INFLUENCE OF DIFFERENT TEMPERATURES AND AIRFLOWS ON DRYING OF NATURAL AND PULPED COFFEE

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KEYWORDS

Coffea arabica L., mathematical modeling, drying rate.

ABSTRACT

This study aimed to evaluate drying kinetics for natural and pulped coffee, using different temperatures and drying airflows. For the conduction of the experiment, coffee fruits (*Coffea arabica* L. cv. Topázio) were harvested manually, selecting only ripe fruits and subsequent to the hydraulic separation. For drying the coffee, use a mechanical dryer with two temperatures (40 and 45°C) and four drying air streams (24; 60; 96 and 132 $m^3.min^{-1}.m^{-2}$). Twelve models for employees to describe the drying kinetics of coffees. Among the models used to describe the drying process of natural coffee and pulped coffee, according to the results of the coefficient of determination, relative mean error, standard deviation of estimates and distribution of waste distribution, proposed model for the only one that presents fit for all as conditions study. The temperature of 45 ° C and the airflows of 96 and 132 $m^3.min^{-1}.m^{-2}$ provide the shortest drying times regardless of the coffee processing type.

INTRODUCTION

Brazil is a leader in the world market for production and export of raw coffee. It has advanced technologies for production and crop protection and is prepared to offer high harvest yields. However, developing technologies that reduce drying time and energy consumption requires a more sustainable solution, which makes drying one of the main bottlenecks in Brazilian coffee farming (Borém, 2013).

Technology currently available for drying coffee only increases drying rates by increasing temperature or airflow. However, coffee mass temperatures above 40 °C cause thermal damage, depreciating drink quality (Isquierdo, 2013).

Drying kinetics of agricultural products has great importance to select suitable temperatures and times required for an adequate drying process and to obtain a final product of higher quality (Avhad & Marchetti, 2016).

An alternative to increase drying rates without exceeding maximum tolerable temperatures for coffee is drying airflows higher than those used commercially. It is necessary to have experimental tests that provide data for process simulation before they are used on a commercial scale.

Several models have been fitted to describe drying process of hygroscopic capillary-porous products. Among these models are Midilli, Page, Thompson, Verma, Henderson and Pabis, modified Henderson and Pabis, two-term, two-term exponential, Newton, Wang and Sing, and Valcam (Corrêa et al., 2014; Goneli et al., 2009; Isquierdo, 2013; Resende et al., 2009; Siqueira et al., 2013).

This research aimed to study the drying kinetics in a thin layer of coffee (*Coffea arabica* L.), cultivar Topázio, to adjust different mathematical models to the experimental values as a function of processing type, temperature, and drying airflow, as well as checking for differences in total drying time with each studied airflow.

MATERIAL AND METHODS

This study was carried out in the Laboratory of Agricultural Products Processing, Department of Engineering, Federal University of Lavras (UFLA), Minas Gerais State, Brazil.

The experiment was conducted with manually harvested coffee (*Coffea arabica* L. cv. Topázio) fruits. Only ripe or "cherry" fruits were selected from UFLA's

experimental field. After harvesting, fruits were subjected to hydraulic separation to remove fruits of a low specific mass (dry, immature, insect-damaged, and malformed), followed by manual selection to remove immature and overripe fruits. Then, part of the fruits was taken to dryers, consisting of "natural" portion or processed through dry route, while the other part was peeled and subjected to spontaneous fermentation in water to remove mucilage under ambient conditions for 20 hours, forming the portion of pulped coffee processed by wet route. After this period, parchment coffees were washed under running water until mucilage was removed entirely and, afterward, a pulped coffee lot was sent for drying.

Drying was carried out in mechanical fixed-layer dryers, which allow flow and temperature control of drying air with precision until coffee reaches 0.125±0.005 (db). Coffee fruits were weighed during the entire drying process for subsequent preparation of curves, drying times, and rates.

Each dryer consisted of four removable trays with perforated bottoms. Four circular-section tubes with a diameter of 0.125 m and a height of 0.17 m, located on a plenum for uniform airflow, were placed on each tray. After processing, this coffee was placed inside these tubes, with approximately 0.17 and 0.315 kg each sample, corresponding to a thin layer of 0.025 and 0.043 m of pulped and natural coffee, respectively.

At the beginning and end of drying process, coffee fruit and parchment coffee moisture contents were determined using standard oven method at 105±3 °C for 24 hours, according to the Rules for Seed Testing (Brasil, 2009). Yet for processed dry coffee, moisture content was determined by the ISO 6673 standard method (International Organization for Standardization – ISO, 2003). After obtaining mass and initial moisture content of coffee fruits and parchment coffee, drying was monitored by gravimetric method (loss of mass) until reaching a content of 0.125±0.005 (db), using a 0.01-g analytical scale, according to the equation below:

$$U_t = \frac{Ma_i - (Mt_i - Mt_t)}{M_{ms}} \qquad (1)$$

Where:

U_t is the moisture content at time t (kg water kg^{-1} dry matter, db);

Ma_i is the initial water mass (kg);

Mt_i is the initial total mass (kg);

Mt_t is the total mass at time t (kg),

M_{ms} is the dry matter mass (kg).

