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Origin of black-green defect in the artificial drying of immature coffees

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ABSTRACT

The inequality of coffee maturation leads to a large portion of green berries in the harvest. Post-harvest management techniques seek to minimize defects during the drying process, such as black-green defects in harvested immature berries. The present study aimed to investigate the minimum occurrence of black-green defects in the drying of immature coffee berries subjected to different temperature conditions and relative humidity values. In addition to fitting mathematical models to the experimental data, the effective diffusion coefficient and the water reduction rate (WRR) were determined. Nine coffee crops (*Coffea arabica* L.) of the Topázio Amarelo variety were harvested manually and selectively during the green maturation stage, with an initial water content of 2.106 ± 0.05 $kg.kg^{-1}$ (dry basis, d.b.). After drying, the coffee was subjected to a drying treatment in a fixed-layer dryer with combined dry bulb temperatures (Dbt) of 35, 40 and 45 °C and dew point temperatures (Dpt) of 2.6, 10.8 and 16.2 °C until a final water content of 0.124 ± 0.05 $kg.kg^{-1}$ (db) was reached. After drying, black-green defects were quantified as percentages. In addition to the drying kinetics, the WRR and effective diffusivity were evaluated. The lowest percentage of black-green defects occurred at a temperature of 35 °C and a Dpt of 2.6 °C (11.00%), which is the most suitable treatment for drying natural green coffees. The highest percentage of defects occurred when a Dbt of 35 °C was combined with a Dpt of 16.2 °C (14.17%). This combination showed the lowest effective diffusion coefficient of 0.551 x 10^{-11} $m^2.s^{-1}$. The Midilli model had the best fit to the experimental data for all drying combinations. The lowest WRR was 0.063 $kg.kg^{-1}.h^{-1}$ and was observed when a Dbt of 35 °C was combined with a Dpt of 16.2 °C.

Keywords: Drying; Coffee; Diffusion coefficient; Mathematical modelling.

1 INTRODUCTION

The ideal time for harvesting coffee is after the berries have achieved physiological maturity, the so-called cherry coffee. However, in Brazil, due to the irregular flowering of crops, coffee plants contain berries at different maturation stages (green, cherry, overripe [raisin] and dry), with varying water contents. The greater presence of immature beans at the beginning of a harvest hinders the type and quality of the beverage, thus affecting the commercial value of the product (Donzeles et al., 2011). To obtain the longest period during which berries are ripe, it is recommended to start harvesting coffeeat a maximum ratio of 30% of immature to pulped cherry on average (Borém, 2008). On a large scale, the amount of harvested green coffee is significant and requires specific management practices, especially during drying, to minimize the generation of black-green defects.

Normative Instruction No. 8 (Brasil, 2003a) brings the approval of the technical regulation of identity and quality for classification of processed raw coffee beans, where it conceptualizes the black-green bean as a black bean that appears shiny due to the adherence of the silver film. When the same grain has more than one defect, the one with the greatest gravity prevails, following the following decreasing scale: black, brown or sour, black-green, shell, malformed, green, broken. The black defect is also called the capital defect, as it is the main one in gravity. More severe defects will affect the drink more negatively. According to Clarke and Macrae (1987), the black defect is associated with a strong unpleasant taste, the sour defect brings a sour taste and the immature defect gives astringency to the drink. According to Mazzafera (1999), immature grains come from immature fruits. Thus, black-green grains are those fruits that fall from the tree, still immature, remain in contact with the soil and become subject to fermentation.

Drying, a highly relevant post-harvest step used to maintain food quality, decreases the water content to reduce the biological activities of microorganisms, thus minimizing spoilage reactions and physical and chemical changes during storage (Araújo et al., 2014).

To minimize the emergence of defects in immature coffees, a maximum temperature of 35 °C is recommended in the coffee mass when drying is performed in a mechanical dryer. In drying yard, drying should be done in thin layers at the beginning, but the thickness can be increased after preliminary drying (‘half dry’), and constant mixing should be performed (Borém; Reinato; Andrade, 2008). However, the combined effect of the temperature and the water reduction rate (WRR) on the formation of these defects is not known.

