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Thermophysical properties of parchment coffee: New Colombian varieties

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Abstract

The thermophysical properties of coffee have a special partaking during the drying process since a material-depending heat and mass transfer occurs between the bean and the drying air. Conditional to the thermophysical properties of the parchment coffee, the drying can be more or less efficient, affecting the final quality and seed safety. Several coffee varieties have been studied; however, the National Coffee Research Center of Colombia has developed new highly productive coffee varieties resistant to different diseases: Cenicafé 1 and Castillo®. Nevertheless, the thermophysical properties of these specific varieties were not yet investigated; moreover, the availability of information related to these properties of different coffee varieties in the literature is relatively scarce. Thus, this study targeted to determine the parchment coffee thermophysical properties of these new varieties at five different moisture contents % (wb): 53%, 42%, 32%, 22% and 11%, using optimized techniques and methods to ensure high accuracy and exactness. It was found that the new varieties have larger, heavier, and denser beans; it was also seen that the bulk thermal conductivity and the bulk-specific heat are higher in these varieties than in the older ones. It was also revealed that the length, width, thickness, and surface area did not change as the moisture was removed, whereas the bulk density, kernel density, mass, bulk-specific heat, and bulk thermal conductivity decreased as the moisture was reduced. Displaying better thermophysical properties will improve the drying and roasting processes; hence, a better final product can be expected from these varieties.

Practical applications

Knowing the thermal and physical properties of these new varieties will allow the growers and coffee processing facilities to predict, simulate and control different post-harvesting processes such as pulping, fermentation, drying, storing, and roasting. Also, the already developed mathematical models to estimate coffee drying times can

be updated, improving the accuracy of the predictions, bed porosities, mass, and heat transfer in order to safeguard the innocuousness of the product.

KEYWORDS
coffee bean, drying, image analysis, parchment coffee, thermal and physical properties

1 | INTRODUCTION

When coffee is processed using the wet method, it undergoes several steps until its final stage before being exported. It is picked, pulped, fermented, washed, and dried (Tarzia et al., 2010). After washing and draining, the beans hold a moisture content of approximately 53% (wb), and they must be dried until reaching 10%–12% (wb) (Manrique et al., 2020). Seeing that coffee has a very high moisture content, it becomes a suitable host for developing microorganisms, fungi, and molds (Batista et al., 2009). That is why the drying process should occur as soon as possible, and it must be duly controlled until the final moisture content is reached. Leading to one issue that the coffee growers face when drying their product since the harvest peaks might overlap with the rainy seasons (García et al., 2014); therefore, the drying process during this time is rather complicated, especially since they tend to sun-dry the coffee (Firdissa et al., 2022) and the temperature inside the drying facilities highly fluctuate.

One of the most important characteristics of grains and agricultural materials is the thermal and physical properties (Mohsenin, 1970, 1980; Phitakwinai et al., 2019); thanks to these attributes, the mass and heat transfer, resistance, storage information and quality standards can be predicted or calculated. These properties mainly affect the drying process (Brooker et al., 1992), contemplating that the distribution in the drying bed depends on the material's size, mass, density (bulk and real), shape and other physical properties, while the drying time, efficiency, heat, and mass transfer, among others, depend on the thermal properties of the product.

The National Coffee Research Center of Colombia, seeking to provide Colombian coffee growers with coffee plants with high yield, good structure, and resistance to different diseases such as coffee rust or coffee berry disease (CBD), have developed new varieties that fulfill the previous requirements: Cenicafe 1 (Flórez et al., 2016) and Castillo® (Flórez et al., 2018). Although these varieties have proved to provide high yields and disease resistance, the physical and thermal properties of the beans have not yet been calculated; on the other hand, the literature offers properties of older coffee varieties (Chandrasekar & Viswanathan, 1999; Severa et al., 2012).

Considering the importance of the physical and thermal properties of coffee beans at different postharvest stages and seeing the lack of information from these high-value coffee varieties, the objective of this study was to determine the thermophysical properties (orthogonal dimensions, surface area, mass, bulk density, kernel density, bulk thermal conductivity, and bulk-specific heat) of the new coffee varieties at five different moisture content values. It aims to gather accurate and relevant information about the changes in these properties as the grain dries. This will enable a deeper understanding of the transport processes that play an essential role in preserving grain quality.

2 | MATERIALS AND METHODS

This research was conducted at the National Coffee Research Center of Colombia (Cenicafé) in the postharvest discipline laboratories and facilities in the municipality of Manizales, Caldas (4°59′30.8″N 75°35′49.7″W; elevation of 1306 m.a.s.l). In this study, two varieties of *Coffea arabica L.* were studied: var. Cenicafé 1 (C1) and var. Castillo® (RC), both developed and bred by Cenicafé.

The physical and thermal characteristics of the parchment coffee were evaluated at five different moisture contents (% wb). A bifactorial experimental design in blocks was considered with three replications per variety; the first factor was the variety (C1 and RC), while the second factor was the moisture content (% wb): 53%, 42%, 32%, 22% and 11% with a ± 1% error margin. The block was defined as the experimental unit: the coffee load, three per variety, each composed of 50 kg of coffee berries at ripe stages 4, 5 and 6 (Pineda et al., 2022).

The response variables were the grain's length (mm), width (mm), thickness (mm), surface area of the endocarp (mm^2), mass of the grain (g), kernel density ($kg\ m^{-3}$), bulk density ($kg\ m^{-3}$), bulk-specific heat ($kJ\ kg^{-1}\ K^{-1}$) and bulk thermal conductivity ($W\ m^{-1}\ K^{-1}$).