Water evaporation speed was determined from the drying rate of the product, according to the following expression:

$$DR = \frac{U_{prev} - U_c}{\Delta t} \qquad (2)$$

Where:

DR is the drying rate (g water kg^{-1} dry matter h^{-1});

U_{prev} is the moisture content in the previous time (g water kg^{-1} dry matter, db);

U_c is the current moisture content (g water kg^{-1} dry matter, db),

Δt is the time interval between weighings (h).

Drying system consisted of three fixed-layer dryers, which allowed controlling drying-airflow and temperature with precision, using an electronic panel.

Drying airspeed was measured using a paddle anemometer. It was regulated and kept constant for all treatments at 0.4, 1.0, 1.6, and 2.2 m s^{-1}, corresponding to flows of 24, 60, 96, and 132 m^3 min^{-1} m^{-2}, respectively. Two temperatures were used for drying air (40 and 45 °C), which were monitored using mercury thermometers placed in the middle of coffee mass. Different drying conditions were obtained depending on combination among processing, temperature, and drying airflows.

Moisture ratio (MR) is essential for drying data analysis since it describes different thin-layer drying models. During drying, it was determined as in [eq. (3)], as a function of evaluated variables. Values of MR as a function of drying time for all tested conditions were fitted to models used to describe coffee drying kinetics, as shown in Table 1.

$$MR = \frac{U - U_e}{U_i - U_e} \qquad (3)$$

Where:

MR is the moisture ratio;

U is the moisture content of the product at time t (decimal, db);

U_e is the equilibrium moisture content of the product (decimal, db), and

U_i is the initial moisture content of the product (decimal, db).

Hygroscopic equilibrium moisture content was calculated by eqs (4) and (5) for natural and pulped coffee (Afonso Júnior, 2001), respectively.

$$U_e = (2.0222 + 0.0288\,T - 18.7397.\,RH^{8.6181})^{-2.1385} \qquad (4)$$

$$U_e = (2.9636 + 0.0530\,T - 10.7837.\,RH^{4.5136})^{-1.6503} \qquad (5)$$

Where:

Ue is the equilibrium moisture content of the product (decimal, db);

T is the drying air temperature (°C),

RH is the relative humidity of the drying air (decimal).

Mathematical models frequently used to represent the drying kinetics of agricultural products were fitted to the experimental data of coffee MR obtained for each type of processing and drying air condition (Table 1).

TABLE 1. Mathematical models used to predict drying kinetics.

Model designation	Model	Equation
Dois termos	$MR = a \cdot \exp(-k_0 \cdot t) + b \cdot \exp(-k_1 \cdot t)$	(6)
Exponencial de dois termos	$MR = a \cdot \exp(-k \cdot t) + (1-a)\exp(-k \cdot a \cdot t)$	(7)
Henderson & Pabis modificado	$MR = a \cdot \exp(-k \cdot t) + b \cdot \exp(-k_0 \cdot t) + c \cdot \exp(-k_1 \cdot t)$	(8)
Henderson & Pabis	$MR = a \cdot \exp(-k \cdot t)$	(9)
Midilli	$MR = a \cdot \exp(-k \cdot t^n) + b \cdot t$	(10)
Newton	$MR = \exp(-k \cdot t)$	(11)
Page	$MR = \exp(-k \cdot t^n)$	(12)
Thompson	$MR = \exp\{[-a-(-a^2 + 4 \cdot b \cdot t)^{0,5}] \cdot (2 \cdot b)^{-1}\}$	(13)
Verma	$MR = -a \cdot \exp(-k \cdot t) + (1-a)\exp(-k_1 \cdot t)$	(14)
Wang e Sing	$MR = 1 + a \cdot t + b \cdot t^2$	(15)
Valcam	$MR = a + b \cdot t + c \cdot t^{1,5} + d \cdot t^2$	(16)
Modelo Proposto	$MR = (a \cdot \exp(k_0 \cdot t)^n) \cdot (b + \exp \cdot (k_1 \cdot t)^n)^{-1}$	(17)

MR – moisture ratio; t – drying time (h); k, k_0, and k_1 – drying constants; a, b, c, d, and n – model coefficients.

