Research, Society and Development, v. 9, n. 7, e539974419, 2020
(CC BY 4.0) | ISSN 2525-3409 | DOI: http://dx.doi.org/10.33448/rsd-v9i7.4419

Rios, PA, Andrade, ET, Cardoso, DB & Silva, SVO (2020). Colour variation in immature coffee dried under different dry bulb and dew point temperature conditions. ***Research, Society and Development***, 9(7): 1-20, e539974419.

Variação da cor de cafés imaturos secados em diferentes condições de temperatura de bulbo seco e temperatura de ponto de orvalho

Colour variation in immature coffee dried under different dry bulb and dew point temperature conditions

Variación de color del café seco inmaturo en diferentes condiciones de temperatura de bulbo seco y temperatura de punto de rocío

Recebido: 12/05/2020 | Revisado: 14/05/2020 | Aceito: 16/05/2020 | Publicado: 26/05/2020

Paula de Almeida Rios
ORCID: https://orcid.org/0000-0002-2836-918X
Universidade Federal de Lavras, Brasil
E-mail: paulariosagricola@gmail.com
Ednilton Tavares de Andrade
ORCID: https://orcid.org/0000-0002-8448-8781
Universidade Federal de Lavras, Brasil
E-mail: ednilton@deg.ufla.br
Danilo Barbosa Cardoso
ORCID: https://orcid.org/0000-0003-1678-2222
Universidade Federal de Lavras, Brasil
E-mail: cardosodb@gmail.com
Samuel Vieira de Oliveira Silva
ORCID: https://orcid.org/0000-0001-6876-0485
Universidade Federal de Lavras, Brasil
E-mail: samueloliveira@estudante.ufla.br

Resumo

Este trabalho teve por objetivo avaliar a variação da cor em função da cinética de secagem de cafés verdes submetidos às diferentes condições de secagem. Além de ajustar modelos matemáticos aos dados experimentais, em camada delgada, submetido a diferentes condições, bem como determinar a taxa de redução de água (TRA). Cada um dos ambientes de secagem foi determinado pela combinação de 3 diferentes temperaturas de do bulbo seco (Tbs) (35, 40 e 45 °C) e 3 temperaturas de ponto de orvalho (Tpo) (2,6; 10,8; 16,2 °C). Foram colhidos manual e seletivamente cafés (*Coffea arabica* L.) da variedade Topázio Amarelo com teor de água inicial de 2,106±0,05 $kg.kg^{-1}$ (bs), processados por via seca e secados até o teor de água final de 0,124±0,05 $kg.kg^{-1}$ (bs), em secador de camada fixa conjugado à um Sistema de Condicionamento de Ar de Laboratório (SCAL). Após este processo, as amostras foram separadas em duas porções, uma só com defeitos preto-verde e ardido, a outra com os demais grãos, em cada uma fez-se a leitura de cor. Para todas as combinações de secagem o modelo de Midilli apresentou os melhores ajustes aos dados experimentais. A menor TRA foi de 0,063 $kg.kg^{-1}.h^{-1}$ e aconteceu na combinação de Tbs de 35 °C com Tpo de 16,2 °C. Na porção de cafés sem defeitos, dentre os tratamentos realizados na Tbs de 35 °C, a combinação com a Tpo de 2,6 °C apresentou os menores valores de “L”. Para a coordenada “a”, os menores valores encontram-se na combinação de Tbs de 35 °C com Tpo de 2,6 °C.

Palavras-chave: Defeito preto-verde; Modelagem matemática; Taxa de redução de água.

Abstract

This study evaluated colour variation as a function of the drying kinetics of immature coffee subjected to different drying conditions. Additionally, mathematical models were fitted to experimental data for green coffee berries dried in a thin layer under different drying conditions, besides the water reduction rate (WRR) was determined. Each of the drying environments was determined by the combination of three different dry bulb temperatures (Tdb) (35, 40 and 45 °C) and three different dew point temperatures (Tdp) (2.6, 10.8 and 16.2 °C). Coffee (*Coffea arabica* L.) berries of the Topázio Amarelo variety were collected manually and selectively with initial water content of 2.106 ± 0.05 $kg.kg^{-1}$ (dry basis, db); they were processed by the dry-processing method and dried to a final water content of 0.124 ± 0.05 $kg.kg^{-1}$ (db) in a fixed-bed dryer combined with a laboratory air conditioning system (LACS). Following this process, the samples were separated into two parts, one containing beans with black-green and sour defects and the other containing the remaining beans, and the colour was read for each group. For all drying combinations, the Midilli model best fit the experimental data. The lowest WRR was 0.063 $kg.kg^{-1}.h^{-1}$ and occurred in the combination with the Tdb of 35 °C and Tdp of 16.2 °C. In the portion of coffee without defects, among the treatments performed at the Tdb of 35 °C, the combination with the Tdp of 2.6 °C had the lowest luminance values. For the “a” coordinate, the lowest values were found in the combination of the Tdb of 35 °C and Tdp of 2.6 °C.

Keywords: Black-green defect; Mathematical modelling; Water reduction rate.

