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MATHEMATICAL MODELING OF THIN-LAYER DRYING KINETICS OF CAPE GOOSEBERRY (*PHYSALIS PERUVIANA* L.)

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ABSTRACT

Drying kinetics of Cape gooseberry was studied and modeled during processing at four temperatures (60, 70, 80 and 90C). Desorption isotherm was obtained at 40C giving a monolayer moisture content of 0.086 g water/g d.m. Experimental drying curves showed that drying process took place only in the falling rate period. Several thin-layer drying models available in the literature were evaluated based on statistical tests as sum squared error (SSE), chi-square (χ^2) and determination coefficient (R^2). Effective moisture diffusivity of Cape gooseberry was in the range of $4.67–14.9 \times 10^{-10}$ m^2/s. A value of 38.78 kJ/mol was determined as activation energy. When comparing the experimental with predicted moisture values, the Midilli–Kucuk model was found to give the best fit quality ($SSE < 0.001$, $\chi^2 < 0.001$, $R^2 > 0.99$), showing this equation to predict very accurately the drying time of Cape gooseberry under the operating conditions studied.

PRACTICAL APPLICATIONS

Demand for natural and healthy fruit and vegetable products with extended shelf life has urged the dehydrated food industry to look for raw materials of desirable nutritional and functional properties. Cape gooseberry, with its highly nutritional composition and its content of biologically active health-promoting components, is therefore an excellent fruit raw material for the dehydrated food industry. Drying has the potential to deliver safe food products through enzyme inactivation and microbe destruction. Therefore, modeling of drying kinetics, as well as acquiring data on desorption isotherm or diffusion coefficient, is needed by the industry to manage efficiently dehydration techniques and avoid energy misuse. This could serve to demonstrate the environmental consciousness of the food processing industry, greatly appreciated by consumers.

INTRODUCTION

Cape gooseberry or goldenberry, with botanical name *Physalis peruviana* Linnaeus, belongs to the family Solanaceae and genus *Physalis*, which includes about 120 species. Most of these species grow in South America, North America, South Africa, India, New Zealand, Australia and Egypt (Ramadan and Mörsel 2007; Fang *et al*. 2009). Cape gooseberry is a herbaceous, semishrub, upright and perennial plant in subtropical zones. Its fruit, also called Cape gooseberry, is covered by a brilliant yellow peel and is protected by an accrescent calyx that acts as a protecting shield against insects, birds, diseases and adverse climatic situations (Puente *et al*. 2011; Ramadan 2011).

The benefits associated with Cape gooseberry are mainly due to its nutritional composition and characteristics besides the presence of biologically active health-promoting components (Puente *et al*. 2011). In addition to having a future as fresh fruits, the exotic fruit can be consumed in many ways as an interesting ingredient in salads, cooked dishes, desserts, jams, natural snacks as well as preserves (Ramadan and Mörsel 2003). They are an excellent source of provitamin A, vitamin C, iron and some of the vitamin B-complex. The protein and phosphorus levels in the fruits are exceptional, likewise pectin which is used in jam production (Salazar *et al.* 2008).

In order to extend the shelf life of food products, drying can be used as an effective method of preservation (Toğrul and Pehlivan 2003). This unit operation is defined as a process of moisture removal, where simultaneous heat and mass transfer occurs, leading to a decrease of the water activity in the product, thus avoiding spoilage and contamination during storage (Akpinar *et al.* 2003). Several authors have suggested that the dominant mechanism in the drying of foods is the water diffusion from inside the food to the surface in contact with the drying air (Barbosa-Cánovas and Vega-Mercado 2000). The mathematical modeling of the drying kinetics is crucial for optimization of the process itself, and helps to control operational parameters. There are many empirical or semiempirical models for the simulation of drying process. Most of these models are derived by simplifying the general solutions of Fick's second law. Therefore, most of them are not arbitrarily chosen models; on the contrary, they are based on physiological characteristics (Hacihafizoğlu *et al.* 2008).

Prior to studying the drying characteristics of any food, it is necessary to evaluate its moisture sorption behavior, represented by the food isotherms that describe the relationship between water activity and equilibrium moisture content of the product under study at a given temperature (Di Scala and Crapiste 2008; Vega-Gálvez *et al.* 2009). 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 aims of the present study were to determine and to model the drying kinetics and the desorption isotherm of Cape gooseberry (*P. peruviana* L.) using specific mathematical equations for both phenomena, and to evaluate the influence of drying air temperature on the kinetic parameters.