2.1 | Sample preparation

After receiving and cleaning the berries, they were pulped, demucilaginated, washed, and dried; the washed and drained wet parchment coffee mass, weighing approximately 20 kg at 53% (wb), was first divided into five samples of 4 kg each before being placed in a forced convection mechanical dryer at 50°C to achieve the required moisture content.

To determine the initial moisture content of the parchment coffee mass, three 10 g samples of wet coffee were placed in a laboratory oven at 105°C for 16 h to achieve complete grain dryness as specified in the international standard ISO6673:2003. The initial moisture content was determined by using the gravimetric ratio shown in Equation (1).

$$m_f = \frac{m_i(1-M_i)}{(1-M_f)}. \tag{1}$$

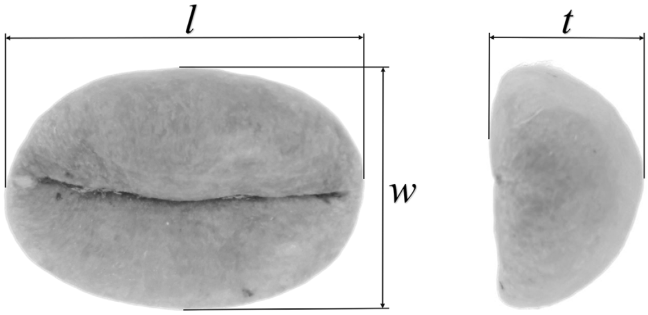

FIGURE 1 Length, width, and thickness of the grain.

The initial and final mass values are given by m_i and m_f, while M_i and M_f correspond to the sample's initial and final moisture contents. After identifying the initial moisture content, knowing the initial mass value and the desired final moisture content, Equation (1) was used to calculate the final mass of coffee in each tray that met the final moisture conditions, and then it was monitored until the target was reached.

As soon as the samples reached the desired moisture content, they were removed from the dryer, tagged, and sealed in airtight plastic bags to prevent moisture loss or gain, and were stored in a temperature and humidity-controlled storage room for further analysis.

2.2 | Physical properties

At the established moistures, the orthogonal dimensions of the grain (length, width, and thickness), the surface area of the parchment (endocarp), mass, kernel density, and bulk density were calculated. Per replication, 60 grains were randomly chosen based on moisture levels. Of these, 30 were used for mass calculations and kernel densities and the other 30 for endocarp area and geometric values measurement, in contrast, the additional properties were calculated in bulk.

2.2.1 | Dimensions

The length (l), the width (w), and the thickness (t) of each grain in the sample were measured with a digital micrometer with a precision of 0.001 mm. Each of these three values was taken between the most distant points in the three-dimensional space (Figure 1). All the beans were coded to ensure their traceability.

2.2.2 | Parchment (endocarp) surface area

In order to provide better contrast, the endocarp from each of the measured and traced beans was carefully removed, flattened, and placed on a blue RGB (53, 90, 255) surface, which depicted the highest contrast with the endocarp colors according to Castrillón et al. (2017). A picture of the endocarp parts was taken with a high-resolution camera at a constant height after capturing a 10 mm quartz pattern to analyze the image further. The samples were illuminated with two 12 W, 50–70 lm W^{-1} LED lights (bottom-top) with a color index of 70 to highlight the area of interest and reduce the brightness for a sharper capture. The complete setup is shown in Figure 2.

Images were imported into ImageJ (Fiji) software and scaled according to the 10 mm quartz pattern after being taken. A macro was developed so all the images could be examined at once following the code protocol; after opening the picture, the program splits the RGB color matrix into three channels: red, green, and blue. The red channel was chosen since it provided the highest contrast between the blue background and the tan endocarp.

Afterwards, a threshold of 90/254 intensity was used to create a binary image out of the red intensity matrix (grayscale of the red channel). Where 1 indicated the target area and 0 the background. The resulting image was then analyzed considering areas larger than 0.2 mm^2, an overlay was also added to identify both the borders and the included areas. The analysis output was the total surface area of the endocarp of each bean in mm^2, attained by the software multiplying the number of pixels set times the resolution. Figure 3 displays the stages of the image during its study.

The resolution of the analysis when setting the scale with the pattern was 0.0002293 mm^2 pixel^{-1}; establishing a relationship between the orthogonal dimensions, and the surface area is one of the expected outputs.

2.2.3 | Mass

The mass of the 30 grains per moisture content was determined by using an analytical balance (Mettler Toledo ML204 NewClassic MF) with a capacity of 220 g and readability and resolution of 0.1 mg. The grains were numbered to track them.

2.2.4 | Kernel density

The kernel density was calculated using the paraffin method (Mohsenin, 1970, 1980), each of the grains numbered in sect. 1.2.3 was covered with paraffin, and the process was performed. The density of paraffin was calculated by pouring liquid paraffin into a known volume, weighing it after solidification, and calculating the mass/volume ratio.