Resumen

Este trabajo tuvo como objetivo evaluar la variación de color en función de la cinética de secado de los cafés verdes sometidos a diferentes condiciones de secado. Además de ajustar modelos matemáticos a los datos experimentales, en capa fina, sometidos a diferentes condiciones, así como determinar la tasa de reducción de agua (TRA). Cada uno de los entornos de secado se determinó combinando 3 temperaturas diferentes de bulbo seco (Tbs) (35, 40 y 45 ° C) y 3 temperaturas de punto de rocío (Tpr) (2.6; 10.8; 16.2 °C). El café (*Coffea arabica L.*) de la variedad Topacio Amarillo con un contenido de agua inicial de 2.106 ± 0.05 $kg.kg^{-1}$ (bs) procesado en seco y secado hasta el contenido final de agua de 0.124 ± 0.05 $kg.kg^{-1}$ (bs), en una secadora de capa fija combinada con un Sistema de aire acondicionado de laboratorio (SAAL). Después de este proceso, las muestras se separaron en dos porciones, una con defectos negro-verdes y quemados, la otra con los otros granos, en cada una se realizó la lectura del color. Para todas las combinaciones de secado, el modelo Midilli presentó los mejores ajustes a los datos experimentales. El TRA más bajo fue 0.063 $kg.kg^{-1}.h^{-1}$ y ocurrió en la combinación de Tbs de 35 °C con Tpo de 16.2 °C. En la porción de cafés sin defectos, entre los tratamientos realizados a Tbs de 35 °C, la combinación con Tpo de 2.6 °C mostró los valores más bajos de "L". Para la coordenada "a", los valores más bajos se encuentran en la combinación de Tbs de 35 °C con Tpo de 2.6 °C.

Palabras clave: Defecto negro-verde; Modelización matemática; Tasa de reducción de agua.

1. Introduction

The coffee production chain is extremely complex, with multiple operations from the plantation to the cup. In this process, the post-harvest stages, especially drying, have a large effect on the resulting beverage quality. The peculiarities of coffee include significant non-uniform maturation and high water content at harvesting (Borém; Reinato; Andrade, 2008). Drying facilitates grain conservation, allowing safe storage without attack from microorganisms, unwanted fermentation or the generation of defects that result from inadequate drying (Christensen & Kaufmann, 1974).

The production of high-quality coffee requires berries at the peak of maturation, called cherries, with a minimum number of green and dried-up berries in the lot. Thus, the non-uniformity of the berries is a challenge both during harvesting and in the post-harvest processes. For this reason, the berries are sorted during processing, and each maturation stage is dried separately (Donzeles et al., 2011).

Borém (2008) recommends that drying yard of immature coffee be initially conducted in thin layers interspersed with narrow, 0.03m height rows and with constant turning until the coffee is half dry. In this first phase, no risk of a temperature increase exists in the grain mass as long as compensation of heat and mass transfer is occurring. Next, after the berries are half dry, rows with berries 0.15 to 0.20 m in height should be formed, and these berries should be turned frequently to reduce the drying rate, thus avoiding the appearance of black-green defects. This technical procedure is currently recommended for the management of drying yard of immature coffee.

Colourimetry aims to numerically describe the colour of an object. During storage, coffee beans may undergo colour changes due to the lighting and temperature of the storage environment and moisture of the grains (Lopes et al., 1998). According to Abreu et al. (2015), coffee processing and storage methods affect the intensity of the green and blue colours and the luminance of the coffee beans.

In drying, mathematical modelling is a tool that enables predicting the behaviour of various agricultural products, in which the following parameters are considered: drying air temperature, speed and relative humidity and characteristics of the studied product. This behaviour is simulated, along with the water content loss in the thin successive layers (Araujo et al., 2017). Several mathematical models have been used for the behavioural prediction of agricultural products during drying and for the development and manufacture of equipment and dryers (Torrez Irigoyen & Giner, 2014).

No reports were found in the literature on the appropriate management for immature coffee drying in an environment with dry bulb and dew point temperature control or about the models that best describe the immature coffee drying phenomenon in these environments. Thus, the objective of this study was to evaluate the evolution of the colour of immature coffee as a function of different temperature conditions during drying and to fit mathematical models to the drying kinetics of natural immature coffee in each treatment.

2. Materials and Methods

A research is done with the purpose of bringing new knowledge to society as recommended by Pereira et al. (2018). For the authors, laboratory research is one in which it is possible to have an environment in which it’s possible to control the variables. The present study was conducted at the Agricultural Products Processing Laboratory (LPPA) of the Department of Agricultural Engineering, Federal University of Lavras (UFLA). Coffee (*Coffea arabica* L. cv. Topázio Amarelo) berries were manually and selectively harvested nine times at the green maturation stage at Faria Farm, located in the municipality of Lavras, Minas Gerais, Brazil. The processing, drying and analysis stages were conducted at the LPPA. The experiment focused on the drying analysis, where nine treatments, resulting from the combination of three air dry bulb temperatures (Tdb) (35, 40 and 45 °C) with three drying air dew point temperatures (Tdp) (2.6, 10.8 and 16.2 °C), were applied.

After being harvested, the green coffee berries were taken to the LPPA and washed in a water tank for the separation of healthy berries by specific density from small, malformed, floater and dried up berries. After being washed, the coffee berries were again sorted for the removal of unripe berries, and only green berries were sent for drying. Unripe beans were removed to standardize the raw material for the experiment, keeping only the ones with a hard mesocarp, while avoiding milky and mucilaginous berries. The coffee was processed using the dry processing method, in which the berries are dried whole. In order to use the green fruits which were separated in the peeler during wet processing.