Non-linear regression analyses were performed by the Gauss-Newton method using the software STATISTICA 7.0® (Statsoft, Tulsa, USA) to adjust mathematical models. The best model was chosen based on statistical parameters, namely: standard deviation of estimates (SD), relative mean error (P), coefficient of determination (r^2), and trend of distribution of residues. The standard deviation of estimates and relative mean error were calculated by eqs (18) and (19), respectively.

$$SD = \sqrt{\sum (Y - \hat{Y})^2 / DF} \qquad (18)$$

$$P = [(100/n) \sum [(|Y - \hat{Y}|/Y)] \qquad (19)$$

Where:

SD is the standard deviation of estimates (decimal);

Y is the value observed experimentally;

$\hat{Y}$ is the value calculated by the model;

DF is the degrees of freedom of the model;

P is the relative mean error (%), and

n is the number of observed data.

Drying time was evaluated in a completely randomized design, in a 2 x 4 factorial scheme for each coffee processing system. Treatments consisted of two temperatures and four drying airflows, with four repetitions. Data were subjected to analysis of variance (ANOVA), and means were compared by Tukey's test at 5% significance using the SISVAR® software (Ferreira, 2011).

RESULTS AND DISCUSSION

Table 2 shows the drying times, initial moisture content of coffee fruits and parchment coffee, final moisture content of processed natural and pulped coffee, and mean and maximum drying rates as a function of temperature and drying airflow.

TABLE 2. Type of processing (natural – NAT and pulped – CD), airflow, drying time, initial and final moisture content, mean and maximum drying rates of natural and pulped coffee as a function of temperature (Tem) and drying airflow.

Processing	Tem (°C)	Airflow (m³ min⁻¹ m⁻²)	Drying time (h)	Moisture content (db)		Drying rate (g kg⁻¹ h⁻¹)	
				Initial	Final	Mean	Maximum
NAT	40	24	73.20	2.19	0.125	39.84	209.25
		60	71.06	2.19	0.125	41.77	217.17
		96	67.92	2.19	0.125	42.44	223.33
		132	66.10	2.20	0.125	44.16	234.27
	45	24	47.93	1.93	0.125	43.78	222.09
		60	45.84	1.93	0.125	45.57	240.23
		96	44.08	1.96	0.125	47.57	239.78
		132	44.46	1.95	0.125	48.79	256.78
CD	40	24	13.30	0.98	0.125	64.27	164.85
		60	12.84	0.99	0.125	69.91	177.63
		96	12.59	0.99	0.125	70.24	177.99
		132	12.13	0.99	0.125	76.45	178.19
	45	24	10.65	1.00	0.125	80.35	210.79
		60	10.44	1.01	0.125	81.24	211.08
		96	10.10	1.01	0.125	88.77	211.20
		132	10.15	1.01	0.125	88.27	221.00

According to Table 1, an airflow of 24 m^3 min^{-1} m^{-2} and increased temperatures (40–45 °C) reduced by 35 (73.20–47.93 hours) and 20% (13.30–10.65 hours) drying times for natural and pulped coffee, respectively. An increased airflow (24–132 m^3 min^{-1} m^{-2}) for natural coffee provided reductions of 10 (73.20–66.10 hours) and 7% (47.93–44.46 hours) in drying time for temperatures of 40 and 45 °C, respectively. The same increase in airflow for pulped coffee provided reductions of 9 (13.30–12.13 hours) and 5% (10.65–10.15 hours) for temperatures of 40 and 45 °C, respectively.

Santos et al. (2016) evaluated temperature influence on drying time in palm fruits and found that a temperature range between 50 and 70 °C decreased drying times from 720 to 540 minutes. Camicia et al. (2015) found a reduction in drying time for cowpeas from 10.4 to 2.1 hours for temperatures of 30 and 50 °C, respectively. These results are in agreement with those obtained in our study. Siqueira et al. (2017) observed that the higher the temperature, the greater the difference between partial vapor pressure of dry air and the product, removing water easily and quickly.

The following factors are attributed to a reduction in drying time due to an increase in temperature: increased temperatures reduce water viscosity and directly influence fluid resistance to flow, while a decreased viscosity facilitates diffusion of water molecules through product capillaries (Corrêa et al., 2010; Tohidi et al., 2017; Araújo et al., 2017), in addition to providing an increase in water molecule vibration levels, which also contributes to increasing drying rates.

Figure 1 (a) and (b) show the drying rates as a function of moisture content in coffee fruits and parchment coffee submitted to complete drying in a dryer, respectively.