MATERIALS AND METHODS

Raw Materials

Cape gooseberries were cultivated and purchased in the city of Olmue (V-Region, Neuquen Agricultural), Chile. The samples were selected to provide a homogeneous group based on date of harvest, color, size and freshness according to visual analysis. They were refrigerated at 5C until drying. The moisture content was determined by AOAC method no. 934.06 (AOAC 1990), employing a vacuum oven (OVL570, Gallenkamp, Loughborough, U.K.) and an analytical balance accurate to ±0.0001 g (Jex120, CHYO, Tokyo, Japan). Crude protein content was determined using the Kjeldahl method with a conversion factor of 6.25. Lipid content was analyzed gravimetrically following Soxhlet extraction. Crude ash was estimated by incineration in a muffle furnace (Felisa, 360D) at 550C. All methodologies followed the recommendations of the Official Method of Analysis (AOAC 1990). Acidity was determined by the adapted AOAC methodology no. 942.15A (AOAC 1990), pH was measured using a potentiometer (Microcomputer pH-Vision 246072, Extech Instruments, Waltham, MA), and sugar content was measured using an Abbé refractometer (1-T, ATAGO, Tokyo, Japan). All the analyses were made in triplicate and expressed in g/100 g fruit.

Sorption Isotherm

Desorption isotherm for Cape gooseberry was determined at 40C. The methodology consisted of taking a known mass of sample (in triplicate) and allowing it to come to equilibrium under 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 constant weight is reached (equilibrium condition). The salts used to obtain a range of water activity of 0.10–0.95 included LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, $Mg(NO_3)_2$, $NaNO_3$, KI, NaCl, KCl and KNO_3 (Labuza *et al.* 1985). Sealed containers with salt solutions that generated a relative humidity greater than 75% had thymol added in a Petri dish separated from the sample and the salt solution in order to prevent the development of fungi in the sample (Vega-Gálvez *et al.* 2009).

The model used to predict the equilibrium moisture content of Cape gooseberry was the equation proposed by Guggenheim, Anderson and de Boer, commonly termed as the GAB model (Eq. 1), which is usually used in moisture sorption experiments for different foods, since it is considered to have parameters based on physicochemical phenomena, such as the monolayer moisture content (X_m), C and K are the adsorption constants, which are related to the energies of interaction between the first and the further sorbed molecules at the individual sorption sites, and A_w is the water activity (Tolaba *et al.* 2004; Ait Mohamed *et al.* 2005; Di Scala and Crapiste 2008; Vega-Gálvez *et al.* 2009). The GAB model has been used due to its theoretical bases, it describes the sorption behavior in a wide range of A_w from 0.1 to 0.9 (Vega-Gálvez *et al.* 2009). In addition, the use of the GAB equation has been recommended by the European COST 90 project (Spiess and Wolf 1983).

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

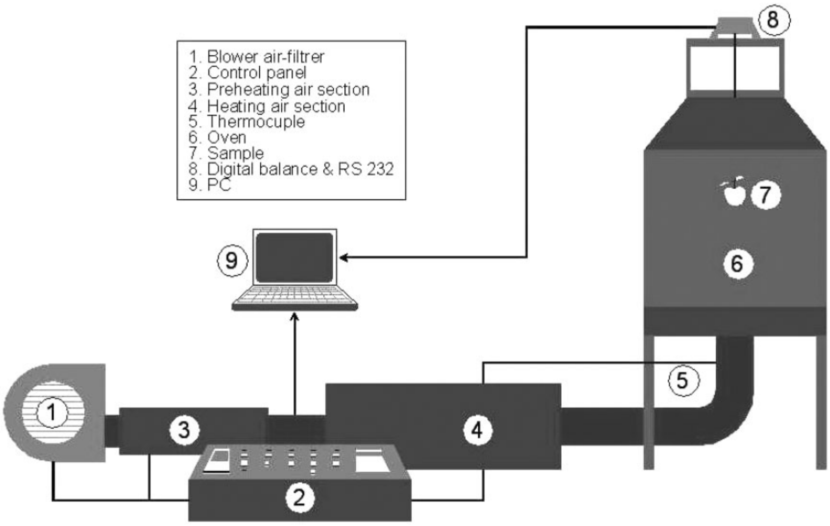

FIG. 1. SCHEMATIC DIAGRAM OF DRYING EQUIPMENT

Drying Experiments

Drying experiments, performed in triplicate, were carried out at four temperatures (60, 70, 80 and 90C), employing a constant air flow of 1.5 ± 0.2 m/s (perpendicular direction to sample). The Cape gooseberry samples were arranged in a thin layer within a stainless steel basket with a load density of 14.51 ± 0.66 kg/m^2. The drying process was carried out in a convective dryer (Fig. 1) designed and built at the Department of Food Engineering of Universidad de La Serena (Vega-Gálvez *et al.* 2009). The mass was measured on an analytical balance (SP402, Ohaus, Pinebrook, NJ), with an accuracy of ±0.01 g at defined time intervals, connected by a system interface (RS232, Ohaus) to a PC, which served as a monitor to record the data until constant weight (equilibrium condition) was reached.