In experiments with natural coffee dried on a drying yard combined with a fixed-layer dryer at dry bulb temperatures (Dbt) of 35 °C, 40 °C and 45 °C and dew point temperatures (Dpt) of 2.6 °C and 16.2 °C, Borém et al. (2018) concluded that temperatures above 40 °C are not recommended for the drying of specialty coffees. In addition, coffees dried at 45 °C are affected by thermal damage. These results are in agreement with those obtained by Marques et al. (2008) and Oliveira et al. (2013).

In the literature, there are studies that correlate the generation of black-green defects with exposure to drying air with high temperatures; however, no studies are available on the combined effect of temperature and the WRR on the formation of this defect. Thus, the experiment was performed to determine how different combinations of dry bulb temperatures (Dbt) and dew point temperatures (Dpt) values of the drying air affect the percentage of this defect. The dew point temperature is the temperature to which the humid air must be cooled, keeping the pressure and mixing ratio constant, so that this way it reaches saturation in relation to liquid water (Talaia; Vigário, 2016). This is because a possibility to increase the drying rate without thermal damage to the grains is to reduce the relative humidity of the drying air, which can be done by circulating the air through desiccant material, which removes moisture from the drying air or then by reducing the dew point temperature of the air (Fortes et al., 2006; Ondier; Siebenmorgen; Mauromoustakos, 2010). In addition, the drying kinetics of green berries were evaluated through the fitting of mathematical models to the experimental values and know your WRRs.

2 MATERIALS AND METHODS

The present study was performed at the Agricultural Products Processing Laboratory (LPPA) of the Department of Agricultural Engineering of the Federal University of Lavras (UFLA). Coffee crops (*Coffea arabica* L.) of the Topázio Amarelo variety were harvested manually and selectively during the green maturation stage at Faria Farm located in the municipality of Lavras in the southern region of Minas Gerais, Brazil. A total of nine harvests were performed, one for each drying treatment. After harvesting, the green coffees were taken to the LPPA and washed in a water tank to separate by density the healthy berries from the empty locules and the poorly formed, floating and over ripe berries. After washing, the coffees were again selected to remove the green cane coffee, and only the immature coffees were sent for drying. The green cane coffee was removed to standardize the raw material of the study, leaving only berries with a rigid mesocarp and avoiding milky and mucilaginous berries.

The processing was carried out by dry process, in which the fruits are dried in their integral form. In wet processing, the portion of green coffee is separated from the ripe at the time of peeling of the ripe. Thus, these green fruits, which are not peeled, are sent by another route, for drying. The drying system consists of a combination of a laboratory air conditioning system and a fixed-layer dryer. The laboratory air conditioning system was proposed by Fortes et al. (2006). This system allows precise control of drying parameters, such as the air temperature, relative humidity, Dpt and drying air flow rate. The air flow rate was adjusted by a propeller anemometer to 24 $m^3.min^{-1}.m^{-2}$, and the drying air temperature and Dpt in the bean mass were controlled by a wet-and dry-bulb mercury thermometer.

In total, nine dryings were performed in a 3x3 factorial arrangement, with a combination of three Dbt values (35, 40 and 45 °C) with three Dpt values (2.6, 10.8, 16.2 °C). Each treatment consisted of four replicates, one in each tray of the fixed-layer dryer. These combinations of Dbt and Dpt values resulted in different relative humidity (RH) values of the drying air. These drying conditions were defined to represent the drying environments of three different coffee regions.

A control treatment was also performed, in which the coffee was dried in the sun in a suspended yard dryer following the management recommendations for the dryer yard of green coffees proposed by Borém, Reinato and Andrade (2008).

To obtain the drying kinetics curves, the water loss of the immature coffee berries was monitored by the gravimetric method. The samples were weighed more frequently at the beginning of drying (hourly, in the first 6 hours), with longer intervals throughout the process (every 2 hours). The green coffee beans were placed in the dryer with an initial water content of 2.106 ± 0.05 kg of water.kg of dry matter^{-1}(db) until they reached a water content of 0.124 ± 0.05 kg of water.kg of dry matter^{-1} (db), a stable water content for safe coffee storage.