As shown in Figure 1 (a) and (b), decreased temperatures provide high drying rates for the same moisture content, and these different rates at different temperatures are high at the beginning of drying, and such differences decrease considerably as coffee fruits and parchment coffee get drier. Airflow effect for the same processing and temperature is more evident at the beginning of drying. As drying process progresses, water removal from coffee becomes more difficult due to a stronger connection between water and other bean constituents. Thus, drying rates for the four airflows and two temperatures tend to be similar or get closer at the end of the process.
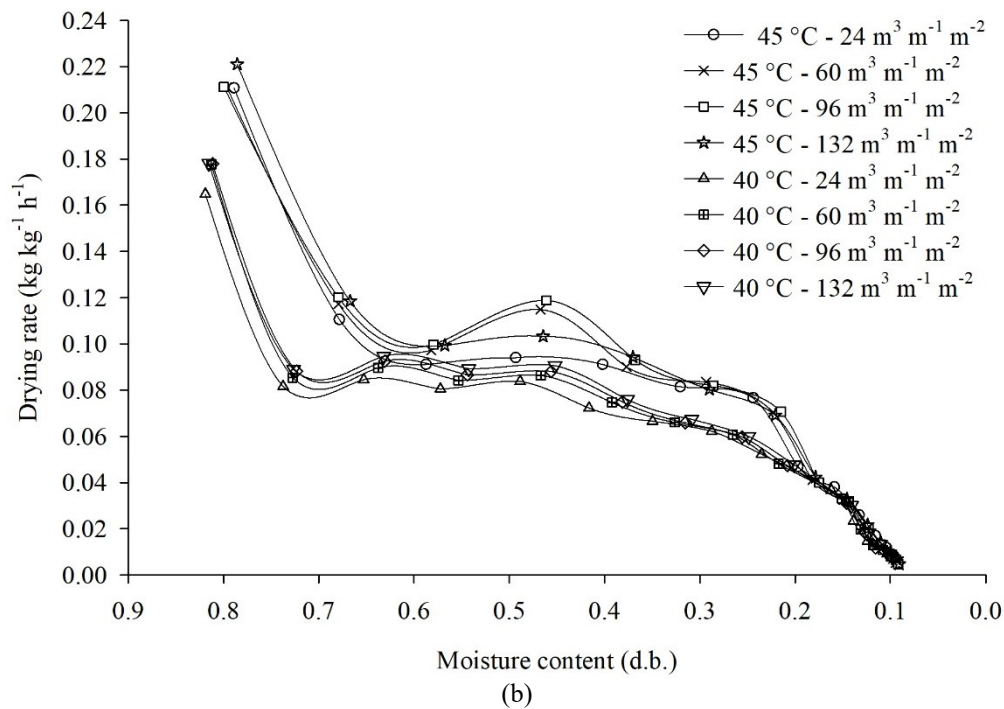

(a)
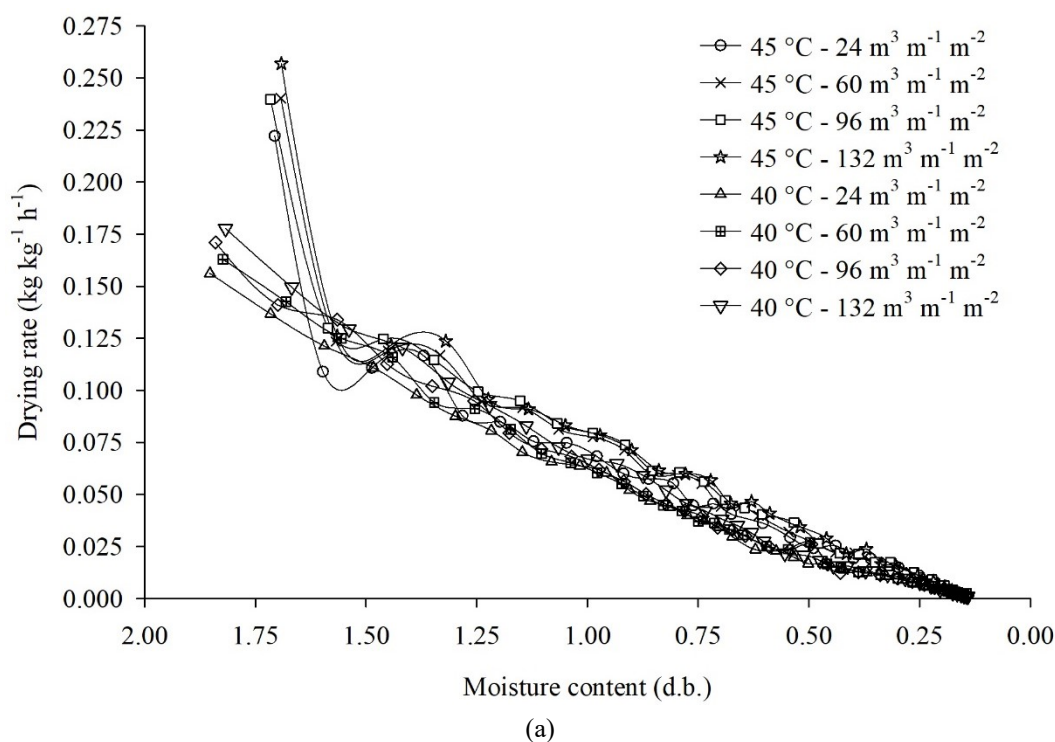
FIGURE 1. Drying rate as a function of moisture content in coffee fruits (a) and parchment coffee (b).