2.2.5 | Bulk density

The bulk density of the coffee was determined by filling a cylinder with a calibrated volume of 1 L with free-falling coffee beans in accordance with the procedure outlined in ISO 6669:1995. Excess grains on top of the cylinder were removed by sliding a stainless-steel rectified ruler lengthwise along the cylinder's border. Once the grain mass in the cylinder was weighed, its mass divided by the volume of the

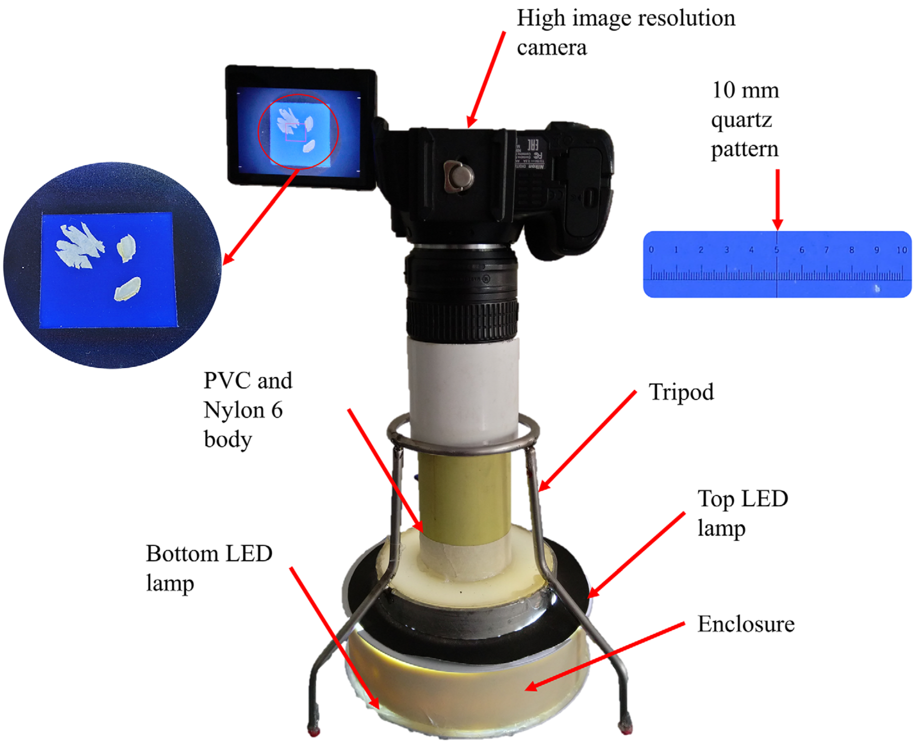

FIGURE 2 Coffee endocarp photographing setup.

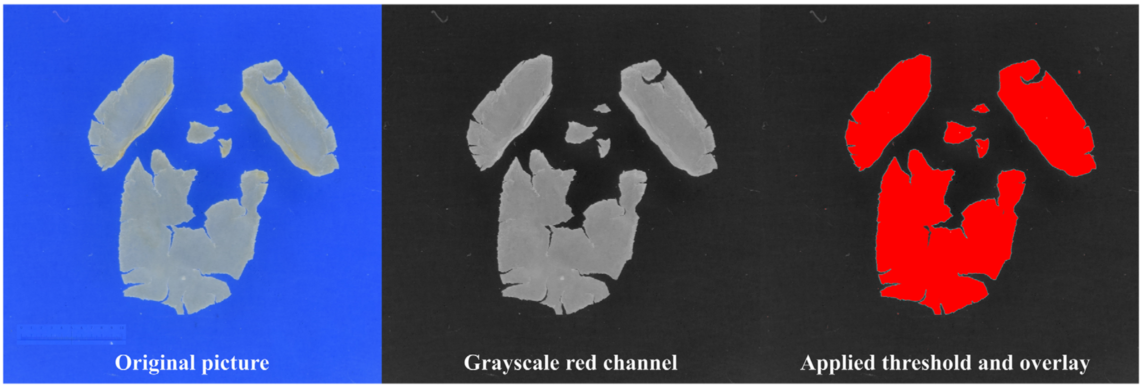

FIGURE 3 Image analysis process.

cylinder yielded the bulk density. Four replications were performed per moisture content per variety.

2.3 | Thermal properties

In the moisture content range of interest, the bulk-specific heat capacity and the bulk thermal conductivity of parchment coffee were calculated.

2.3.1 | Bulk-specific heat capacity C_p

To determine the bulk-specific heat capacity of the coffee ($C_{pcoffee}$), the method of mixtures (Monirul Islam Chowdhury et al., 2001; Siriprom et al., 2014) was used. A 100 g sample of coffee was heated indirectly in a water bath; a thermocouple temperature sensor controlled the grain temperature. To ensure a homogeneous temperature profile throughout all samples, the system was stabilized once the coffee mass reached 80°C ($T_{icoffee}$) for 10 min. It was then dropped into a calorimeter containing 500 g of water (m_{water}) at ambient temperature (T_{iwater}) previously measured by a DS18B20 digital temperature sensor mounted on top of the calorimeter, and the system was then gently stirred. As the temperature rose, the system reached equilibrium temperature (T_{eq}) and considering that the water gains (Q_{water}) the heat lost by the coffee (Q_{coffee}) and the specific heat capacity of the water is known (C_{pwater}), the following balance was obtained.

$$Q_{water} = -Q_{coffee},$$

where

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$$Q_{water} = m_{water} C_{p_{water}} \left(T_{eq} - T_{i_{water}} \right),$$

$$Q_{coffee} = m_{coffee} C_{p_{coffee}} \left(T_{eq} - T_{i_{coffee}} \right).$$

Hence, the bulk-specific heat capacity can be calculated as shown in Equation (2),

$$C_{p_{coffee}} = \frac{-m_{water} C_{p_{water}} \left(T_{eq} - T_{i_{water}} \right)}{m_{coffee} \left(T_{eq} - T_{i_{coffee}} \right)}. \tag{2}$$

The bulk-specific heat capacity of the coffee measurement was replicated three times at each moisture content level per variety to decrease the error. The temperature change was measured by a DS18B20 digital temperature sensor and registered on an Arduino-based data logger.