After washing and sorting, the green coffee berries were placed in the dryer, which is the combination of a laboratory air conditioning system (LACS) coupled to a fixed-bed dryer. The system allows precise control of the air temperature, relative humidity, dew point temperature and drying air-flow parameters. To obtain lower dew point temperatures, three air-conditioning systems were connected to the LACS so that the external air is cooled in these air-conditioning systems before passing through the LACS.

The fixed-bed dryer consists of four perforated and removable trays that can be rotated. The trays are 0.3 m in length and 0.1 m deep and are mounted over a plenum chamber that homogenously distributes the drying air. The air flow was adjusted with the aid of a fan anemometer to 24 $m^3.min^{-1}.m^{-2}$, and the drying air temperature and the dew point temperature in the grain mass were controlled by a wet and dry bulb mercury thermometer.

In total, nine drying treatments were applied in a 3x3 factorial arrangement, with a combination of three Tdb with three Tdp, which resulted in different relative humidity (RH) values. Each treatment consisted of four replicates, one in each tray of the fixed-bed dryer. The drying conditions were defined to represent the drying environments of different coffee growing regions.

A control treatment was also dried, with the coffee being dried in the sun on a suspended bed, following the management recommendations for yard dryer immature coffee of Borém, Reinato and Andrade (2008).

For the elaboration of drying kinetics curves, the water loss of the green coffee berries was monitored by the gravimetric method. Weight loss was monitored using an analytical balance (Shimadzu, model UX420H) with a resolution of 0.01 g. The samples were weighed more frequently at the beginning of drying (hourly, in the first 6 hours) and less frequently as the drying process progressed (every 2 hours). The green coffee berries were placed in the dryer with an initial water content of 2.106 ± 0.05 kg water.kg dry matter^{-1} (db) until they reached a water content of 0.124 ± 0.05 kg water.kg dry matter^{-1} (db), which is a stable water content for safe coffee storage. When the initial weight and water content of the coffee berries is known, the water content at time t can be determined using equation 1:

$$U_t = \frac{W_{wi} - (W_{ti} - W_{tt})}{W_{dm}} \qquad (1)$$

where

U_t: water content at time t (kg water.kg dry matter^{-1} (db))

W_{wi}: initial water weight (kg)

W_{ti}: initial total weight (kg)

W_{tt}: total weight at time t (kg)

W_{dm}: dry matter weight (kg)

The water reduction rate expresses the amount of water evaporated from the product per unit of dry weight of the product per unit of time, as determined by Corrêa et al. (2001):

$$WRR = \frac{(W_{wo} - W_{wi})}{(W_d\ (t_i - t_o))} \qquad (2)$$

where

WRR: water reduction rate (kg. kg $^{-1}$. h^{-1})

W_{wo}: previous total water mass (kg)

W_{wi}: current total water mass (kg)

W_d: mass of dry matter (kg)

t_o: total previous drying time (h)

t_i: total current drying time (h)

The moisture ratio of the product during drying varies from 1 (initial water content) to 0 (when the product reaches the equilibrium water content). At each experimental drying time, the moisture ratio is known, enabling the water content of the product at that time to be correlated with the equilibrium water content and the initial water content for specific conditions that occur during drying, as demonstrated by equation 3.

The experimental moisture ratio curves generated in the different treatments were fitted to the mathematical models in Table 1.

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

where

MR: moisture ratio of the product (dimensionless)

U: water content of the product at time t (kg water.kg dry matter^{-1})

U_i: initial water content of the product (kg water.kg dry matter^{-1})

U_e: equilibrium water content of the product (kg water.kg dry matter^{-1})

To determine the hygroscopic equilibrium water content of immature coffee, equation 4 was used (LEMOS, 2018):

$$\mathrm{Ue} = \exp\left(-2.65798 - (0.005699 * \mathrm{T}) + (1.504139 * \mathrm{UR})\right) \qquad (4)$$

where

Ue: hygroscopic equilibrium water content of the product (decimal, (db))

T: temperature of the drying air (°C)

RH: relative humidity of the drying air (decimal)

Table 1. Mathematical models applied to the experimental drying curves.

Model	Designation of the model	Equation
Two-term	$MR = a\exp(-k_0t)+b\exp(-k_1t)$	(5)
Modified Henderson & Pabis	$MR = a\exp(-kt)+b\exp(-k_0t)+c\exp(-k_1t)$	(6)
Henderson & Pabis	$MR = a\exp(-kt)$	(7)
Midilli	$MR = a\exp(-kt^n)+bt$	(8)
Newton	$MR = \exp(-kt)$	(9)
Page	$MR = \exp(-kt^n)$	(10)
Thompson	$MR = \exp\{[-a-(-a^2+4bt)^{0.5}](2b)^{-1}\}$	(11)
Verma	$MR = -a\exp(-kt)+(1-a)\exp(-k_1t)$	(12)
Wang & Sing	$MR = 1+at+bt^2$	(13)
Valcam	$MR = a+bt+ct^{1,5}+dt^2$	(14)
Two-term exponential	$MR = a\exp(-kt)+(1-a)\exp(-kat)$	(15)
Diffusion approximation	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	(16)

where:

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

Nonlinear regression analysis was performed using the Gauss-Newton method in Statistica 5.0.® software for fitting the mathematical models to the experimental drying data. To determine the goodness-of-fit for each drying temperature, 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) were considered. These coefficients were calculated with equations 17, 18 and 19.