Drying rates of pulped coffee become slightly steady for moisture contents from 0.7 to 0.4 (db). This behavior is related to a constant drying rate, as there is much free water in the surroundings of coffee beans before that interval, greatly increasing drying rates. However, the amount of water present in the product is much lower for the period after the above-mentioned interval, thus reducing drying rates.

Overall, water withdrawal speed from fruits decreases as drying progresses. This is because differences in heat and mass transfer between product and drying air are not compensated, and fruit temperature tends to increase, reaching a value close to that of drying air due to a high need for energy for evaporation of water, which is more strongly bonded (Alves et al., 2013; Siqueira et al., 2016, 2017).

Table 3 shows the statistical parameters for the eleven models used to describe drying kinetics of natural and pulped coffee, and respective coefficients of determination (r^2), standard deviation of estimates (SD), and relative mean error (P). The mean initial moisture content was 2.07 and 1.00 kg water kg^{-1} dry matter (db) for natural and pulped coffee, respectively, after subjected to both temperatures and the four airflows.

TABLE 3. Coefficients of determination (r^2), standard deviation of estimates (SD), and relative mean error (P) for the models used to describe drying kinetics of natural and pulped coffee under different temperatures and airflows.

Model	Pulped coffee (40 °C) Airflow (m³ min⁻¹ m⁻²)											
	24			60			96			132		
	SD	P (%)	r² (%)	SD	P (%)	r² (%)	SD	P (%)	r² (%)	SD	P (%)	r² (%)
6	0.03	29.57	99.47	0.04	48.03	98.67	0.04	50.66	98.74	0.03	12.10	99.48
7	0.04	68.18	98.32	0.04	51.16	98.59	0.04	54.14	98.65	0.04	25.31	98.58
8	0.02	23.36	99.71	0.08	46.47	94.04	0.09	38.27	95.03	0.02	4.57	99.79
9	0.04	63.22	98.46	0.04	48.03	98.67	0.04	50.67	98.74	0.04	24.00	98.66
10	0.02	19.61	99.68	0.02	15.29	99.69	0.02	15.94	99.70	0.02	6.61	99.74
11	0.04	68.18	98.32	0.04	51.16	98.59	0.04	54.14	98.65	0.04	25.31	98.58
12	0.03	29.01	99.33	0.03	23.33	99.35	0.03	23.93	99.41	0.03	12.97	99.31
13	0.04	68.18	98.32	0.04	51.15	98.59	0.04	54.15	98.65	0.04	25.32	98.58
14	0.03	31.43	99.40	0.02	23.88	99.44	0.04	54.14	98.65	0.03	12.72	99.41
15	0.02	13.98	99.72	0.02	12.53	99.64	0.02	15.84	99.65	0.02	2.73	99.69
16	0.01	6.78	99.87	0.01	4.43	99.85	0.01	5.71	99.87	0.01	3.21	99.84
17	0.01	3.85	99.88	0.01	5.85	99.86	0.01	5.20	99.87	0.01	3.17	99.85
	Pulped coffee 45 °C											
6	0.03	37.23	99.38	0.02	23.48	99.60	0.02	30.35	99.60	0.02	38.94	99.53
7	0.04	76.11	98.65	0.02	29.03	99.51	0.02	37.38	99.52	0.03	83.47	98.91
8	0.12	128.02	90.73	0.04	56.92	98.95	0.02	36.60	99.68	0.15	205.23	84.59
9	0.04	72.50	98.70	0.03	56.93	98.95	0.03	72.78	98.90	0.03	79.41	98.96
10	0.02	29.24	99.57	0.02	21.58	99.66	0.02	26.21	99.67	0.02	32.76	99.64
11	0.04	76.11	98.65	0.03	61.01	98.88	0.03	78.32	98.81	0.03	83.45	98.91
12	0.03	38.50	99.23	0.02	24.27	99.49	0.02	30.12	99.51	0.03	41.11	99.40
13	0.04	76.11	98.65	0.03	61.03	98.88	0.04	78.35	98.81	0.03	83.47	98.91
14	0.04	76.10	98.65	0.02	27.14	99.68	0.04	78.35	98.81	0.02	32.38	99.69
15	0.03	33.09	99.37	0.03	42.01	99.40	0.03	56.64	99.42	0.03	61.99	99.21
16	0.02	7.99	99.79	0.01	12.12	99.85	0.01	16.85	99.85	0.01	12.18	99.84
17	0.02	7.81	99.76	0.01	7.48	99.84	0.01	7.81	99.86	0.02	3.40	99.82
	Natural coffee 40 °C											