2.3.2 | Bulk thermal conductivity *K*

The conductometer shown in Figure 4 was designed and built to measure the bulk thermal conductivity of the parchment coffee. Its working principle relies on the line heat source method (Banaszkiewicz et al., 1997; Vacquier, 1985; Zhu et al., 2021), where a constant heat source within a material rises the temperature of such medium. The linear temperature change in the material can be estimated and depending on the time it takes the temperature to travel through a certain length, the conductivity of the material can be determined.

In this case, a 20-gauge stainless steel wire, with a resistivity of 1.4 $\Omega\, m^{-1}$ was connected through a 14-gauge copper cable to a D.C. power supply. The power supply was set to deliver 1.2 V with a current of 4.33 A, raising the wire's temperature to 86°C. The inner cylinder of the apparatus was made out of a 110 mm PVC pipe with a length of 20 cm; the outer cylinder was constructed with a 160 mm PVC pipe, allowing a gap between cylinders of 22.9 mm where polyurethane foam was applied as thermal insulation.

A set of five NTC100 thermistors were parallelly located to the wire 1 cm apart, starting from the central axis of the device toward the wall. Once the wire was heated, each thermistor registered the temperature change linearly for 45 min with intervals of 0.5 s. The data was directly saved in an Arduino-based data logger with a mega ADK microcontroller board with a real-time clock, adjusted with a signal conditioning circuit and an SD storage module.

The process was repeated three times per moisture content; the obtained data was then used to calculate the bulk thermal conductivity using Equation (3) (Morita & Paul Singh, 1979). Which involves the voltage (*V*), electrical current (*I*), distance from the central axis (*L*), time (t^*) and temperature (*T*).

$$K = \left[\frac{V\, I \ln\left(\frac{t_2^*}{t_1^*}\right)}{4\pi L \left(T_2 - T_1\right)} \right]. \tag{3}$$

3 | RESULTS AND DISCUSSION

As shown in Table 1, both varieties exhibited similar physical and thermal properties; however, the RC variety had higher values in terms of length, width, and thickness. With the RC seed being longer, wider, and thicker, it makes sense that its surface area is also higher than the

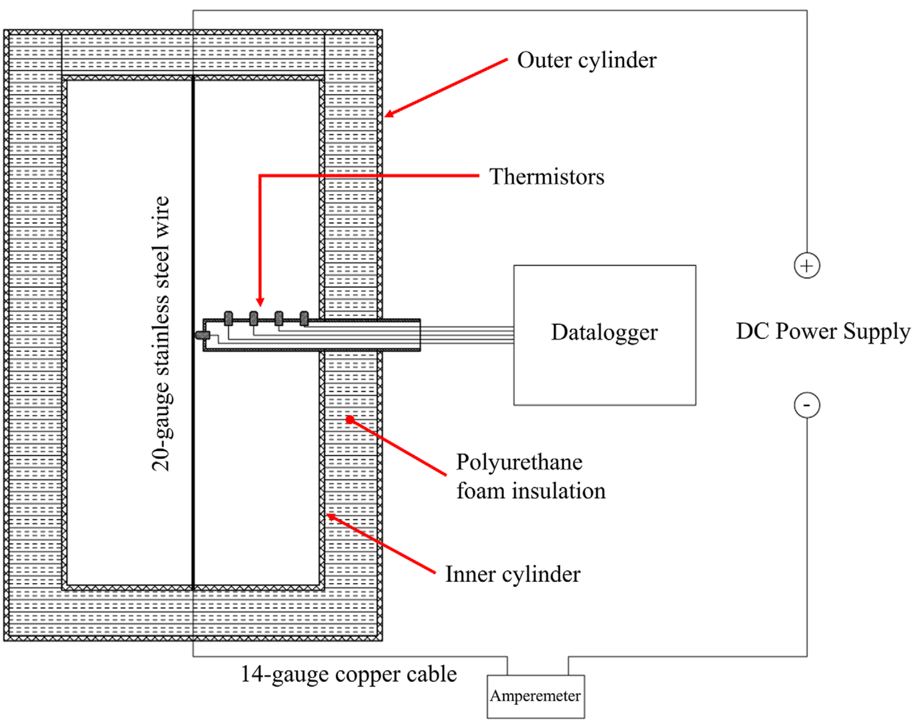

FIGURE 4 Conductometer setup.

TABLE 1 Mean, standard deviation and 95% confidence interval for the evaluated variables.