To determine the initial water content, the standard oven method was used; the coffee was dried at 105 ± 3 °C for 24 hours according to the Seed Analysis Rule (Brasil, 2009). To assess the water content at the end of each drying period of the processed dry coffee, the standard oven method was used at 105 ± 1 °C for 16 ± 0.5 hours, according to the International Standard Method of ISO 6673 (International Organization for Standardization - ISO, 2003).

To monitor drying, the gravimetric method of mass-loss analysis was used until the desired water content was reached. Mass loss was monitored with the use of an analytical balance (Shimadzu, model UX420H) with a precision of 0.01 g.

The WRR expresses the amount of water evaporated from the product per unit of dry mass of the product per unit of time, as determined by the following Equation 1 (Corrêa et al., 2010):
where
WRR: water reduction rate (kg. $kg^{-1}.h^{-1}$);
M_{wo}: previous total water mass (kg);

$$WRR = \frac{(M_{wo} - M_{wi})}{(Md(t_i - t_o))} \quad (1)$$

M_{wi}: current total water mass (kg);
M_d: mass of dry matter (kg);
t_o: total time of previous drying (h);
t_i: total time of current drying (h).

At each experimental drying time, the moisture ratio was determined, correlating the water content of the product at a given time with the equilibrium water content and the initial water content for specific conditions that occur during drying, as shown by Equation 2. The experimental curves of the moisture ratio generated in the different treatments were fitted to the mathematical models in Table 1.

$$RX = \frac{WC - WC_e}{WC_i - WC_e} \quad (2)$$

where
RX: moisture ratio of the product (dimensionless);
WC: water content of the product at time t (kg of water, kg of dry matter^{-1});
WC_i: initial water content of the product (kg of water, kg of dry matter^{-1});
WC_e: equilibrium water content of the product (kg of water, kg of dry matter^{-1}).

To determine the moisture content atthe hygroscopic equilibrium of immature coffee, Equation 3 was used (Andrade, 2019):

$$WCe = \exp\left(-2.65798 - \left(0.005699^*T\right) + \left(1.504139^*RH\right)\right) \quad (3)$$

where
WCe: water content at hygroscopic equilibrium of the product (decimal (db));
T: drying air temperature (° C);
UR: drying air relative humidity (decimal).

Table 1 Mathematical models applied to the experimental drying curves.

Model	Model designation	Equation
Two-term	$RX = a\exp(-k_0 t)+b\exp(-k_1 t)$	(4)
Modified Henderson and Pabis	$RX = a\exp(-kt)+b\exp(-k_0 t)+c\exp(-k_1 t)$	(5)
Henderson and Pabis	$RX = a\exp(-kt)$	(6)
Midilli	$RX = a\exp(-kt^n)+bt$	(7)
Newton	$RX = \exp(-kt)$	(8)
Page	$RX = \exp(-kt^n)$	(9)
Thompson	$RX = \exp\{[-a-(-a^2+4bt)^{0,5}](2b)^{-1}\}$	(10)
Verma	$RX = -a\exp(-kt)+(1-a)\exp(-k_1 t)$	(11)
Wang and Sing	$RX = 1+at+bt^2$	(12)
Valcam	$RX = a+bt+ct^{1,5}+dt^2$	(13)
Two-term exponential	$RX = a\exp(-kt)+(1-a)\exp(-kat)$	(14)
Approximation of diffusion	$RX = a\exp(-kt)+(1-a)\exp(-kbt)$	(15)

where:
RX: moisture ratio (dimensionless);
t: drying time (h);
k, k_0 and k_1: drying constants;
a, b, c, d and n: coefficients of the models.

Non-linear regression analysis was performed using the Gauss-Newton method in the Statistica 5.0 software (Statsoft, Tulsa, USA) to fit the mathematical models to the experimental drying data. The effective diffusion coefficient was also determined by fitting the mathematical models based on the liquid diffusion, the experimental data of the immature coffee drying kinetics and non-linear regression. Equation 19, which is the analytical solution for Fick's second law, was used, considering a spherical geometric shape, disregarding the volumetric shrinkage of the berries and considering the water content boundary condition on the product surface.