6	0.01	2.43	99.95	0.01	4.23	99.93	0.01	2.99	99.96	0.01	3.87	99.94
7	0.02	18.00	99.42	0.04	34.88	97.21	0.02	19.60	99.47	0.02	23.40	99.26
8	0.01	1.61	99.96	0.00	2.63	99.99	0.00	2.05	100.00	0.01	3.87	99.94
9	0.03	24.46	98.63	0.03	25.85	98.66	0.03	26.55	98.67	0.03	29.56	98.46
10	0.01	2.45	99.96	0.00	1.08	99.99	0.00	2.21	99.98	0.01	2.66	99.96
11	0.04	32.92	97.28	0.04	34.88	97.21	0.04	34.80	97.44	0.04	38.02	97.07
12	0.01	4.30	99.94	0.00	4.80	99.96	0.01	5.52	99.95	0.01	6.62	99.92
13	0.01	4.14	99.92	0.01	3.59	99.90	0.01	3.12	99.95	0.01	3.17	99.93
14	0.01	3.11	99.91	0.04	34.88	97.21	0.01	4.21	99.93	0.04	38.02	97.07
15	0.12	87.40	78.66	0.12	98.53	76.07	0.12	101.93	76.40	0.13	114.05	72.19
16	0.02	11.59	99.65	0.02	11.82	99.61	0.02	13.14	99.61	0.02	16.08	99.45
17	0.01	2.04	99.96	0.01	2.54	99.93	0.01	1.60	99.98	0.01	2.69	99.96
	Natural coffee 45 °C											
6	0.01	1.78	99.96	0.01	2.06	99.96	0.01	2.22	99.95	0.01	2.22	99.94
7	0.01	2.46	99.94	0.02	12.73	99.26	0.01	3.25	99.93	0.02	17.10	99.07
8	0.01	1.78	99.96	0.01	2.06	99.96	0.00	1.48	99.99	0.00	0.86	100.00
9	0.02	11.35	99.61	0.01	8.01	99.71	0.02	12.02	99.56	0.02	12.15	99.57
10	0.00	1.04	99.98	0.00	1.24	99.98	0.00	1.07	99.98	0.00	0.83	99.98
11	0.02	15.96	99.17	0.02	12.73	99.26	0.02	17.06	99.05	0.02	17.10	99.07
12	0.00	2.84	99.97	0.00	1.45	99.98	0.00	2.91	99.97	0.01	3.88	99.95
13	0.01	1.82	99.94	0.01	3.17	99.90	0.01	2.11	99.93	0.01	2.14	99.91
14	0.01	2.53	99.94	0.01	2.59	99.95	0.01	3.17	99.93	0.01	4.07	99.90
15	0.08	45.58	91.63	0.07	36.89	93.38	0.08	46.94	91.04	0.08	47.22	90.98
16	0.01	3.10	99.96	0.01	2.42	99.96	0.01	3.37	99.95	0.01	2.55	99.95
17	0.01	1.67	99.97	0.01	1.94	99.97	0.01	1.95	99.96	0.01	2.67	99.94

The analysis of statistical parameters was performed separately for each type of processing due to high differences in drying kinetics of natural and pulped coffee.

The analysis of a single parameter is not a useful tool for evaluation of non-linear models, requiring a joint analysis of parameters: coefficient of determination, standard deviation of estimate, and relative mean error. The ability of a model to accurately describe a particular physical process is inversely proportional to the standard deviation of estimates. Relative mean errors below 10% are recommended (Madamba et al., 1996; Mohapatra & Rao, 2005).

Regarding the coefficients of determination (r^2) of pulped coffee, both Valcam (16) and Proposed Model (17) presented the highest values (above 99.76%). Natural processed coffee presented a coefficient of determination (r^2) higher than 97.07% for almost all models used, except for Wang and Sing model (15), which, according to Madamba et al. (1996), is a value considered acceptable to describe drying phenomena.

Considering the criterion of relative mean errors (P) below 10% for acceptable fit, the results obtained for pulped coffee showed that only the Proposed Model (17) presented a satisfactory fit for dry coffee at 45 °C (P<7.81%), and the best value of relative mean error for dry coffee at 40 °C (P<5.85%). Additionally, the models two-term (6), modified Henderson & Pabis (8), Midilli (10), Page (12), Thompson (13), and Proposed Model (17) had relative mean errors lower than 10% for natural coffee, and they can also be used in other applications.

All models used presented SD<0.05, except for the modified Henderson & Pabis (8) and Wang and Sing (15) models.