Mathematical Modeling of Drying Kinetics

In the present experiment, the moisture ratio (MR) as dependent variable (Eq. 12) was used. This relates the gradient of the sample moisture in real time with the initial and equilibrium moisture content (Babalis and Belessiotis 2004). The integrated equation of Fick's second law was also used for long time periods and spherical geometry in one dimension (Eq. 13), which leads to Eq. (14), representing the first term in the development of the series (Crank 1975; Pardeshi and Chattopadhyay 2010), from which the diffusional coefficient is obtained for each temperature, where X_{wt} is the real time moisture content (g water/g d.m.); X_{wo} is the initial moisture content (g water/g d.m.); X_{we} is the equilibrium moisture content (g water/g d.m.); j is the number of terms; t is time (minute); and r is the mean equivalent ratio.

Numerous mathematical models have been proposed to describe the characteristics of agricultural products during drying (Doymaz 2008; Pardeshi and Chattopadhyay 2010). All the equations applied in this study to model the drying kinetics of Cape gooseberry are shown in Table 1. In this research, the shrinkage phenomenon was assumed as negligible, although it is widely well known that it is notorious in fruit dehydration.

$$MR = \frac{X_{wt} - X_{we}}{X_{wo} - X_{we}} \tag{12}$$

$$MR = \frac{6}{\pi^2} \sum_{j=1}^{\infty} \frac{1}{j^2} \exp\left[\frac{-j^2 D_{we} \pi^2 t}{r^2}\right] \tag{13}$$

$$MR = \frac{6}{\pi^2} \exp\left[\frac{-D_{we} \pi^2 t}{r^2}\right] \tag{14}$$

To evaluate the dependence on temperature of the diffusion coefficient (D_{we}) and the empirical parameters k_i, (i = 1, 2 . . . 12), n_i (i = 1, 2 . . . 12), c, α and β, an Arrhenius-type equation (Eq. 15) was used, from which the activation energy (E_a) was determined.

$$Y = Y_o \cdot \exp[-E_a/RT] \tag{15}$$

Statistical Analysis

The statistical analysis of experimental data was determined using StatGraphics Plus 5.1 (Statistical Graphics Corp., Herndon, VA), applying an analysis of variance (ANOVA) to estimate any statistically significant difference at a confidence level of 95% ($P < 0.05$). Goodness of fit of the proposed models for the desorption isotherm and drying kinetics data was evaluated by means of statistical tests

TABLE 1. MATHEMATICAL MODELS USED BY VARIOUS AUTHORS IN STUDYING DRYING BEHAVIOR

Eq.	Name	Model equation	References
2	Newton	$MR = \exp(-k_1 t)$	Vega-Gálvez *et al.* 2009
3	Henderson and Pabis	$MR = n_1 \cdot \exp(-k_2 t)$	Doymaz 2007
4	Page	$MR = \exp\left(-k_3 t^{n_2}\right)$	Senadeera *et al.* 2003
5	Modified page	$MR = \exp\left(-(k_4 t)^{n_3}\right)$	Toğrul and Pehlivan 2003
6	Wang–Singh	$MR = k_5 t^2 + n_4 t + 1$	Ertekin and Yaldiz 2004
7	Logarithmic	$MR = n_5 \cdot \exp(-k_6 t) + c$	Akpinar 2006
8	Two-term	$MR = n_6 \cdot \exp(-k_7 t) + n_7 \cdot \exp(-k_8 t)$	Doymaz 2007
9	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
10	Weibull	$MR = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right]$	Corzo *et al.* 2008
11	Midilli–Kucuk	$MR = n_{11} \cdot \exp\left(-k_{12} t^{n_{12}}\right) + ct$	Midilli *et al.* 2002

including the determination coefficient (R^2), sum squared error (SSE) (Eq. 16) and chi-square (χ^2) (Eq. 17). The lowest values of SSE and χ^2, together with the highest values of R^2 ($\approx$1.0), were considered as criteria in selecting the best fit among models.

$$SSE = \frac{1}{N}\sum_{j=1}^{N}\left(MR_{ej} - MR_{cj}\right)^2 \tag{16}$$

$$\chi^2 = \frac{\sum_{j=1}^{N}\left(MR_{ej} - MR_{cj}\right)^2}{N - z} \tag{17}$$

RESULTS AND DISCUSSION

Raw Material and Physicochemical Analysis

Proximate analysis of Cape gooseberry presented an initial moisture content of 83.45 ± 0.15 g/100 g w.m., crude protein (nitrogen × 6.25) of 1.23 ± 0.15 g/100 g w.m., total lipids of 0.35 ± 0.05 g/100 g w.m., crude fiber of 2.41 ± 0.17 g/100 g w.m., crude ash of 0.77 ± 0.03 g/100 g w.m., and available carbohydrates (by difference) of 11.79 ± 0.10 g/100 g w.m., acidity of 2.01 ± 0.09% citric acid, pH of 3.51 ± 0.10 and soluble solids content of 13.96 ± 0.16°Brix. Mean equivalent ratio of berries as measured by a Vernier caliper (Mitutoyo Digimatic Caliper, 500-144, Shanghai, China) was 8.59 ± 0.34 mm. These values were close to those reported by Puente *et al.* (2011) and Ramadan (2011).