To determine the goodness of fit for each drying temperature, the following parameters were considered: the significance of the regression coefficients by the t-test at 5% significance, the values of the coefficient of determination (R^2), the mean relative error (P), the estimated mean error (SE) and the chi-square test (χ^2). These coefficients were calculated with equations 16, 17 and 18.

$$P = \frac{100}{n}\sum\frac{|Y - Y_0|}{Y} \quad (16)$$

$$SE = \sqrt{\sum\frac{\left(Y - Y_0\right)^2}{GLR}} \quad (17)$$

$$\chi^2 = \sum\frac{\left(Y - Y_0\right)^2}{GLR} \quad (18)$$

where:
Y: experimentally observed value;
Y_0: value calculated by the model;
n: number of experimental observations;
DF: degrees of freedom of the model.

$$RX = \frac{WC - WC_e}{WCi - WC_e} = \frac{6}{p^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2p^2D_{eff}}{R^2}t\right] \quad (19)$$

where:
D_{eff}: effective diffusion coefficient ($m^2.s^{-1}$);
R: equivalent radius of the coffee berries (m);
n: number of terms;
t: time (s).

The classification established by Normative Instruction no. 8, of 06/11/2003, which defines the "Technical standards for identity and quality for classification of processed green coffee beans" (Brasil, 2003b), was used to identify coffee defects.

To assess the percentage of black-green defects, the number of defects in 100-bean portions of the sample that were already homogenized and quartered was counted, so that the final number expressed a percentage of that defect.

The experiment was set up in a 3x3 factorial arrangement in a completely randomized design, with four replicates (four trays in the fixed-layer dryer). The results of counting the number of black-green defects were subjected to analysis of variance, and the means were compared by the Scott-Knott test at 5% probability.

3 RESULTS

Table 2 shows the results as a percentage of black-green defects originating in each of the immature coffee drying treatments.

Table 2: Percentage of black-green defects in immature coffee drying treatments.

Dbt (°C)	Dpt (°C)		
	2.6	10.8	16.2
35	11.00% aA	11.94% aA	14.17% aB
40	13.93% bB	12.44% aA	13.61% aB
45	12.78% bA	11.56% aA	12.86% aA

Means followed by the same lowercase letters within the same column and uppercase letters within the same row do not differ (P> 0.05) by the Scott-Knott test.

In the control treatment with sun-dried coffee, there was a lower percentage of black-green defects (8.25%), as predicted. In addition, the treatments subjected to mechanical drying had different and higher mean numbers of defects.

Table 3 shows the drying times of each of the treatments, the respective water contents of the natural immature coffee at the beginning and end of drying and the effective diffusion coefficients (D_{eff}).

The water content of the natural immature coffee berries was 2.106 ± 0.05 $kg.kg^{-1}$ (db) at the beginning of the drying process, and drying proceeded until a water content of 0.124 ± 0.05 $kg.kg^{-1}$ (db) was reached. The drying times decreased as the air temperature of each treatment increased. Furthermore, at the same dry bulb temperatures, the drying times increased as the dew point temperatures (Dpt) values increased, as expected for slower drying times.

For the same Dpt of 2.6 °C, there was a 25.6% decrease in the drying time from a Dbt of 35 °C (99.5 hours) to a Dbt of 40 °C (74 hours). Comparing the values at 35 and 45 °C showed that the drying time decreased by 48.74%, i.e., by nearly 50%, which is relevant for decision-making in the implementation of drying systems, provided that there are no decreases in product quality.

The effective diffusion coefficient demonstrates the fluidity of water from the interior of the coffee bean towards the surface and exterior. The lowest effective diffusion coefficient occurred for a Dbt of 35 °C and a Dpt of 16.2 °C, which was also the combination with the highest percentage of black-green defects, suggesting that effective diffusion coefficient values equal to or less than 0.551 x 10^{-11} m^2 s^{-1}indicate inadequate drying for natural immature coffee.

The highest initial WRR (0.160 $kg.kg^{-1}.h^{-1}$) was observed at a Dbt of 45 °C and a Dpt of 2.6 °C, as expected, for the fastest drying. The lowest initial WRR was 0.063 $kg.kg^{-1}.h^{-1}$ and occurred for a Dbt of 35 °C and a Dpt of 16.2 °C. For this combination, there was a higher percentage of black-green defects, confirming that a slow WRR at the beginning of the drying process of immature coffees is favourable to the onset of this defect. The mean WRR also has the same behaviour (Table 3).