$$P = \frac{100}{n}\sum\frac{|Y - Y_0|}{Y} \qquad (17)$$

$$SE = \sqrt{\sum\frac{(Y - Y_0)^2}{DF}} \qquad (18)$$

$$\chi^2 = \sum\frac{(Y - Y_0)^2}{DF} \qquad (19)$$

where

Y: experimentally observed value

Y_0: value calculated by the model

n: number of experimental observations

DF: degrees of freedom of the model

The effective diffusion coefficient was determined by fitting the mathematical model, based on net diffusion, to the experimental immature coffee drying kinetics data, using nonlinear regression in Statistica 5.0® (Statsoft, Tulsa, Okla., USA). This equation is the analytical solution for Fick's second law and considers the spherical geometric shape, disregarding the volumetric shrinkage of the berries, and considers the water content boundary condition on the product’s surface, as described by equation 20:

$$RU = \frac{U - U_e}{Ui - U_e} = \frac{6}{p^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[\frac{-n^2 p^2 D_{eff}}{R^2}t\right] \qquad (20)$$

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 colour of the dried and processed green coffee berries was measured using a colorimeter (Minolta, model CR 300), in which three readings of each of the four replicates of the nine treatments were performed. In this system, the direct reading of the a, b (chromaticity) and L (luminosity) coordinates was performed by employing the Hunter colour system described by Nobre (2005).

The results of the colour analysis were subjected to analysis of variance (ANOVA) and to a comparison of means using the Scott-Knott test at 5% probability.

3. Results and Discussion

Table 2 shows the initial and final water contents of each drying treatment, in addition to showing the initial and mean WRR in $kg.kg^{-1}.h^{-1}$.

Table 2. Drying time, initial and final water content and effective diffusion coefficient for each combination of drying air Tdb and Tdp.

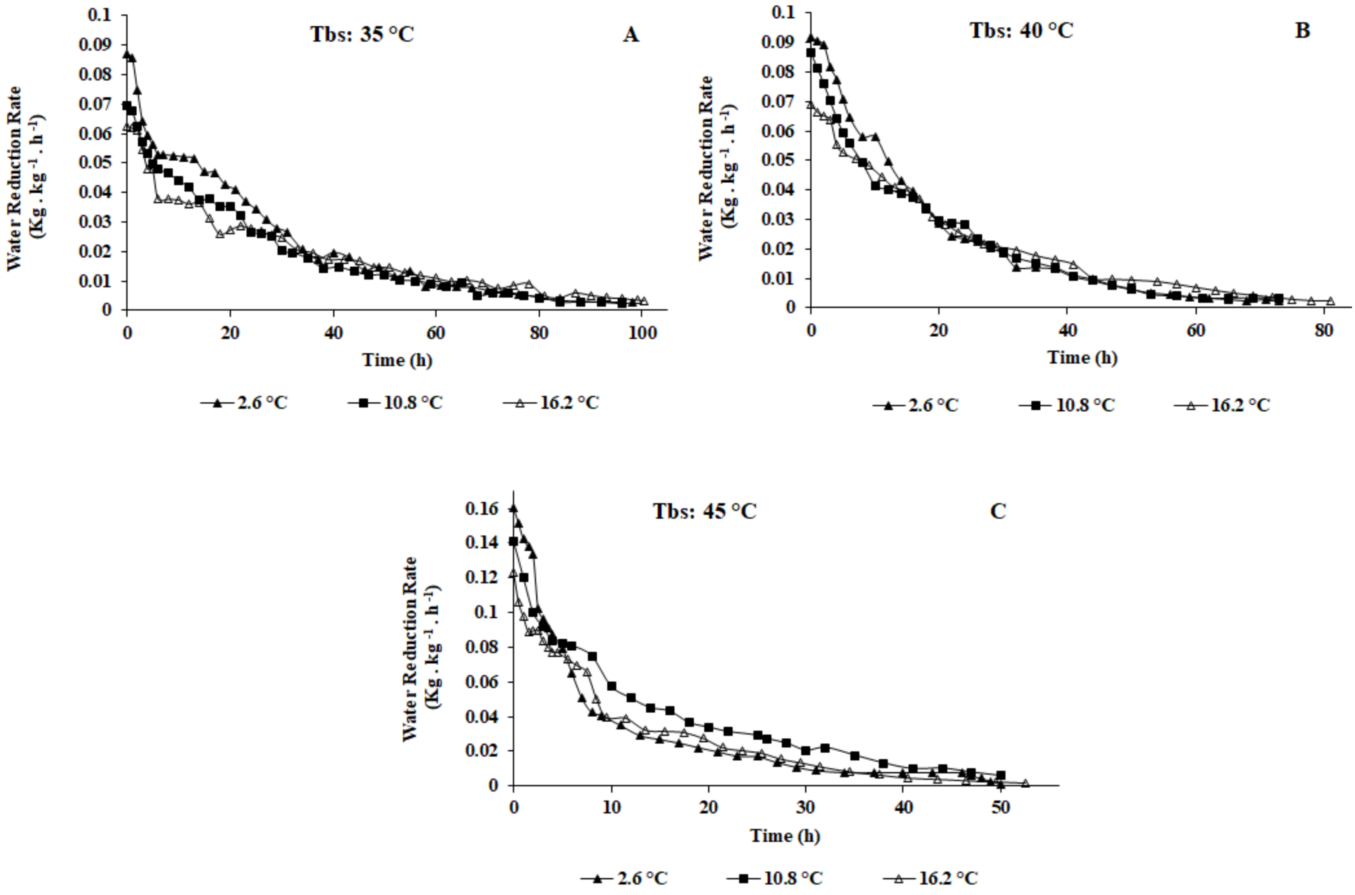
Tdb (°C)	**Tdp (°C)**	**RH (%)**	**Water content kg.kg^{-1} (db)**		**Water reduction rate (kg.kg^{-1}.h^{-1})**	
			Initial	**Final**	**Initial**	**Mean**
35	2.6	13.1	2.106±0.05	0.124±0.05	0.087	0.022
	10.8	23	2.106±0.05	0.124±0.05	0.070	0.019
	16.2	32.7	2.106±0.05	0.124±0.05	0.063	0.019
40	2.6	10	2.106±0.05	0.124±0.05	0.092	0.024
	10.8	17.5	2.106±0.05	0.124±0.05	0.087	0.022
	16.2	25	2.106±0.05	0.124±0.05	0.069	0.021
45	2.6	7.7	2.106±0.05	0.124±0.05	0.160	0.029
	10.8	13.5	2.106±0.05	0.124±0.05	0.141	0.028
	16.2	19.2	2.106±0.05	0.124±0.05	0.123	0.026