Moisture Desorption Isotherm

The average initial moisture content of Cape gooseberry samples was 5.42 ± 0.02 g water/g d.m. Figure 2 shows the desorption isotherm at 40C with the experimental moisture contents obtained at equilibrium and calculated by the GAB equation. A good fit to the experimental moisture data is also observed (SSE = 0.005; $\chi^2 = 0.008$ and $R^2 = 0.95$), and values of 0.086 (g water/g d.m.), 0.956 and 32.88 were obtained for X_m, k and C, respectively. Similar results for the monolayer moisture content, X_m, have been observed in grapes, apricots, apples and potatoes, 0.073–0.220 g water/g d.m. at 30–60C (Kaymak-Ertekin and Gedik 2004), in strawberries, 0.098 g water/g d.m. at 30C (Moraga *et al.* 2004), in potato slices, 0.076–0.106 g water/g d.m. at 20–40C (Iguedjtal *et al.* 2008), in figs, 0.083–0.300 g water/g d.m. at 5–40C (Farahnaky *et al.* 2009), and in blueberries, 0.084 g water/g d.m. at 60C (Vega-Gálvez *et al.* 2009). Monolayer moisture content (X_m) is an important parameter with a physicochemical significance, since it represents the first layer of water molecules that can thermodynamically interact with other food compounds (Vega-Gálvez *et al.* 2009). The desorption isotherm modeled by the GAB equation was used to estimate the equilibrium moisture content at each temperature, giving values of $X_{we} = 0.120$ g

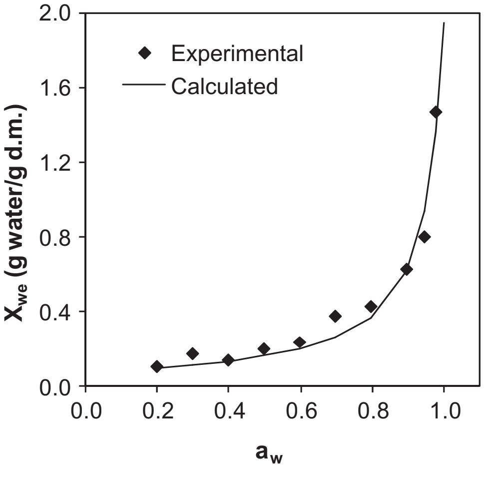

FIG. 2. DESORPTION ISOTHERM FOR CAPE GOOSEBERRY AT 40C AS MODELED BY THE GUGGENHEIM–ANDERSON–DE BOER EQUATION

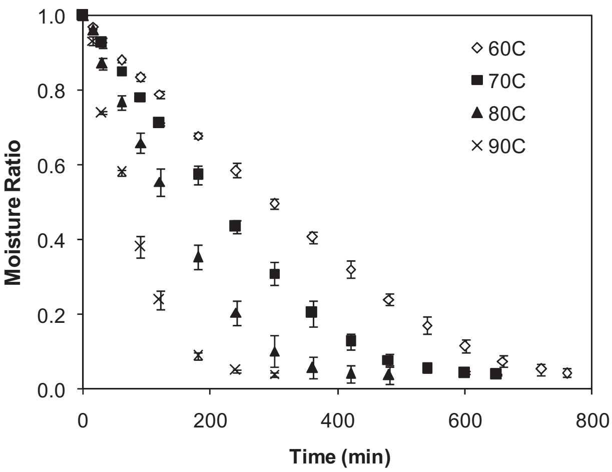

FIG. 3. EXPERIMENTAL DATA FOR DRYING OF CAPE GOOSEBERRY AT FOUR DIFFERENT WORKING TEMPERATURES

water/g d.m. at 60C; $X_{we} = 0.096$ g water/g d.m. at 70C; $X_{we} = 0.080$ g water/g d.m. at 80C; and $X_{we} = 0.065$ g water/g d.m. at 90C; in all cases, $A_w < 0.5$ was obtained.

The graphic representation of moisture desorption isotherm for Cape gooseberry at 40C (Fig. 2) showed a tendency of type III isotherms of the Van der Waals classification (Erbaş *et al.* 2005). This type of isotherm is typical for most foods rich in soluble components, such as sugars, owing to the solubility of the sugars in water (Al-Muhtaseb *et al.* 2002). Working with strawberries, Moraga *et al.* (2004) reported that a slow increase in the equilibrium moisture content in the low A_w range and a sharp increase at intermediate A_w values (≈0.50) are due to the prevailing effect of solute–solvent interactions associated to sugar dissolution. Other authors working with other types of food have observed the same behavior, including Tolaba *et al.* (2004) in quinoa; Kaymak-Ertekin and Gedik (2004) in grapes, apricots, apples and potatoes; Moraga *et al.* (2004) in strawberries; and Erbaş *et al.* (2005) in semolina and farina.