Table 4 shows the statistical parameters, including the values for the coefficient of determination (R^2), the standard

Table 3: Values of drying time, initial and final water contents and effective diffusion coefficients for each combination of Dbt and Dpt of the drying air.

Dbt (° C)	Dpt (° C)	RX (%)	Drying time (h)	Water content $kg.kg^{-1}$ (db)		D_{eff} x 10^{-11} ($m^2.s^{-1}$)	Water reduction rate ($kg.kg^{-1}.h^{-1}$)	
				Initial	Final		Initial	Mean
35	2.6	13.1	99.50	2.106±0.05	0.124±0.05	0.688	0.087	0.022
	10.8	23	100.00	2.106±0.05	0.124±0.05	0.654	0.070	0.019
	16.2	32.7	101.00	2.106±0.05	0.124±0.05	0.551	0.063	0.019
40	2.6	10	74.00	2.106±0.05	0.124±0.05	0.927	0.092	0.024
	10.8	17.5	75.00	2.106±0.05	0.124±0.05	0.855	0.087	0.022
	16.2	25	84.00	2.106±0.05	0.124±0.05	0.752	0.069	0.021
45	2.6	7.7	51.00	2.106±0.05	0.124±0.05	1.323	0.160	0.029
	10.8	13.5	53.00	2.106±0.05	0.124±0.05	1.120	0.141	0.028
	16.2	19.2	55.50	2.106±0.05	0.124±0.05	1.181	0.123	0.026

error of the estimate (SE) and the mean relative error (P), from fitting the Midilli mathematical model by non-linear regression to the experimental data for thin-layer drying kinetics.

The most appropriate mathematical model was chosen according to several criteria. The mean error (P) values express the deviation of the experimental values relative to the curve estimated by the model. Thus, values greater than 10% do not properly represent the experimental drying data. The values of the coefficient of determination (R^2), which indicates the goodness of fit of the model to the experimental data, should be higher than 90% (Mohapatra; Rao, 2005).

Out of the 12 models tested, the Midilli model showed the best fit to the nine drying treatments, with the highest R^2values and the lowest P values. The Midilli model is often used because it is easy to apply and has a smaller number of coefficients (Kashaninejad et al., 2007).

Figures 1A to 1C show the drying curves of natural green coffee with the experimental data and the data estimated by the Midilli model of the moisture ratio as a function of time (hours). The figures were grouped according to the Dbt values, with the three different Dpt values. A satisfactory fit was confirmed by observing the agreement between the experimental values and those estimated by the Midilli model in the description of the drying kinetics, as shown in Figures 1A to 1C.

The coefficients of the Midilli model fitted to the experimental drying kinetics data of the different drying air conditions are shown in Table 5.

Table 4: Statistical parameters resulting from the mathematical fit of the Midilli model to describe the drying kinetics of immature coffee berries in each treatment.

Models	Statistical parameters	35 °C			40 °C			45 °C		
		2.6 ° C	10.8 ° C	16.2 ° C	2.6 ° C	10.8 ° C	16.2 ° C	2.6 ° C	10.8 ° C	16.2 ° C
Midilli	R^2(%)	99.991	99.992	99.992	99.985	99.985	99.989	99.981	99.985	99.980
	P	0.842	1.362	1.153	1.677	2.382	1.739	3.538	3.385	4.531
	SE	0.011	0.019	0.023	0.023	0.048	0.035	0.065	0.072	0.080