Variable	Variety	Moisture content % (wb)	Mean	Standard deviation	Confidence interval	
					Lower bound	Upper bound
Length (mm)	C1	53	13.06	0.94	12.71	13.41
		42	12.80	0.62	12.57	13.03
		32	12.56	0.81	12.26	12.87
		22	12.39	0.82	12.08	12.69
		12	12.41	0.88	12.08	12.73
	RC	53	13.42	0.74	13.14	13.69
		42	13.27	0.76	12.99	13.56
		32	13.02	0.67	12.77	13.27
		22	13.26	0.73	12.99	13.53
		12	12.69	0.70	12.43	12.95
Width (mm)	C1	53	9.36	0.48	9.18	9.54
		42	8.93	0.55	8.73	9.14
		32	9.08	0.39	8.94	9.23
		22	9.09	0.42	8.93	9.24
		12	9.12	0.65	8.87	9.36
	RC	53	9.46	0.43	9.30	9.62
		42	9.38	0.75	9.10	9.66
		32	9.13	0.48	8.95	9.31
		22	9.32	0.49	9.14	9.50
		12	9.22	0.61	9.00	9.45
Thickness (mm)	C1	53	5.68	0.33	5.56	5.80
		42	5.45	0.29	5.34	5.56
		32	5.57	0.32	5.45	5.69
		22	5.47	0.39	5.32	5.61
		12	5.68	0.33	5.56	5.80
	RC	53	5.45	0.29	5.34	5.56
		42	5.57	0.32	5.45	5.69
		32	5.47	0.39	5.32	5.61
		22	5.68	0.33	5.56	5.80
		12	5.45	0.29	5.34	5.56
Surface area (mm^2)	C1	53	315.95	58.40	294.14	337.76
		42	275.71	24.60	266.53	284.90
		32	279.34	20.35	271.74	286.94
		22	277.65	27.69	267.31	287.99
		12	289.35	31.71	277.51	301.19
	RC	53	286.73	23.39	277.99	295.46
		42	303.05	25.71	293.45	312.65
		32	288.37	23.76	279.50	297.24
		22	295.35	27.05	285.25	305.46
		12	293.05	22.65	284.59	301.51
Bulk density (kg m^{-3})	C1	53	0.70	0.002	0.70	0.71
		42	0.57	0.03	0.50	0.63
		32	0.49	0.01	0.45	0.52
		22	0.42	0.02	0.36	0.47
		12	0.39	0.002	0.38	0.39

TABLE 1 (Continued)

Variable	Variety	Moisture content % (wb)	Mean	Standard deviation	Confidence interval Lower bound	Upper bound
	RC	53	0.70	0.003	0.69	0.70
		42	0.58	0.01	0.56	0.59
		32	0.49	0.01	0.47	0.51
		22	0.43	0.01	0.40	0.46
		12	0.39	0.01	0.37	0.42
Kernel density (kg m^{-3})	C1	53	0.959	0.00001	0.96	0.96
		42	0.897	0.00005	0.90	0.90
		32	0.839	0.00018	0.84	0.84
		22	0.781	0.00010	0.78	0.78
		12	0.722	0.00017	0.72	0.72
	RC	53	0.954	0.00004	0.95	0.95
		42	0.891	0.00011	0.89	0.89
		32	0.834	0.00010	0.83	0.83
		22	0.776	0.03341	0.71	0.88
		12	0.729	0.00007	0.72	0.72
Mass (g)	C1	53	0.4975	0.01042	0.47	0.52
		42	0.4297	0.06302	0.27	0.59
		32	0.3430	0.01434	0.31	0.38
		22	0.3036	0.00514	0.29	0.32
		12	0.3096	0.06393	0.15	0.47
	RC	53	0.4696	0.01865	0.42	0.52
		42	0.3787	0.02644	0.31	0.44
		32	0.3214	0.00433	0.31	0.33
		22	0.3083	0.01264	0.28	0.34
		12	0.2651	0.00652	0.25	0.28
C_p (kJ kg^{-1} K^{-1})	C1	53	4.722	0.002	4.717	4.728
		42	4.127	0.007	4.110	4.145
		32	3.572	0.004	3.563	3.581
		22	3.043	0.003	3.036	3.050
		12	2.502	0.002	2.496	2.508
	RC	53	4.652	0.003	4.644	4.659
		42	4.065	0.000	4.064	4.065
		32	3.507	0.009	3.485	3.529
		22	2.974	0.004	2.963	2.985
		12	2.443	0.013	2.411	2.475
K (W m^{-1} K^{-1})	C1	53	0.023	0.00011	0.023	0.023
		42	0.021	0.00018	0.020	0.021
		32	0.018	0.00003	0.018	0.018
		22	0.015	0.00016	0.015	0.016
		12	0.013	0.00023	0.013	0.014
	RC	53	0.022	0.00002	0.022	0.022
		42	0.019	0.00012	0.019	0.020
		32	0.017	0.00005	0.017	0.017
		22	0.014	0.00028	0.014	0.015
		12	0.012	0.00023	0.012	0.013

C1. However, it is also noted that the surface area and orthogonal dimensions do not change substantially when the moisture is removed, indicating that they may not be entirely dependent on the moisture content, as suggested by Chandrasekar and Viswanathan (1999). Both C1 and RC parchment coffees are larger than other varieties (Chandrasekar & Viswanathan, 1999; Ghosh & Gacanja, 1970; Montilla-Pérez et al., 2008) or mutations such as Caturra (Pérez-Alegría et al., 2001).

As Figure 5 shows, during drying, there was a significant shrinkage ratio of ~7% (Duque-Dussán & Banout, 2022) for the endosperm (seed) than the one for the endocarp (Burmester & Eggers, 2010; Nilnont et al., 2012; Sfredo et al., 2005). This generates an air chamber that restricts the moisture flow from the inner part to the surface, making the coffee drying process more energy-demanding than other grains (Duque-Dussán et al., 2022). However, the grain's outer orthogonal dimensions did not change significantly.

In contrast, there was a notable reduction in other properties with moisture removal. The bulk density of C1 and RC exhibited similar behavior, with RC's density slightly higher than C1's. Despite C1's higher kernel density at all moisture stages, C1 and RC had higher kernel density values than other varieties (Chandrasekar & Viswanathan, 1999; Pérez-Alegría et al., 2001).