Drying Curves Behavior

Figure 3 shows the experimental drying curves for the four working temperatures (60, 70, 80 and 90C). All curves showed a clear exponential tendency with MR decreasing rapidly as the air-drying temperature increased. As expected, it was observed that the drying time to reach similar moisture content decreased as temperature increased. For example, the time required to achieve a moisture content lower than 0.330 g water/g d.m. at 60C was 760 min, nearly time doubled necessary to reach the same moisture content at a temperature of 80C (420 min), and thrice the time required at a temperature of 90C (240 min). These results are similar to those reported by Akpinar (2006), Karabulut *et al.* (2007), Doymaz (2007, 2008, 2009), Mundada *et al.* (2010), Vega-Gálvez *et al.* (2011), and Doymaz and Ismail (2011), working with potato, apple and pumpkin, kurut, sour cherry, strawberry, spinach leaves, pomegranate arils, blueberries and sweet cherry, respectively. Likewise, only the presence of the falling rate period was observed explaining the use of the empirical models presented in Table 1.

Determination of Water Diffusion Coefficient

The traditional method to study mass transfer in a transient state for foodstuff drying uses the equation of Fick's second law, from which the water diffusion coefficient (D_{we}) could be determined. The values of D_{we} obtained for different working temperatures are presented in Table 2. For the Cape gooseberry samples dried at 60–90C, D_{we} varied within a range of $4.67–14.9 \times 10^{-10}$ m^2/s. These values for D_{we} confirm that the drying rate increases as drying air temperature is raised. These values were close to those reported by Doymaz (2007) for sour cherry ($0.48–1.03 \times 10^{-9}$ m^2/s); Chong *et al.* (2008) for apricot ($8.9 \times 10^{-10}–1.3 \times 10^{-9}$ m^2/s), grape ($7.91–2.5 \times 10^{-9}$ m^2/s) and carrot ($0.9–3.3 \times 10^{-9}$ m^2/s); Aghbashlo *et al.* (2008) for *Berberis* fruit ($0.32–9.00 \times 10^{-9}$ m^2/s); Mundada *et al.* (2010) for pomegranate arils ($2.60–4.89 \times 10^{-10}$ m^2/s); Vega-Gálvez *et al.* (2011) for blueberries ($9.51–17.71 \times 10^{-10}$ m^2/s); and Doymaz and Ismail (2011) for sweet cherry ($0.55–1.54 \times 10^{-9}$ m^2/s).

According to ANOVA carried out to the medias of the diffusional coefficient at a confidence level of 95%, a $P < 0.05$ was obtained, concluding a significant influence of drying air temperature on D_{we}. The activation energy was determined by plotting the natural logarithm of D_{we} versus the reciprocal of drying temperature ($1/T$) as presented in Fig. 4. A value of 38.78 kJ/mol was obtained for activation energy together with an Arrhenius factor (D_o) of 5.53×10^{-4} m^2/s. This result of activation energy for D_{we} agreed with those obtained by other researchers: 39.5 kJ/mol for bean (Senadeera *et al.* 2003); 37.27 kJ/mol for figs

TABLE 2. AVERAGE VALUES OF THE DIFFUSION COEFFICIENT D_{WE} (EQ. 14) OF CAPE GOOSEBERRY AT DIFFERENT WORKING TEMPERATURES

T (C)	$D_{we} \times 10^{-10}$ (m^2/s)	R^2
60	4.67 ± 0.29 ^{a}	0.96
70	6.82 ± 0.29 ^{a}	0.98
80	9.95 ± 2.25 ^{b}	0.98
90	14.90 ± 0.56 ^{c}	0.98

Different letters in the same column indicate that the values are significantly different ($P < 0.05$).

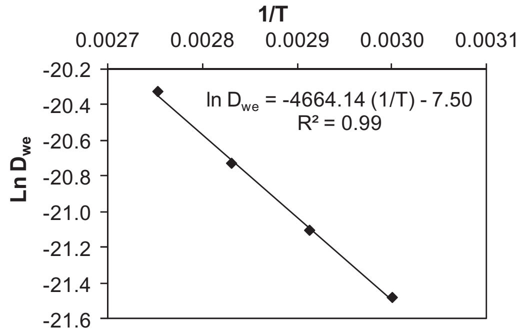

FIG. 4. ARRHENIUS-TYPE RELATIONSHIP BETWEEN WATER DIFFUSION COEFFICIENT AND ABSOLUTE TEMPERATURE

(Babalis and Belessiotis 2004); and 38.60 kJ/mol for kiwifruit (Orikasa *et al.* 2008); it is, however, lower than the activation energy of *Berberis* fruit (110.84–130.61 kJ/mol; Aghbashlo *et al.* 2008); pomegranate arils with and without osmotic dehydration (42.06 and 66.12 kJ/mol; Mundada *et al.* 2010); or sweet cherry pretreated with alkali emulsion of ethyl oleate and untreated (49.17 and 43.05 kJ/mol; Doymaz and Ismail 2011).