Source: Own Research.

The natural immature coffee was harvested and sent to drying with an initial water content of 2.106 ± 0.05 kg.kg^{-1} (db), and drying was completed at a water content of 0.124 ± 0.05 kg.kg^{-1} (db). At the same Tdp values, when the Tdb is increased, the WRR also increases, as also observed by Siqueira et al. (2017) when drying natural coffee with high water content. For the same Tdb values, the WRR showed a decreasing trend as the Tdp increased.

Figure 1 shows the behaviour of the WRR for the nine different drying treatments.

Figure 1. Water reduction rate (WRR) during drying of immature coffee at different air temperature conditions. A) Tdb of 35 °C and Tdp of 2.6, 10.8 and 16.2 °C. B) Tdb of 40 °C and Tdp of 2.6, 10.8 and 16.2 °C. C) Tdb of 45 °C and Tdp of 2.6, 10.8 and 16.2 °C.



Source: Own Research.

The highest WRRs occurred at the beginning of drying and decreased during the process. The initial WRR values were 0.087, 0.070 and 0.063 (kg water kg dry matter^{-1} hour^{-1}) for the Tdb of 35 °C and Tdp of 2.6, 10.8 and 16.2 °C, respectively; 0.092, 0.087 and 0.069 (kg of water kg dry matter^{-1} hour^{-1}) for the Tdb of 40 °C and Tdp of 2.6, 10.8 and 16.2 °C, respectively; and 0.160, 0.141 and 0.123 (kg water kg dry matter^{-1} hour^{-1}) for the Tdb of 45 °C and Tdp of 2.6, 10.8 and 16.2 °C, respectively. The highest WRR (0.160 kg.kg^{-1}.h^{-1}) was observed at Tdb of 45 °C and Tdp of 2.6 °C, as expected, at the faster drying. The lowest WRR was 0.063 kg.kg^{-1}.h^{-1} and occurred at the combination of Tdb of 35 °C and Tdp of 16.2 °C.

After the loss of free water and solvent during the drying process, greater resistance to water migration from the interior to the surface of the berries is present (Borém; Reinato; Andrade, 2008), so that the WRR decreases until it becomes stable. The same trend was observed by Alves et al. (2013) and Siqueira et al. (2017) when working with natural coffee drying.

Malta et al. (2013), working with slow drying (suspended screen in the shade) and fast drying (fixed-bed dryer at 35 ºC) in different coffee processing methods, observed better sensory and physiological quality of coffee subjected to the slow drying, where the electrical conductivity, potassium leaching and total titratable acidity values were lower and the enzymatic activity values of polyphenol oxidase were higher, which indicates lower damage to the cell membrane systems in the drying method with the lower WRR. Additionally, according to Kurzrock et al. (2004), the drying of coffee at high temperatures, combined with high WRRs and with longer storage times, leads to damage of the cell membranes, which causes the extravasation of oils and oxidation, which increases the levels of fatty acids.

Table 3 shows the statistical parameters, with the values of the coefficient of determination (R^2), standard deviation of the estimate (SE) and mean relative error (P) resulting from the fitting of the mathematical models by nonlinear regression to the experimental data on the drying kinetics of the nine analysed treatments.

Table 3. Statistical parameters resulting from the mathematical fitting of each model to describe the drying kinetics of immature coffee berries.