Some authors stated that the denser the seed, the better the quality of the coffee, arguing that the roasting process can be done evenly across the volume of the beans (Burmester & Eggers, 2010; Cardoso et al., 2018; Fadai et al., 2017), hence, the greater kernel density makes the two evaluated varieties more attractive to customers. According to Table 1, the C1 bean mass was larger than its counterpart RC, which is indicative of a higher kernel density. This property showed that while RC grain is overall bigger than C1, it is also less dense and lighter; still, both RC and C1 produce heavier grains than other varieties (Figure 7).

Likewise, the thermal properties of the bean change significantly according to the moisture content. The water held in the bean's inner structure strongly influences both the C_p and the K; C1 presented higher values than RC in both variables. Despite this, C1 and RC shared similar values, which were higher than those documented for Caturra by Pérez-Alegría et al. (2001) and other varieties (Chandrasekar & Viswanathan, 1999).

These results were positive as the evaluated properties affect the quality of the coffee and several postharvest processes, mainly the drying stage. When the new varieties are packed on the drying bed, the grains will have a larger surface area and a more extensive contact zone, intensifying the heat and mass transfer. Moreover, when presenting better bulk-thermal conductivity and bulk-specific heat, the drying process could be faster for such varieties, and their preservation, storage, and quality will be easier to attain.

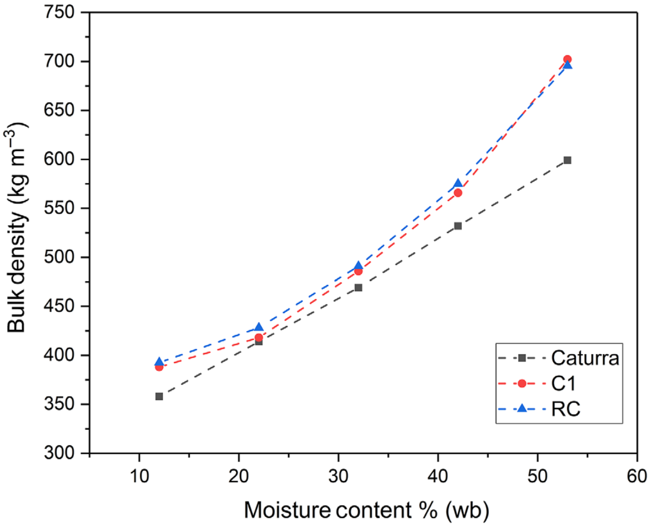

FIGURE 6 Comparative bulk densities as a function of the moisture content.

Table 2 shows an averaged result for each variable per variety without considering the moisture content, with a 95% confidence interval.

The averaged variable value per variety, disregarding the moisture, confirmed the information displayed in Table 1. RC held higher orthogonal dimensions, surface area, and bulk density, whereas C1 had higher kernel density, mass, bulk-specific heat, and bulk thermal conductivity values.

To find how the factors affected the response variables, an ANOVA table followed by a Tukey test is displayed in Table 3. The p-values and the test indicated no interaction between the moisture content and the variety for the length, but they did interact independently. The mean of the bean's width was higher in RC independently from the moisture content; there was no interaction between the

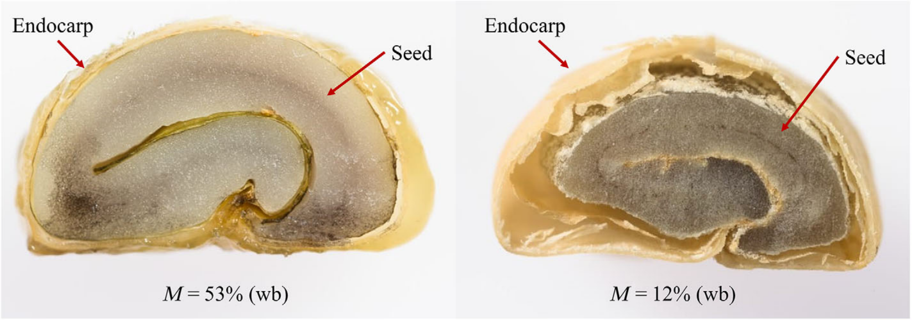

FIGURE 5 Parchment coffee cross-sections at different moisture contents *M*.

TABLE 2 Mean, standard deviation and 95% confidence interval for the evaluated variables, averaged values.

Variable	Variety	Mean	Standard deviation	Confidence interval	
				Lower bound	Upper bound
Length (mm)	C1	12.64	0.85	12.51	12.78
	RC	13.13	0.76	13.01	13.25
Width (mm)	C1	9.12	0.52	9.03	9.20
	RC	9.30	0.57	9.21	9.39
Thickness (mm)	C1	5.53	0.35	5.48	5.59
	RC	5.56	0.28	5.52	5.61
Surface area (mm^2)	C1	287.60	37.84	281.50	293.71
	RC	293.31	24.92	289.29	297.33
Bulk density (kg m^{-3})	C1	0.51	0.13	0.36	0.67
	RC	0.52	0.12	0.37	0.67
Kernel density (kg m^{-3})	C1	0.840	0.093	0.724	0.955
	RC	0.839	0.090	0.727	0.950
Mass (g)	C1	0.377	0.084	0.272	0.481
	RC	0.349	0.079	0.251	0.447
C_p (kJ kg^{-1} K^{-1})	C1	3.593	0.874	2.508	4.678
	RC	3.528	0.871	2.446	4.610
K (W m^{-1} K^{-1})	C1	0.018	0.004	0.012	0.022
	RC	0.017	0.004	0.013	0.023

variety and the moisture content, and they did not separately influence the thickness or the surface area.