Regarding the behavior (or trend) of distribution of residuals for the studied models, the models Valcam (16) for pulped coffee, Midilli (10) for natural coffee, and Proposed Model (17) had a random distribution of residuals for all studied conditions.

Among the models used in this study to describe the drying process of pulped coffee and considering the analysis of coefficients of determination, relative mean errors, standard deviations of estimates, and trend of distribution of residuals, the Proposed Model (17) presented the best fit. The models showing the best fit for natural coffee were Midilli (10) and Proposed Model (17), also considering the same evaluation parameters.

The Proposed Model (17) was adopted to represent drying kinetics of natural and pulped coffees under the conditions considered in this study due to its satisfactory fit under all drying conditions and ease of use.

Table 4 shows the coefficients of the Proposed Model for natural and pulped coffee, fitted to the observed data of thin-layer drying kinetics under the conditions considered in this experiment.

TABLE 4. Proposed Model coefficients fitted to the thin-layer drying characteristics of natural and pulped coffee.

Processing	Temperature (°C)	Airflow (m^3 min^{-1} m^{-2})	Model coefficient				
			a	b	k_0	k_1	N
Natural	40	24	33.3836	33.1341	-15.5549	44.3614	0.0083
		60	46.0625	46.0433	-0.3655	0.9937	0.3984
		96	33.8310	33.5280	-18.1085	47.3185	0.0080
		132	60.2551	60.3382	-1.7779	5.1655	0.0861
	45	24	0.1086	-0.8896	-0.7714	0.1474	0.0480
		60	0.7720	-0.2166	1.1412	2.3307	0.0510
		96	0.1208	-0.8770	-0.4736	0.1119	0.0720
		132	0.0916	-0.9066	-0.2470	0.0402	0.1532
Pulped	40	24	0.3742	-0.6176	0.0863	0.4642	0.0885
		60	0.3402	-0.6503	0.0370	0.3516	0.1082
		96	0.3101	-0.6839	0.0036	0.2948	0.1138
		132	0.2371	-0.7575	-0.0316	0.1994	0.1340
	45	24	18.1339	17.6652	-22.3481	52.5765	0.0072
		60	17.3364	16.6682	-23.0004	52.5763	0.0075
		96	21.1488	20.5184	-21.9210	52.5764	0.0081
		132	20.4160	19.8862	-23.7046	52.5764	0.0076