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**
Two-term	**R^2**	99.990	99.980	99.865	99.983	99.941	99.973	99.978	99.938	99.979
	P	0.844	2.664	10.793	1.220	6.370	4.336	3.342	7.912	7.123
	SE	0.011	0.048	0.214	0.015	0.125	0.078	0.062	0.146	0.132
Modified Henderson & Pabis	**R^2**	99.990	99.988	99.865	99.983	99.941	99.973	99.978	99.938	99.983
	P	0.843	2.644	9.246	1.220	6.370	4.336	3.342	7.912	2.879
	SE	0.010	0.050	0.188	0.015	0.125	0.078	0.062	0.146	0.044
Henderson & Pabis	**R^2**	99.990	99.980	99.865	99.979	99.941	99.973	99.849	99.938	99.941
	P	1.319	2.548	9.246	2.396	6.370	4.336	6.121	7.912	8.898
	SE	0.021	0.045	0.188	0.035	0.125	0.078	0.098	0.146	0.169
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
Newton	**R^2**	99.987	99.942	99.865	99.968	99.917	99.955	99.578	99.917	99.867
	P	1.634	2.607	9.303	5.488	5.831	3.737	11.361	7.303	12.705
	SE	0.026	0.036	0.189	0.025	0.108	0.063	0.159	0.128	0.208
Page	**R^2**	99.989	99.976	99.897	99.973	99.922	99.959	99.975	99.928	99.979
	P	1.053	3.602	7.003	2.952	6.745	4.585	3.795	8.733	5.509
	SE	0.016	0.071	0.141	0.043	0.129	0.080	0.098	0.163	0.100
Thompson	**R^2**	99.989	99.959	99.948	99.968	99.918	99.955	99.907	99.917	99.960
	P	0.946	3.971	3.680	2.058	5.027	3.399	6.678	7.359	6.476
	SE	0.012	0.077	0.069	0.030	0.089	0.055	0.076	0.130	0.100
Verma	**R^2**	99.990	99.980	99.988	99.980	99.942	-	99.849	99.962	99.941
	P	1.319	2.548	1.526	2.286	6.214	-	6.121	2.387	8.898
	SE	0.021	0.045	0.029	0.033	0.122	-	0.123	0.030	0.169
Wang & Sing	**R^2**	97.737	97.568	98.999	97.999	98.140	98.034	96.144	97.782	93.594
	P	33.734	31.879	16.540	33.327	27.040	30.976	33.422	34.760	110.851
	SE	0.641	0.656	0.300	0.619	0.594	0.597	0.505	0.758	2.036
Valcam	**R^2**	99.975	99.987	99.994	99.947	99.997	99.990	99.968	99.989	99.965
	P	1.669	1.229	0.719	2.093	0.749	0.951	4.747	2.035	6.332
	SE	0.023	0.016	0.010	0.028	0.013	0.012	0.085	0.035	0.103
Two-term exponential	**R^2**	-	99.988	99.859	-	-	-	99.924	99.944	99.946
	P	-	2.626	9.708	-	-	-	6.430	8.101	5.583
	SE	-	0.049	0.198	-	-	-	0.122	0.153	0.101
Diffusion approximation	**R^2**	99.989	99.988	99.925	99.983	99.947	99.977	99.973	99.945	99.976
	P	1.224	2.651	5.693	2.603	6.537	4.496	3.355	8.167	6.208
	SE	0.020	0.050	0.114	0.039	0.130	0.082	0.061	0.155	0.117

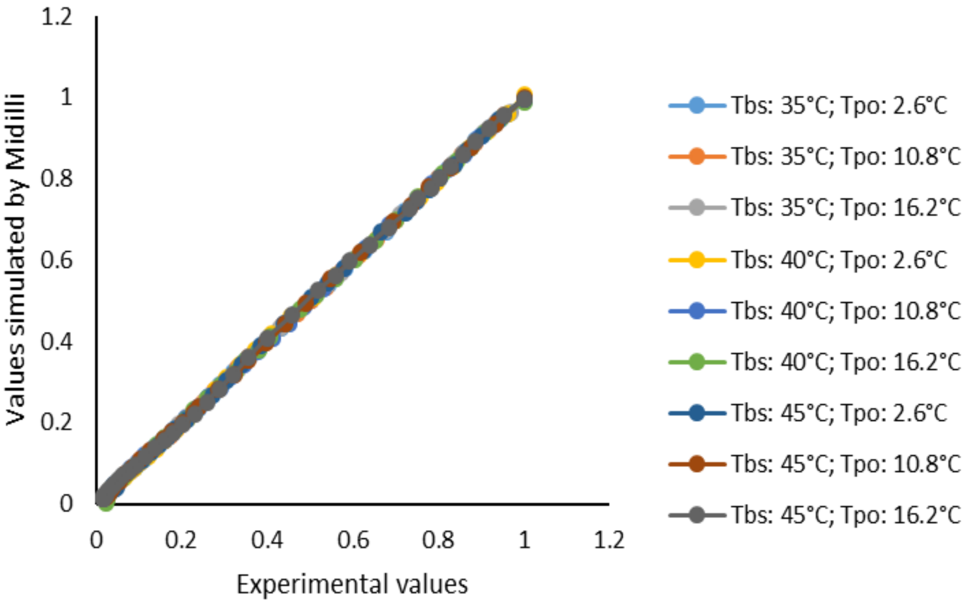
Source: Own Research.

Certain criteria should be followed when choosing the most suitable mathematical models to fit the drying kinetics data. According to Mohapatra and Rao (2005), for a satisfactory fit of the model to the experimental data, R^2 must be greater than 90%, which is the value observed under most drying conditions when most models met this criterion, except for the Verma and two-term exponential models. Furthermore, the lower the SE value, the more satisfactory the representation is of the drying process.

According to Kashaninejad et al. (2007), mean relative error values represent the amount of deviation of the experimental values relative to the curve estimated by the model, and P values greater than 10% do not satisfactorily represent the experimental drying data (Mohapatra; Rao, 2005). The P values for the drying treatments were also appropriate in most models, except for the two-term, Newton, Verma, Wang & Sing and two-term exponential models.