Mathematical Modeling of Drying Curves

Table 3 shows the average values and standard errors of the kinetic and empirical parameters k_i (i = 1, 2 . . . 12), n_i (i = 1, 2 . . . 12), c, α and β, obtained for all proposed models. Similar to diffusion coefficient, it was found that parameters k_i followed the same increasing tendency with drying air temperature. It may thus be assumed that these constants (k_i) would be directly proportional to temperature. However, the n_i values remained relatively unchanged, suggesting them to be most probably dependent on the characteristics of the cell tissue and on flow of drying air (Vega-Gálvez *et al.* 2009). From the ANOVA carried out to evaluate the parameters k_i (i = 1, 2, . . . 12), n_i (i = 1, 2, . . . 12), c, α and β of the proposed models at a confidence level of 95%, a $P < 0.05$ was obtained in most cases, except for k_3, k_{12}, n_1, n_2, n_3, n_4, n_6, n_7, n_8, n_9, n_{10}, n_{11}, n_{12}, c and α that showed statistically significant differences, and thus a dependence on the drying temperature of most of these kinetic parameters. To the parameters that showed dependence on temperature, an Arrhenius-type equation was applied, resulting in an activation energy (kJ/mol) of 39.90 for k_1, 36.49 for k_2,

TABLE 3. VALUES OF THE KINETIC AND EMPIRICAL PARAMETERS FOR MODELS OF THE DRYING BEHAVIOR OF CAPE GOOSEBERRY

		Drying temperatures (C)			
Eq.	Parameters	60	70	80	90
2	k_1 ($\times10^{-3}$)	3.577 ± 0.243^{a}	4.936 ± 0.245^{a}	7.424 ± 1.477^{b}	11.748 ± 0.322^{c}
3	k_2 ($\times10^{-3}$)	4.036 ± 0.318^{a}	5.473 ± 0.233^{a}	7.982 ± 1.805^{b}	11.954 ± 0.434^{c}
	n_1	1.274 ± 0.049^{a}	1.271 ± 0.023^{a}	1.202 ± 0.132^{a}	1.042 ± 0.044^{b}
4	k_3 ($\times10^{-4}$)	9.722 ± 0.265^{a}	7.875 ± 1.377^{a}	13.449 ± 4.189^{a}	30.779 ± 6.854^{b}
	n_2	1.187 ± 0.003^{a}	1.292 ± 0.022^{b}	1.294 ± 0.076^{b}	$1.265 \pm 0.047^{a,b}$
5	k_4 ($\times10^{-3}$)	2.895 ± 0.105^{a}	3.941 ± 0.189^{b}	5.901 ± 0.542^{c}	10.223 ± 0.204^{d}
	n_3	1.187 ± 0.003^{a}	1.292 ± 0.022^{b}	1.294 ± 0.076^{b}	$1.265 \pm 0.047^{a,b}$
6	k_5 ($\times10^{-5}$)	0.097 ± 0.006^{a}	0.240 ± 0.026^{b}	0.540 ± 0.053^{c}	1.700 ± 0.100^{d}
	n_4	$-0.002 \pm 5.01 \times 10^{-5a}$	$-0.003 \pm 1.51 \times 10^{-4b}$	$-0.005 \pm 3.01 \times 10^{-4c}$	$-0.008 \pm 2.82 \times 10^{-4d}$
7	k_6 ($\times10^{-2}$)	0.140 ± 0.010^{a}	0.290 ± 0.030^{b}	0.480 ± 0.030^{c}	1.040 ± 0.070^{d}
	n_5	1.516 ± 0.057^{a}	1.245 ± 0.032^{b}	1.159 ± 0.020^{c}	1.082 ± 0.008^{d}
	C	-0.508 ± 0.059^{a}	-0.206 ± 0.034^{b}	-0.122 ± 0.015^{c}	-0.041 ± 0.011^{d}
8	k_7 ($\times10^{-2}$)	0.290 ± 0.010^{a}	0.420 ± 0.020^{b}	0.620 ± 0.050^{c}	1.140 ± 0.050^{d}
	k_8 ($\times10^{-2}$)	0.290 ± 0.010^{a}	0.420 ± 0.020^{b}	0.620 ± 0.050^{c}	1.140 ± 0.050^{d}
	n_6	0.537 ± 0.005^{a}	0.556 ± 0.002^{b}	0.540 ± 0.010^{a}	0.534 ± 0.005^{a}
	n_7	0.515 ± 0.002^{a}	0.519 ± 0.002^{a}	0.518 ± 0.004^{a}	0.516 ± 0.002^{a}
9	k_9 ($\times10^{-2}$)	0.290 ± 0.010^{a}	0.420 ± 0.020^{b}	0.620 ± 0.050^{c}	1.140 ± 0.050^{d}
	k_{10} ($\times10^{-2}$)	0.290 ± 0.010^{a}	0.420 ± 0.020^{b}	0.620 ± 0.050^{c}	1.140 ± 0.050^{d}
	k_{11} ($\times10^{-2}$)	0.290 ± 0.010^{a}	0.420 ± 0.020^{b}	0.620 ± 0.050^{c}	1.140 ± 0.050^{d}
	n_8	0.357 ± 0.003^{a}	0.370 ± 0.001^{b}	0.359 ± 0.006^{a}	0.355 ± 0.003^{a}
	n_9	0.353 ± 0.001^{a}	0.361 ± 0.001^{b}	0.355 ± 0.004^{a}	0.353 ± 0.002^{a}
	n_{10}	0.342 ± 0.001^{a}	0.345 ± 0.001^{b}	$0.344 \pm 0.003^{a,b}$	$0.342 \pm 0.001^{a,b}$
10	α	1.187 ± 0.003^{a}	1.292 ± 0.022^{b}	1.294 ± 0.076^{b}	$1.265 \pm 0.047^{a,b}$
	β	345.736 ± 12.771^{a}	254.098 ± 11.837^{b}	170.388 ± 14.929^{c}	97.845 ± 1.9423^{d}
11	n_{11}	0.981 ± 0.008^{a}	0.977 ± 0.006^{a}	0.986 ± 0.004^{a}	1.002 ± 0.005^{b}
	n_{12}	1.275 ± 0.082^{a}	1.445 ± 0.052^{b}	$1.377 \pm 0.011^{a,b}$	1.284 ± 0.046^{a}
	k_{12} ($\times10^{-2}$)	0.050 ± 0.020^{a}	0.030 ± 0.010^{a}	0.090 ± 0.040^{a}	0.310 ± 0.050^{b}
	c ($\times10^{-4}$)	-1.364 ± 0.217^{a}	-0.085 ± 0.180^{b}	$0.107 \pm 0.571^{b,c}$	0.791 ± 0.375^{c}