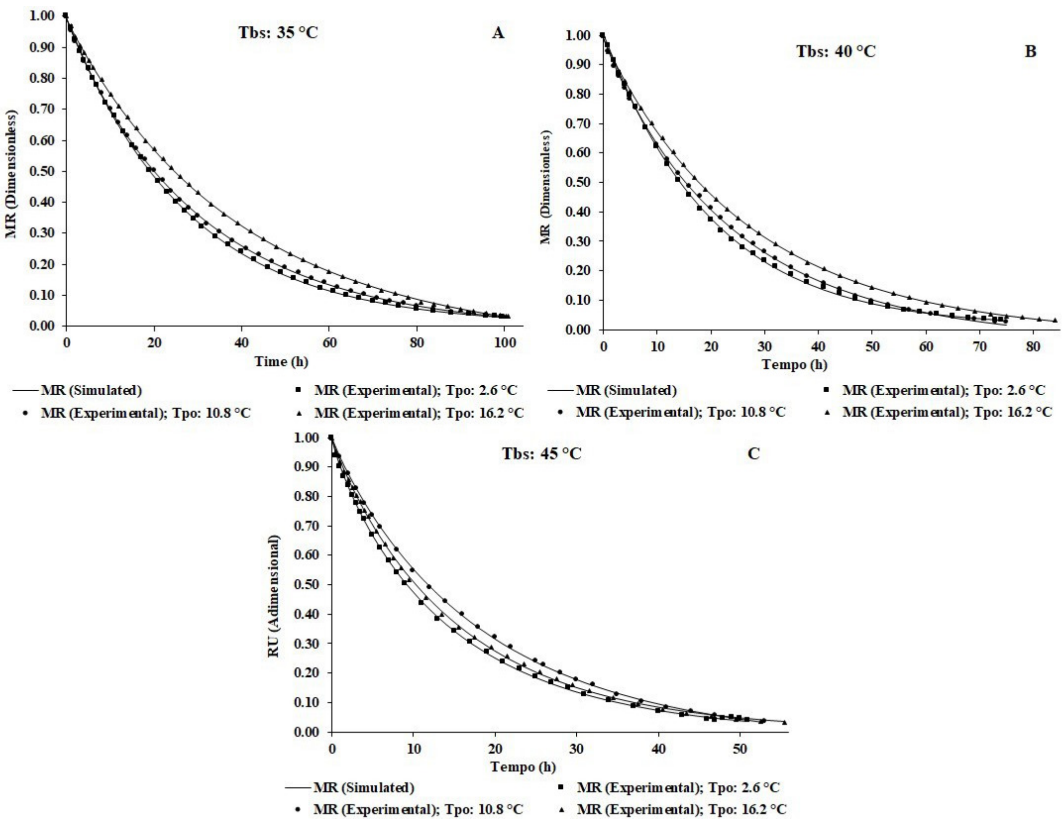

Figure 1: Drying kinetics of green coffee with moisture ratio of the experimental data and the data simulated by the Midilli model. A) Dbt of 35 °C and Dpt of 2.6, 10.8 and 16.2 °C. B) Dbt of 40 °C and Dpt of 2.6, 10.8 and 16.2 °C. C) Dbt of 45 °C and Dpt of 2.6 and 10.8 °C.

Table 5: Coefficients of the Midilli model fitted to the drying data of the coffee berries for the different combinations of Dbt and Dpt of the drying air.

Dbt (°C)	Dpt (°C)	Midilli modelcoefficients			
		a	k	b	n
35	2.6	0.9959	0.0358	0.0000	1.0029
	10.8	0.9942	0.0385	-0.0001	0.9593
	16.2	0.9928	0.0284	-0.0004	0.9840
40	2.6	1.0070	0.0471	0.0001	1.0147
	10.8	0.9920	0.0486	-0.0004	0.9630
	16.2	0.9895	0.0399	-0.0002	0.9828
45	2.6	0.9963	0.0953	-0.0001	0.8889
	10.8	0.9984	0.0662	-0.0005	0.9433
	16.2	0.9952	0.0759	0.0000	0.9460

The coefficient "k" represents the external characteristics of the drying process. Note that these values increase as the temperature increases, which may indicate that the drying process can be controlled by effective diffusivity in the falling rate period, a period in which the internal water transport rate is lower than the water evaporation rate of the product (Rodovalho et al., 2015). However, the same coefficient does not show a trend when its values are observed at the same temperature with the variation in Dpt. The other coefficients, a, b and n, showed no clear trendsas Dbt and Dpt increased.