Among the models that obtained the highest R^2 values and lowest P and SE values (Midilli, Valcam and modified Henderson & Pabis), the Midilli model was selected for ease of application, as is often recommended in the prediction of drying phenomena of agricultural products. According to Kashaninejad et al. (2007), the Midilli mathematical model is considered one of the most practical and easy-to-apply models due to the smaller number of coefficients and is often applied in drying simulations. Figure 2 shows the suitability of the Midilli model for the experimental data, given that, for all drying conditions, similar lines are formed from the experimental and simulated moisture ratio values.

Figure 2. Moisture ratio values, experimental and simulated by the Midilli model, for immature coffee drying.



Source: Own Research

The values close to a 45° line reinforce the suitability of the model for the experimental data on the drying of agricultural products (Goneli et al., 2014).

Table 4 shows the mean L, a and b values for the green coffee berries portion, excluding the portion of berries with black, green and sour defects.

Table 4. Colourimetric parameters of luminosity (L) and a and b coordinates of the portion of dried and processed immature coffees berries excluding the portion with the black, green and sour defects.

Colourimetric coordinates	**Treatment**		Tdp (° C)		
			2.6	**10.8**	**16.2**
Luminosity (L)	Tdb (° C)	**35**	42.94 aA	43.56 bA	44.72 bB
		40	41.95 aA	42.10 aA	41.71 aA
		45	46.67 bC	41.09 aA	42.96 aB
a	Tdb (° C)	**35**	0.36 aA	0.62 aB	0.86 bC
		40	0.76 bB	0.77 aB	0.52 aA
		45	0.83 bA	0.76 aA	0.76 bA
b	Tdb (° C)	**35**	15.47 aA	15.30 bA	16.61 cB
		40	14.67 aA	14.68 aA	14.33 aA
		45	17.18 bC	14.29 aA	15.53 bB

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

These samples were read after drying for each of the analysed treatments, where it is possible to observe that the drying treatments had an effect on the variation in the colorimetry factors.

A drying air temperature of 35 °C is recommended for drying green coffee berries; 40 °C is the recommended maximum air temperature for ripe coffee berries, and 45 °C exceeds the recommended temperature for drying quality coffee (Borém et al., 2018).

The L coordinate refers to the coffee bean luminance, where the values range from 0 (black) to 100 (white). Among the treatments applied at Tdb of 35 °C, the combination with Tdp of 2.6 °C resulted in the lowest L values, which is desirable for adequate drying of coffee. As the Tdp was increased at the Tdb of 35 °C, the L values also increased.

The a and b coordinates vary from -80 to +80, and negative a values represent green, and positive values, red. The negative b values represent blue tones, and the positive ones represent yellow tones. That said, the desired colours in dry processed coffee are represented by the lowest a and b values, representing blue-green tones. According to Abreu et al. (2015), the intensity of the green and blue colours and luminance of the coffee beans are affected according to the processing and storage conditions.

The lowest mean a coordinate value was found in the Tdb treatment at 35 °C with a Tdp of 2.6 °C (0.36), the value closest to the control (0.27). Coradi et at. (2008) also observed higher a coordinate values at the drying temperature of 60 °C, in which the coffees were classified as being of poorer quality than those dried at 40 °C in the mechanical dryer. Regarding the values of the b coordinate, a trend towards lower values, closer to the blue tone, was observed with the Tdb of 40 °C.

Table 5 shows the results of the colourimetric parameters of the dark defects portion (black, green and sour) of each of the treatments after drying.

Table 5. Colourimetric parameters of luminosity and a and b coordinates of the portion of dried and processed immature coffee berries with black, green and sour defects.

Colourimetric coordinates	**Treatment**		Tdp (° C)		
			2.6	**10.8**	**16.2**
Luminosity (L)	Tdb (° C)	**35**	38.26 bA	37.93 bA	37.72 aA
		40	36.24 aA	36.33 aA	36.55 aA
		45	39.27 bB	35.63 aA	36.60 aA
a	Tdb (° C)	**35**	0.91 aA	1.71 aB	2.08 bC
		40	1.54 bA	1.55 aA	1.36 aA
		45	1.45 bA	1.43 aA	1.30 aA
b	Tdb (° C)	**35**	11.94 bA	11.72 bA	12.41 bA
		40	10.83 aA	10.80 aA	11.07 aA
		45	13.29 cC	10.25 aA	11.34 aB

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

A trend was observed towards lower L values in the treatments with Tdb of 40 °C. For coordinate a, the lowest value was found in the combination of Tdb of 35 °C with Tdp of 2.6 °C, as shown for a value reported in Table 4; this colour parameter thus suggests that this combination is the most suitable for use when drying immature coffee.

When the means of the luminosity readings of the portion without and with defects were compared, a decrease was found in L in the portion with defects due to browning of the beans, which according to Franca et al. (2005), allows to say that the parameter L alone can be used to distinguish between portions of coffee with and without defects for separation of the beans prior to roasting.

The same authors, working with physical and chemical attributes of coffee defects, performed colour readings, and as in the present study, mixed black, green and sour defects and obtained a mean L value of 39, which is similar to the L values shown in Table 5.

4. Conclusion and Suggestions

Under the conditions of the present study, the following conclusions were made:

For all drying combinations of three different Tdb (35, 40 and 45 °C) with three different Tdp (2.6, 10.8 and 16.2 °C), the Midilli model showed the best fit to the experimental data.

The lowest mean WRR was found with the combination of Tdb of 35 °C with Tdp of 16.2 °C (0.019 $kg.kg^{-1}.h^{-1}$).

In the portion of coffee without defects, among the applied treatments at Tdb of 35 °C, the combination with Tdp of 2.6 °C resulted in the lowest L values, making this treatment desirable for adequate coffee drying.