Figures 2 and 3 show the behavior of the moisture ratio observed and estimated by the Proposed Model (17) for natural and pulped coffee dried at 40 and 45 °C in a thin layer. The high agreement between the moisture ratios obtained experimentally and those estimated by the Proposed Model for all studied conditions confirms the satisfactory fit of this model to describe drying kinetics for each type of processing under the studied conditions.
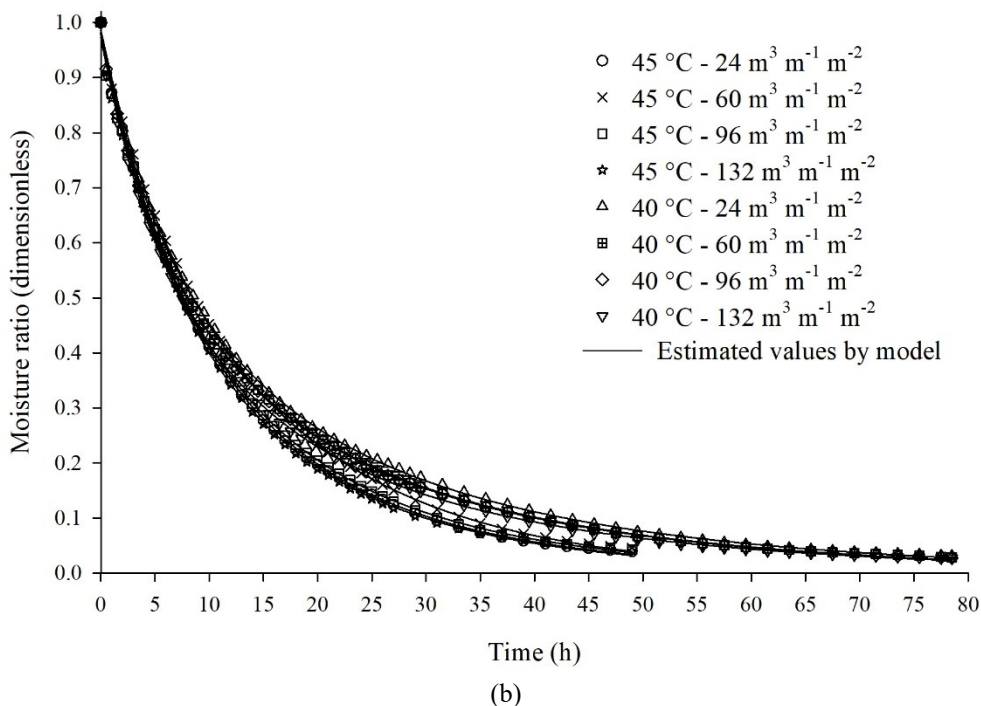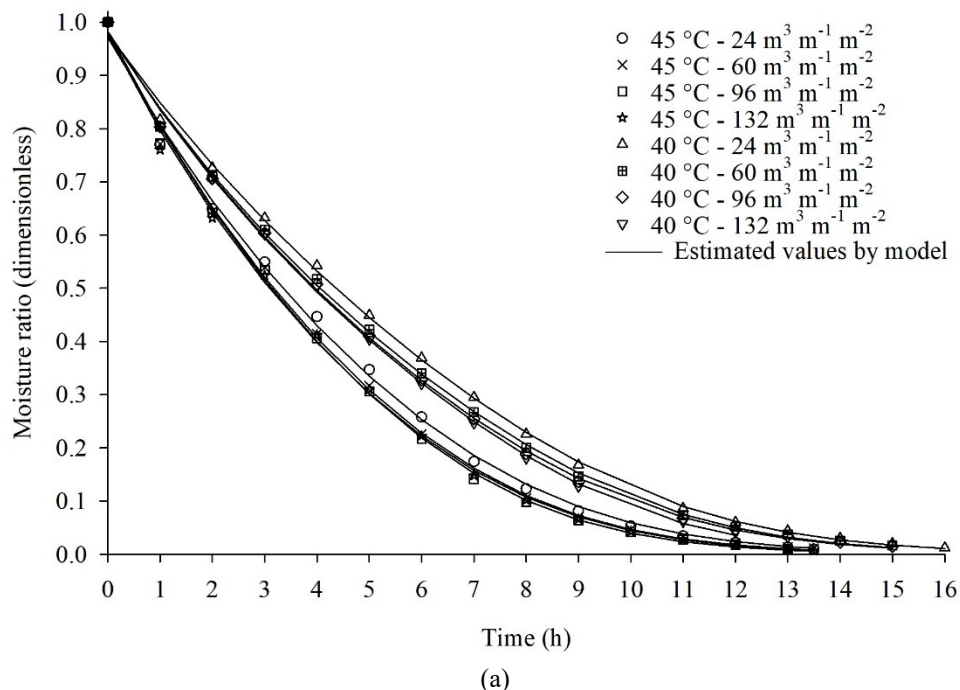
(a)

(b)

FIGURE 2. Moisture ratios observed and estimated by the Proposed Model for drying pulped (a) and natural (b) coffee as a function of time.

Table 5 shows the splitting of drying treatment effects for each temperature and airflow on the drying times of pulped and natural coffee. A significant interaction was observed between temperatures and drying airflows only for pulped coffee. Therefore, we presented means of natural coffee treatments and their comparisons with means of temperature and airflow.

Regarding the airflows for both drying temperatures, a flow of 24 m^3 min^{-1} m^{-2} had the longest drying times for pulped and natural coffee. But at 45 °C, no significant differences were observed when compared to a flow of 60 m^3 min^{-1} m^{-2} for both pulped and natural coffee.

Significant differences were observed between temperatures for all airflows in CD processing. The two highest flows, however, did not differ from each other for a temperature of 40 °C, which was also seen for the three highest flows at 45 °C. In this sense, flows of 96 and 132 m^3 min^{-1} m^{-2} are recommended to speed up drying process regardless of the air temperature.

TABLE 5. Means of drying time (hours) until coffee beans reach 0.125±0.005 kg water kg^{-1} dry matter (db) for natural (NAT) and pulped (CD) coffee as a function of airflow and temperature.

Processing	Temperature (°C)	Airflow (m^3 min^{-1} m^{-2})				Mean
		24	60	96	132	
CD	40	13.30aA	12.84aB	12.59aC	12.13aC	
	45	10.65bA	10.44bAB	10.10bB	10.15bB	
NAT	40	73.20	71.06	67.92	66.10	69.57a
	45	47.93	45.84	44.08	44.46	45.58b
	Mean	60.57A	58.45AB	56.00BC	55.28C	

Means followed by different lowercase letters in the columns and uppercase letters in the rows differ from each other for each type of coffee by Tukey's test at 5% probability.

CONCLUSIONS

The Proposed Model presented the best fit to natural and pulped coffee drying data at drying air temperatures of 40 and 45 °C and airflows from 24 to 132 m^3 min^{-1} m^{-2}.

Temperature and air-flow rises increase coffee drying rates and thereby reduce drying times.

The shortest drying times can be achieved at 45 °C and at 96 and 132 m^3 min^{-1} m^{-2} regardless of the coffee processing type.

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