4 DISCUSSION

The lowest percentage of black-green defects occurred at a temperature of 35 °C and a Dpt of 2.6 °C (11.00%). At a Dbt of 35 °C, with the increase in Dpt, there was an increase in the number of black-green defects (Table 2). This result is in accordance with the current recommendations for the drying in the yard of immature coffees, in which drying must be initiated in thin layers, and after preliminary drying ('half dry'), the thickness of the layers is increased (Borém; Reinato; Andrade, 2008). During the process, the WRR is higher at the beginning of drying and decreases during the process. In contrast, the highest percentage of black-green defects occurred with a Dbt of 35 °C and a Dpt of 16.2 °C (14.17%), which confirms the current recommendations for drying in the yard immature coffee berries.

In Table 3, as the Dbt increases, the effective diffusion coefficient also increases. The increase in drying air temperature leads to a decrease in water viscosity, which encounters lower resistance when flowing from the interior to the surface of the coffee berries (Corrêa et al., 2010). The effective diffusion coefficient values of the different drying treatments are between 0.551 and 1.323 x 10^{-11} m^2 s^{-1}. These values are in the same range as the values found by Alves et al. (2013) when analysing coffee drying (1.908 and 3.721 x 10^{-11} m^2 s^{-1}) and similar to those found by Madamba, Driscoll and Buckle (1996), with values between 10^{-9} to 10^{-11} m^2 s^{-1}. This coefficient is often used because of its complexity and because the data on water movement inside the coffee bean during the drying process are still limited (Araujo et al., 2017).

Throughout the drying process, the WRR decreases until it becomes stable, because after the free water and solvent leaves the coffee berry, there is a greater resistance to water flow from the interior to the surface, hindering the evaporation of water (Doymaz, 2011; Jangam; Law; Mujumdar, 2010). A similar behaviour has been observed by other authors in the drying kinetics of agricultural products such as adzuki beans (Almeida et al., 2009), popcorn (Corrêa; Machado; Andrade, 2001), goat peppers (Rodovalho et al., 2015) and natural coffee (Siqueira et al., 2017).

In experiments with natural coffee drying at the same Dbt values as those used herein and a Dpt of 2.6, Alves et al. (2013) concluded that among the tested models, the modified Henderson and Pabis model exhibited greater randomness in the distribution of the residuals, indicating that it is the most suitable model for representing the data in that study. However, the results of the modified Midilli model were also satisfactory. In studies on the drying of other agricultural products, such as the drying kinetics of adzuki beans (Resende; Ferreira; Almeida, 2010), cowpea (Camicia et al., 2015), *Schinus terebinthifolius* Raddi leaves (Goneli et al., 2014), blackberry (Martins et al., 2018), *Moringa oleifera* (Nascimento; Biagi; Oliveira, 2015), jatropha (Siqueira; Resende; Chaves, 2012) and strawberry (Sousa et al., 2014), the Midilli model has shown the best fit to the experimental data. In other studies, the Valcam model provided the best fit for *Bauhinia forficata* Link leaves (Silva et al., 2017), and the modified Henderson and Pabis model showed the best fit for buriti pulp (Cardoso et al., 2017) and jagua leaves (Silva et al., 2015).

5 CONCLUSIONS

Under the conditions of the present study, the following conclusions can be made:

The lowest percentage of black-green defects occurred at a temperature of 35 °C and a Dpt of 2.6 °C (11.00%). This combination is the most appropriate treatment for the drying of green natural coffee. In contrast, the highest percentage of defects occurred for a Dbt of 35 °C and a Dpt of 16.2 °C (14.17%).

For the same Dpt, the drying time decreased by almost 50% for a Dbt of 35 °C compared to a Dbt of 45 °C.

The lowest effective diffusion coefficient was obtained with a Dbtof 35 °C and a Dptof 16.2 °C, suggesting that effective diffusion coefficient values equal to or less than 0.551 x 10^{-11} m^2 s^{-1}indicate inadequate drying for immature natural coffee.

The Midilli model showed the best fit to the experimental data for all the drying combinations of the natural green coffee, three Dbt values (35, 40 and 45 °C) and three Dpt values (2.6, 10.8 and 16.2 °C).

The lowest initial WRR was 0.063 $kg.kg^{-1}.h^{-1}$ and occurred for a Dbt of 35 °C and a Dpt of 16.2 °C, and this combination also yielded the highest percentage of black-green defects, confirming that a slow WRR at the beginning of the drying process for immature coffee is favourable to the onset of this defect.

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