For a coordinate, the lowest values were found in the combination of Tdb of 35 ° C with Tdp of 2.6 °C for the portions without and with defects. This colour parameter suggests that these conditions provided the most suitable combination for drying immature coffee.

To deepen their knowledge of black-green coffee defects, in addition to the color analysis carried out in the present work, the authors suggest carrying out other analyzes, mainly chemical ones. These better clarify the transformations that occur within the grains. Such as gas chromatography analysis, to identify defective grain compounds, compared to those without defects.

References

Abreu, GFD et al. (2015). Alterações na coloração de grãos de café em função das operações pós-colheita. *Coffee Science*, Lavras, *10* (4): 429-36.

Alves, GE et al. (2013). Cinética de secagem de café natural para diferentes temperaturas e baixa umidade relativa. *Coffee Science*, Lavras, *8* (2): 238-247.

Araujo, WD et al. (2017). Modelagem matemática da secagem dos frutos de amendoim em camada delgada. *Revista de Ciências Agronômicas*, Fortaleza, *48* (3): 448-457.

Botelho, FM et al. (2018). Modelagem matemática da contração volumétrica de grãos de soja durante o processo de secagem. *Revista Engenharia na Agricultura*, *26* (1): 1-12.

Borém, FM et al. (2018). Quality of natural coffee dried under different temperatures and drying rates. *Coffee Science*, Lavras, *13* (2): 159-167.

Borém, FM. (2008). *Processamento do café*. In: Borém, FM. (2008). *Pós-colheita do café. Lavras*: UFLA. p. 127-158.

Borém, FM, Reinato, CHR & Andrade, ET. (2008). *Secagem do café*. In: Borém, FM. (Ed.). (2008). *Pós-colheita do café*. Lavras: UFLA. p. 205-240.

Coradi, PC, Borem, FM, Oliveira, JA. (2008). Qualidade do café natural e despolpado após diferentes tipos de secagem e armazenamento. *Revista Brasileira de Engenharia Agrícola e Ambiental, 12* (2): 181-188.

Corrêa, PC, Machado, PF, Andrade, ED. (2001). Cinética de secagem e qualidade de grãos de milho-pipoca. *Ciência e Agrotecnologia*, Lavras, *25* (1): 134-142.

Christensen, CM, Kaufmann, HH. Microflora. In: Christensen, C. M. Storage of cereal grain and their products. St. Paul, MN: American Association of Cereals Chemists, 1974. p. 158-192.

Donzeles, SML et al. Colheita e processamento do café arábica. In: REIS, P. R; CUNHA, R. L.; CARVALHO, G. R. Café Arábica da pós-colheita ao consumo. Lavras: U. R. EPAMIG SM, p. 19-67, 2011.

Franca, AS et al. (2005). Physical and chemical attributes of defective crude and roasted coffee beans. Food Chemistry, *90* (1-2): 89-94.

Goneli, ALD et al. (2014). Modelagem matemática e difusividade efetiva de folhas de aroeira durante a secagem. *Pesquisa agropecuária tropical*, Goiânia, *44* (1).

International Organization for Standardization. Green coffee: determination of loss mass at 105 °C: ISO 6673. Geneva, 2003. 17 p.

Kashaninejad, M. (2007). Thin-layer drying characteristics and modeling of pistachio nuts. *Journal of Food Engineering, 78* (1): 98-108.

Kurzrock, T, Kolling-speer, I, Speer, K. (2004). Effects of Controlled Storage on the Lipid Fraction of Green Arabica Coffee Beans. *Food Chemistry*, *66*, 161-168.

Lemos, IA. (2018). Determinação da qualidade imediata e latente de café secado com baixas umidades relativas do ar. 2018. 67 p. Dissertação (Mestrado em Engenharia Agrícola) – Universidade Federal de Lavras, Lavras, MG.

Lopes, RP, Hara, T, Silva, JS. (1998). Avaliação da qualidade de grãos de café pela colorimetria. *Engenharia na Agricultura*, Viçosa, *6* (3): 160-169.

Malta, MR et al. (2013). Alterações na qualidade do café submetido a diferentes formas de processamento e secagem. *Revista Engenharia na Agricultura-Reveng*, *21* (5): 431-440.

Mohapatra, D, Rao, PS. (2005). A thin layer drying model of parboiled wheat. *Journal of Food Engineering*, *66* (4): 513-518.

Pereira, AS et al. (2018). *Methodology of cientific research*. [*e-Book*]. Santa Maria City. UAB / NTE / UFSM Editors. Accessed on: May, 14th, 2020. Available at: https://repositorio.ufsm.br/bitstream/handle/1/15824/Lic_Computacao_Metodologia-Pesquisa-Cientifica.pdf?sequence=1.

Siqueira, VC et al. (2017). Drying kinetics of processed natural coffee with high moisture content. *Coffee Science*, Lavras, *12* (3): 400 - 409.

Torrez Irigoyen, RM, Giner, SA. (2014). Drying-toasting kinetics of presoaked soybean in fluidised bed. Experimental study and mathematical modelling with analytical solutions. *Journal of Food Engineering*, London, *128* (1): 31-39.

Percentage of contribution of each author in the manuscript

Paula de Almeida Rios – 40%

Ednilton Tavares de Andrade – 20%

Danilo Barbosa Cardoso – 20%

Samuel Vieira de Oliveira Silva – 20%