A statistically different bulk density was found for each moisture level, and the higher the grain moisture, the higher the bulk density. The average C_p value was higher in C1, regardless of the moisture content. The average C_p value differed for each moisture, the highest being at the value of 53%, irrespective of the variety. There was no interaction between the variety and the moisture content on the C_p value; the same phenomenon was seen in the bulk thermal conductivity K.

Because of the importance of the bulk density, kernel density, bulk-specific heat and thermal conductivity and their dependence on the moisture content, they were further compared (Figures 6–9) with the values obtained for the same variables for the Caturra mutation published by Pérez-Alegría et al. (2001).

As seen in Figure 6, both C1 and RC have higher bulk density values; the linear regressions for C1 and RC are:

$$\rho_{b,\,C1} = 266.053 + 763.742M_{\%(wb)}\ (r^2 = 0.94997), \tag{4}$$

$$\rho_{b,\,RC} = 278.088 + 740.38M_{\%(wb)}\ (r^2 = 0.95). \tag{5}$$

As seen in Figure 6, the bulk density values for Caturra were considerably lower than RC and C1. This property could impact storage and drying matters; since the bulk density is high, its porosity will be lower (López-Córdoba & Goyanes, 2017). Hence, when drying, the air will be forced through the grain bed, performing a homogeneous moisture removal (Cenkowski et al., 1993; Liu et al., 2015).

In Figure 7, the behavior of the kernel density, as mentioned before, was highly affected by the moisture content. The three lines were closely related, yet, both C1 and RC were higher than Caturra. Their linear regression equations as a function of the moisture content were found to be:

$$\rho_{k,C1} = 577.54M_{\%(wb)} + 653.82\ (r^2 = 0.9997), \tag{6}$$

$$\rho_{k,RC} = 572.95M_{\%(wb)} + 650.56\ (r^2 = 0.9996). \tag{7}$$

C1 and RC had a higher bulk-specific heat than Caturra (Figure 8), meaning that the grains need more energy to raise their temperature. Nonetheless, it also means that they will hold the heat during a more extended period than their counterpart Caturra; this characteristic could have a positive impact on reducing drying times, allowing even moisture removal across the bean's volume (Ramirez-Martinez et al., 2010; Ramírez-Martínez et al., 2013). Relevant outcomes when sun drying, for example, where the temperature fluctuations occur rapidly in time (Briceño-Martínez et al., 2020; Elavarasan et al., 2017; Udomkun et al., 2020).

The bulk-specific heat linear regression equations for C1 and RC are shared as following:

$$C_{p,\,C1} = 5.42M_{\%(wb)} + 1.85\ (r^2 = 0.9998), \tag{8}$$

TABLE 3 ANOVA analysis (*p*-values) and Tukey test (observation).

Variable	Variation source	*p*-value	Observation
Length (mm)	*V*	<.0001	RC grain's length was in average larger independently from the moisture content
	M	.12	The moisture content did not affect the length
	V * *M*	.516	There was no interaction between the variety and the moisture content over the length
Width (mm)	*V*	.023	RC bean's width was in average larger independently from the moisture content
	M	.136	The moisture content did not affect the width
	V * *M*	.475	There was no interaction between the variety and the moisture content over the width
Thickness (mm)	*V*	.513	The variety did not influence the thickness
	M	.069	The moisture content did not influence the thickness of the grain
	V * *M*	.652	There was no interaction between the variety and the moisture content over the thickness
Surface area (mm^2)	*V*	.478	The variety did not influence the surface area
	M	.682	Moisture content did not influence surface area
	V * *M*	.247	There was no interaction between the variety and the moisture content over the surface area
Bulk density (kg m^{-3})	*V*	.346	Variety did not influence bulk density
	M	<.0001	The average bulk density was higher when the moisture content of the grain is 53% and decreases as the humidity decreases
	V * *M*	.808	There was no interaction between variety and moisture content over bulk density
Kernel density (kg m^{-3})	*V*	.804	The variety did not influence the kernel density
	M	<.0001	The average kernel density of the grain was different for each moisture, decreasing when the moisture content decreases
	V * *M*	.445	There was no interaction between variety and moisture content over kernel density
Mass (g)	*V*	.026	Regardless of the moisture content, C1 had a higher average mass than the RC
	M	<.0001	The average mass of the grain was different for each moisture, decreasing when the moisture content decreases
	V * *M*	.590	There was no interaction between the variety and the moisture content on the mass
C_p (kJ kg^{-1} K^{-1})	*V*	<.0001	The average C_p value was higher in C1, regardless the moisture content
	M	<.0001	The average C_p value was different for each moisture content, the highest being at 53% (wb), regardless of variety
	V * *M*	.462	There was no interaction between the variety and the moisture content on the C_p value
K (W m^{-1} K^{-1})	*V*	<.0001	The average *k* value was higher in C1, regardless the moisture content
	M	<.0001	The average *K* value was different for each moisture content, the highest being at 53% (wb), regardless of variety
	V * *M*	.370	There was no interaction between the variety and the moisture content on the value of *K*

Abbreviations: *M*, moisture content; *V*, variety.

