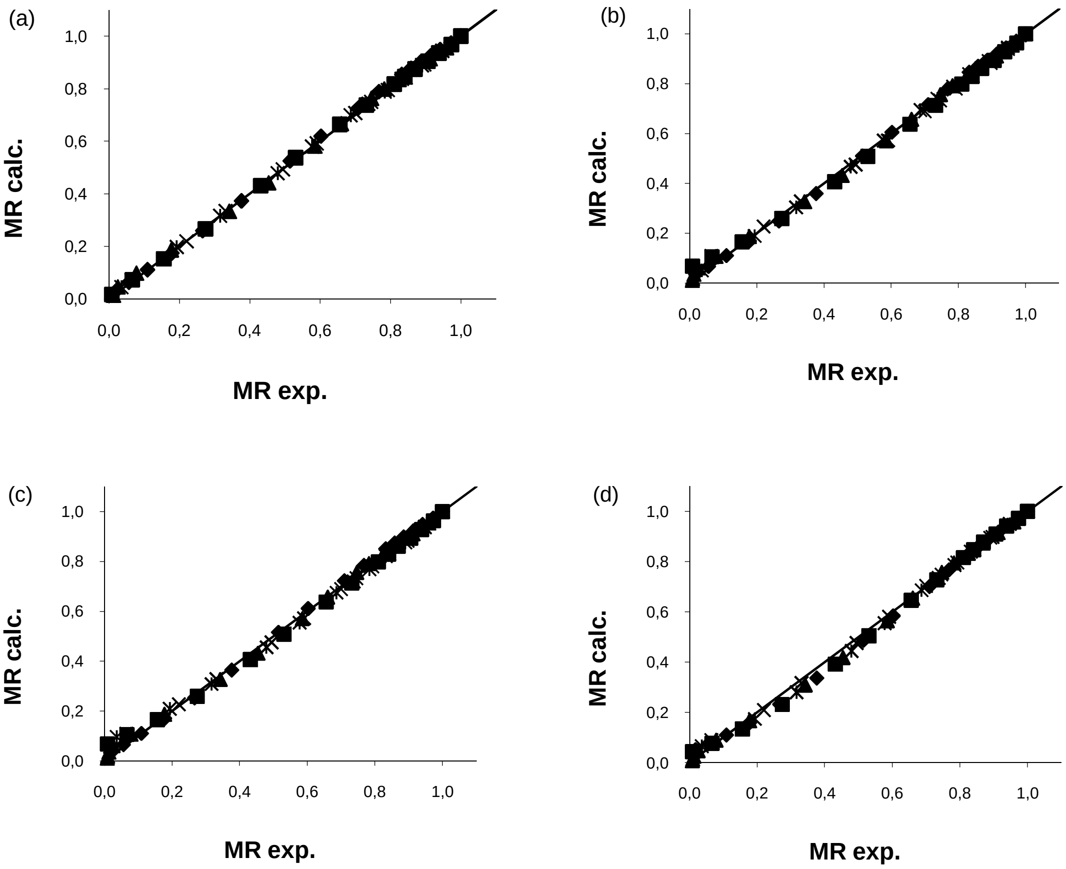

Figure 4 - Comparison of the experimental and predicted moisture ratios by (a) Logarithmic (b) Two-Term, (c) Modified Henderson-Pabis and (d) Weibull models for rats feed. ♦= 50 ºC; ■= 60 ºC; ▲=70ºC; X = 80ºC and ✳=90 ºC.

CONCLUSIONS

The drying characteristics of quinoa-supplemented rat feed at different temperatures were studied in this work. The desorption isotherm showed a sigmoidal shape, which gave a good fit for the experimental data using GAB equation (r^2= 0.94; SSE= $2.24x10^{-4}$ and χ^2= $3.20x10^{-4}$). The drying curves showed a clear exponential tendency. An increase of the drying temperature from 50 to 90ºC decreased in one third the drying time (from 600 to 240 minutes). All the kinetic parameters of the proposed models showed positive dependence on temperature, except for n_1, n_2, n_3, n_6, n_8 and α. According to the statistical tests applied, the Logarithmic model gave the best fit for the experimental data, with $r^2 \geq 0.994$, SSE< 0.00015 and χ^2< 0.00018 indicating that this model was the most suitable to simulate the product drying rates under the process conditions presented. This study corresponds to the first stage for evaluating quinoa as rat feed supplement. However, more accurate studies are necessary in relation to the influence of temperature on the nutritional value of this food supplement.

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