k_i (min^{-1}); n_i, c and α (dimensionless); β (min). Different letters in the same row indicate that the values are significantly different ($P < 0.05$).

TABLE 4. STATISTICAL RESULTS OF TESTS APPLIED TO EVALUATE THE SELECTED DRYING MODELS

		Drying temperatures (C)			
Eq.	Statistics	60	70	80	90
2	R^2	0.934	0.967	0.975	0.976
	SSE	0.011	0.013	0.009	0.002
	χ^2	0.011	0.014	0.010	0.003
3	R^2	0.955	0.981	0.983	0.977
	SSE	0.016	0.013	0.009	0.002
	χ^2	0.017	0.014	0.010	0.003
4	R^2	0.985	0.993	0.992	0.985
	SSE	0.001	0.001	<0.001	0.001
	χ^2	0.001	0.001	<0.001	0.001
5	R^2	0.985	0.993	0.992	0.985
	SSE	0.001	<0.001	<0.001	0.001
	χ^2	0.001	<0.001	<0.001	0.001
6	R^2	0.998	0.998	0.998	0.994
	SSE	<0.001	0.001	0.001	0.001
	χ^2	<0.001	0.001	0.001	0.001
7	R^2	0.995	0.992	0.992	0.992
	SSE	<0.001	0.002	0.001	0.002
	χ^2	<0.001	0.002	0.001	0.002
8	R^2	0.977	0.980	0.986	0.990
	SSE	0.003	0.004	0.003	0.002
	χ^2	0.004	0.004	0.003	0.002
9	R^2	0.977	0.980	0.986	0.990
	SSE	0.003	0.004	0.003	0.002
	χ^2	0.004	0.004	0.003	0.002
10	R^2	0.985	0.993	0.992	0.977
	SSE	0.001	<0.001	<0.001	0.001
	χ^2	0.001	0.001	<0.001	0.001
11	R^2	0.998	0.998	0.998	0.997
	SSE	<0.001	<0.001	<0.001	<0.001
	χ^2	<0.001	<0.001	<0.001	<0.001
13	R^2	0.955	0.981	0.983	0.977
	SSE	0.011	0.013	0.009	0.002
	χ^2	0.011	0.014	0.010	0.003

SSE, sum squared error.

41.97 for k_4, 94.50 for k_5, 65.57 for k_6, 45.07 for k_7, 45.07 for k_8, 45.07 for k_9, 45.07 for k_{10}, 45.07 for k_{11}, 41.95 for β, and 10.97 for n_5.