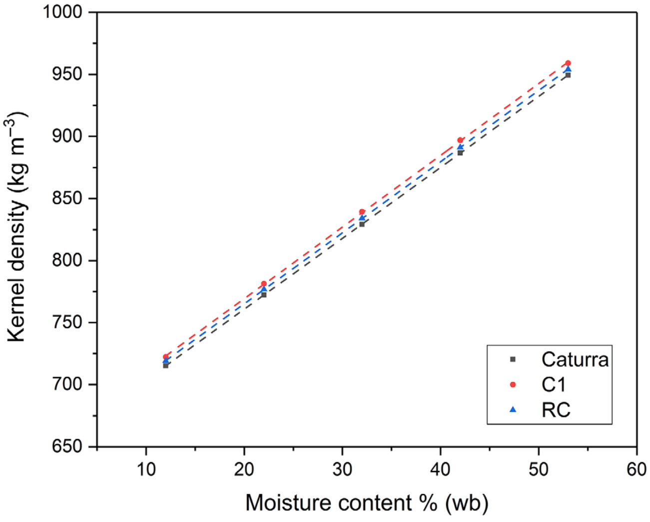

FIGURE 7 Comparative kernel densities as a function of the moisture content.

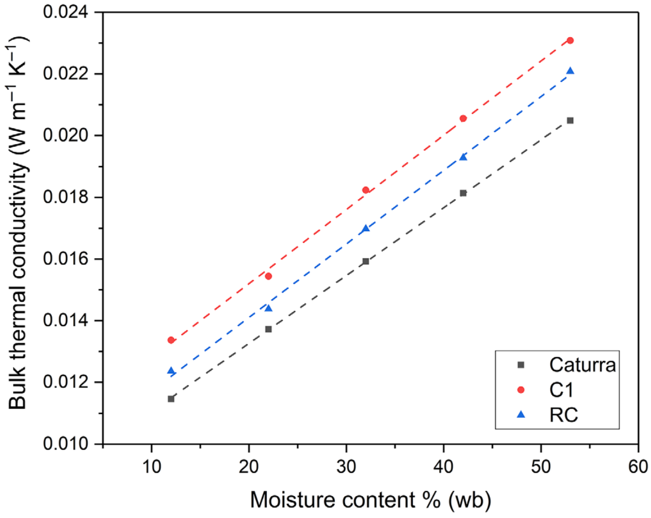

FIGURE 9 Comparative bulk thermal conductivities as a function of the moisture content.

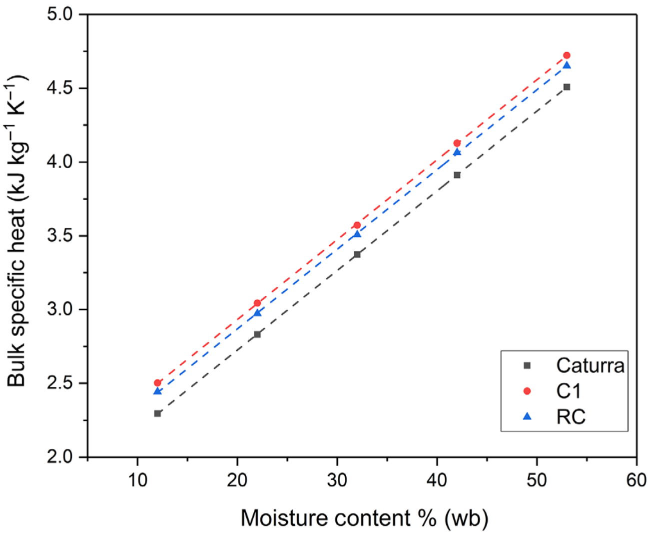

FIGURE 8 Comparative bulk-specific heats as a function of the moisture content.

$$C_{p,RC} = 5.40M_{\%(wb)} + 1.78\ (r^2 = 0.9997). \quad (9)$$

Even though the bulk thermal conductivity values were low when compared to different agricultural products (Doymaz & Pala, 2003; Siriprom et al., 2014; Sreenarayanan & Chattopadhyay, 1986), both evaluated varieties presented higher bulk thermal conductivity values than the Caturra mutation and other varieties (Chandrasekar & Viswanathan, 1999; Ghosh & Gacanja, 1970; Pérez-Alegría et al., 2001), implying that they are able to transfer heat faster than other ones (Figure 9). Suppose this property is combined with the fact that they also displayed higher C_p values, then, for such varieties, the heat will travel faster across the grain bed thanks to the bulk thermal conductivity and will also remain for a more extended time due to the C_p. Processes such as drying and fermentation using the wet method (Elhalis et al., 2021; Pereira et al., 2020) could be improved.

The bulk thermal conductivity linear regression equations for C1 and RC are presented as:

$$K_{C1} = 0.0241M_{\%(wb)} + 0.0104\ (r^2 = 0.9984), \quad (10)$$

$$K_{RC} = 0.0239M_{\%(wb)} + 0.0093\ (r^2 = 0.9986). \quad (11)$$

As seen in Figure 9, the bulk thermal conductivity values decreased as the moisture content decreased; nonetheless, a significant difference was noted between the evaluated varieties once the grain reached the desired moisture content.

4 | CONCLUSIONS

The new parchment coffee beans of the new varieties developed by Cenicafé have different thermal and physical properties than the traditional varieties, so those processes that depend on them can be improved and optimized. The results of this study will help to understand the heat and mass transfer singularities during the drying process of the two studied varieties. They can also be used to design coffee dryers and update the drying simulation models to predict the coffee drying curves accurately. Furthermore, they allow for estimating the roast quality values and controlling possible storage damage.

There is no relationship between the moisture content of the parchment coffee and its geometric properties: length, width, thickness, and surface area. While the other physical properties studied: mass, bulk density, and kernel density, are dependent on moisture content, meaning that reducing moisture content will decrease their value and vice versa. Additionally, the study revealed that the bean's moisture content has a direct proportionality to the thermal properties such as bulk-specific heat and bulk thermal conductivity, both decreasing as moisture decreases and increasing as moisture rises.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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