Statistical Analysis of Models

Table 4 shows the results of the statistical tests (SSE, χ^2 and R^2) applied to analyze the goodness of fit of all proposed models. These statistical tests have been used by other researchers to analyze experimental data acquired in the study of food drying (Akpinar 2006; Doymaz 2008). According to these results, the models that best fitted the experimental data, considering the determination coefficient ($R^2 > 0.99$) as the first criterion of selection, were Wang–Singh, logarithmic and Midilli–Kucuk. However, when evaluating the fit quality with the other two statistical tests applied, the lowest values for $\text{SSE} < 0.001$ and $\chi^2 < 0.001$ were calculated for the Midilli-Kucuk and the Wang–Singh models. Thus, if the three statistical tests applied are considered, the equation that best fitted the experimental moisture data would be the Midilli-Kucuk model. Similar observations were made by Ertekin and Yaldiz (2004), Akpinar (2006), Doymaz (2007), Mundada *et al.* (2010) and Schössler *et al.* (2012), working with eggplant, potato, apple and pumpkin, sour cherry, pomegranate arils, and apple and red bell pepper. This good fit quality on experimental data can be explained because the Midilli–Kucuk model presents four terms, which provides a better mathematical approximation on the drying curves with exponential tendency. Figure 5a,b shows the experimental drying data together with the calculated drying curves by Midilli–Kucuk and Wang–Singh models, which presented

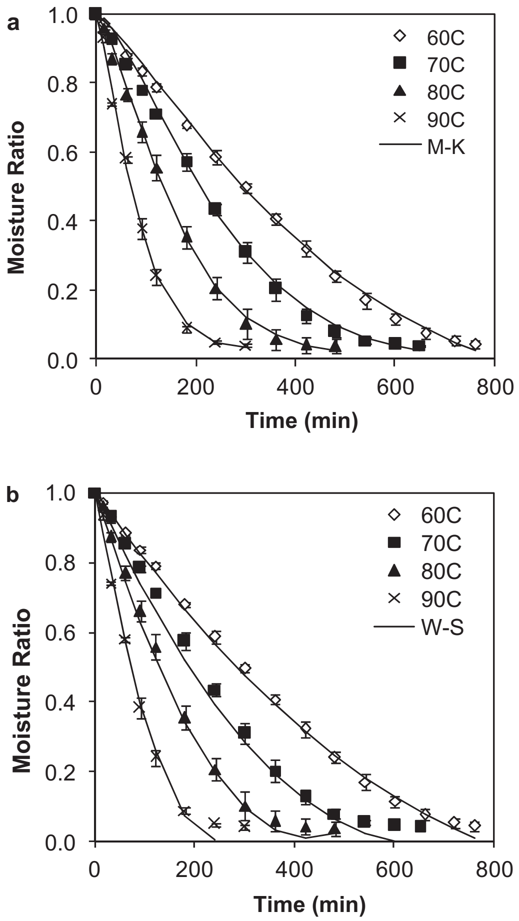

FIG. 5. EXPERIMENTAL DATA AND DRYING CURVES CALCULATED WITH THE MODELS OF (A) MIDILLI–KCUK AND (B) WANG–SINGH AT THE FOUR WORKING TEMPERATURES

the best graphical and statistical fit of experimental moisture values at all drying temperatures.

CONCLUSIONS

The drying kinetic characteristics of Cape gooseberry were studied between 60 and 90C for dehydration in a convective dryer. The GAB equation was proven to be useful in predicting equilibrium moisture content of samples ($R^2 = 0.95$; $\mathrm{SSE} = 0.005$ and $\chi^2 = 0.008$). Drying of Cape gooseberry had a clear dependence on drying air temperature, showing only a falling rate period, and reaching average equilibrium moisture close to 0.33 g water/g d.m. All analyzed models could be used to describe the dehydration kinetics. Nevertheless, based on statistical evaluation, the Midilli–Kucuk model gave the best goodness of fit to drying experimental data at all working temperatures. Effective moisture diffusivity of Cape gooseberry increased from 4.67×10^{-10} to 14.9×10^{-10} m^2/s, giving activation energy of 38.78 kJ/mol. The mentioned model can therefore be applied to estimate optimum drying conditions (e.g., temperature and time) needed to achieve a final water content of the Cape gooseberry required for further processing.

NOMENCLATURE

A_w	water activity (dimensionless)
X_{we}	equilibrium moisture content (g water/g d.m.)
X_{wt}	moisture content (g water/g d.m.)
X_{wo}	initial moisture content (g water/g d.m.)
X_m	monolayer moisture content (g water/g d.m.)
C, k	parameters of GAB model
D_{we}	water diffusion coefficient (m^2/s)
r	equivalent radius (m)
k_i	kinetic parameters (1/min)
n_i, c	empirical parameters (dimensionless)
α	shape parameter (dimensionless) of the Weibull model
β	scale parameter (min) of the Weibull model
t	drying time (s, min)
i	number of terms
Y	parameter to be studied by Arrhenius
Y_o	Arrhenius factor
R	universal gas constant (8.314 J/mol K)
T	absolute temperature (K)
E_a	activation energy (kJ/mol)
MR_{ej}	experimental moisture ratio (dimensionless)
MR_{cj}	calculated moisture ratio (dimensionless)
$\overline{MR}_{ej}$	average experimental moisture ratio (dimensionless)
z	number of constants of the model
N	number of data values
w.m.	wet matter
d.m.	dry matter

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