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Hygroscopic equilibrium and physical properties evaluation affected by parchment presence of coffee grain

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Abstract

Physical properties are essential for the development of silos, transport calculations, separation and classification of grain and seeds. The present work evaluates the influence of the parchment on the drying and physical properties of coffee grains. The true density (ρ_t), bulk density (ρ_b) and porosity (ε) were evaluated for coffee grains (cv. Catuaí Amarelo) with and without parchment. Four mathematical models (Chung-Pfost, GAB, Modified Henderson and Oswin) were fitted to the experimental data to acquire desorption isotherms. The drying treatment was conducted in a factorial scheme with four levels of temperature (20, 35, 45 and 55°C) and five levels of relative humidity of the drying air (30, 40, 50, 60 and 80%) in a completely randomized design. The respective equilibrium moisture contents of the coffee grains were measured for each drying condition. No differences were observed among the products on the desorption isotherms. The pulped coffee with parchment (PP) had higher ε values than the pulped coffee without parchment (PR). The true density was higher for the PP coffee, but as the moisture content (X) increased, the true densities became more similar for the two samples. The ρ_b was higher for the PP coffee than for the PR coffee. Higher initial and final values of ρ_b were found for the PR and PP coffee, respectively. The Guggenheim-Anderson-de Bôer model was the model that best represented the experimental data for the drying process.

Additional key words: density, drying, porosity, sorption isotherms.

Resumen

Evaluación del equilibrio higroscópico y de las propiedades físicas afectadas por la presencia de pergamino en los granos de café

Las propiedades físicas son esenciales para el desarrollo de los silos y cálculos de transporte, separación y clasificación de granos y semillas. El presente trabajo evaluó la influencia del pergamino en el secado y en las propiedades físicas de los granos de café. Se evaluaron la densidad real (ρ_t), la densidad aparente (ρ_b) y la porosidad (ε) para los granos de café (cv. Catuaí Amarelo) con y sin pergamino. Se ajustaron cuatro modelos matemáticos (Chung-Pfost, GAB, Henderson Modificado y Oswin) a los datos experimentales para obtener isotermas de desorción. El tratamiento de secado se realizó en un esquema factorial con cuatro niveles de temperatura (20, 35, 45 y 55°C) y cinco niveles de humedad relativa del aire de secado (30, 40, 50, 60 y 80%) en un diseño completamente al azar. Se midió el contenido de humedad de equilibrio de los granos de café para cada condición de secado. No se observaron diferencias entre los productos en las isotermas de desorción. El café despulpado con pergamino (PP) presentó mayores valores de ε que el café despulpado sin pergamino (PR). La densidad real fue mayor para el café PP, pero según se incrementó el contenido de humedad (X), la densidad real se hizo más similar para ambas muestras. El ρ_b fue mayor para el café PP que para el café PR. Los valores más altos iniciales y finales de ρ_b se observaron en el café PR y PP, respectivamente. El modelo Guggenheim-Anderson-de Boer fue el que mejor representó los datos experimentales para el proceso de secado.

Palabras clave adicionales: densidad, isotermas de adsorción, porosidad, secado.

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Abbreviations used: a_w (water activity, decimal), a, b, c (parameters of the models), *DF* (degrees of freedom of the model), EMC (equilibrium moisture content, % d.b.), *n* (number of observed data), *P* (mean relative percent deviation, %), RH (relative humidity, decimal), R^2 (determination coefficient, %), *SE* (standard error, decimal), T (temperature, ºC), *X* (moisture content, % d.b.), *Y* (observed value), $\hat{Y}$ (estimated value through the model), ρ_b (bulk density, kg m^{-3}), ρ_t (true density, kg m^{-3}), ε (porosity, %).

Introduction

Coffee, one of the most important commodities in the world, provides direct and indirect employment from its production and final sale to the consumer. Any loss during its production and commercialization leads to price variations and social cost (unemployment). These losses are mainly due to the high initial moisture content of coffee.

Production of coffee can be accomplished by dry or wet processing, and these approaches result in different products and qualities. During dry processing, coffee is dried in its integral form, resulting in cherry coffee or natural coffee. On the other hand, wet processing can produce any of the following: pulped natural coffee, in which the exocarp and pulp are removed; parchment coffee, which is semi-washed with the exocarp and mesocarp removed; and pulped coffee, which is fully washed with the mucilage removed by controlled fermentation after the exocarp is removed (Borém *et al.,* 2002). Besides fermentation, pulped coffee can also be obtained through removal of the exocarp and mucilage mechanically.

According to Resende *et al*. (2007), water is the main component of most agricultural products and has an enormous influence on their physical properties. The external structures that constitute coffee (the exocarp and endocarp) are physical obstacles to water loss. Different chemical compositions of the water directly affect the drying rate and the physical properties, which affect the final quality of the product. The endocarp (or parchment) has a different shrinkage rate than the grain itself, leading to possible differences in the final moisture content of the coffee and alteration of its physical properties. All of these factors affect the handling and drying procedures. The different qualities of the coffee can be analyzed by the coffee beverage test.

Several factors contribute to the final quality of the coffee. These factors include the methods used for the cultivation, harvest, drying and storage. The density and ε of the grain mass are important parameters for storage. These factors are also significant for the commercialization of the products and are required to develop silos driers, warehouses, transport systems and processing machinery. Like several other agricultural products, coffee requires practical procedures to allow conservation for long periods of time. Cleaning operations, drying and aeration processes are especially important.

Agricultural products are often dried to control and maintain their quality. The goal of drying is to diminish the water activity (a_w), the property of the product that promotes physical-chemical processes. Drying diminishes the respiration rate of the product and increases the storage time with the minimum possible loss. Water activity drives several processes that occur after the harvest such as plague incidence, fungi attacks and product fermentation. Because coffee is an agricultural product that is harvested with a high moisture content (X) (100-233% dry basis), the coffee beans must be quickly dried to decrease possible losses. During processing and storage, the coffee goes through several stages in which the temperature (T) and relative humidity (RH) are altered. These changes directly affect the equilibrium moisture content (EMC) (and consequently the physical properties) of the coffee.

The physical properties and behavior of agricultural products are important factors that affect post-harvest technology. The accurate determination of these parameters is essential for the development of silos, transport calculations, separation and classification of grain and seeds and other processes intended to improve the productive system of crops or that affect production costs and the final quality of the product. A correct understanding of the existing relationships among the physical properties and the deterioration factors of agricultural products can provide solutions to the problems related to heat and mass transfer during the drying and aeration stages and the safe storage of the product.

Understanding the physical properties (*e.g.,* density) is often important (*e.g.,* certain factors may change the density of the grain). The most important factors are X, the shape and the surface area of grain. Porosity (ε) has a strong influence on the air flow that crosses the grain mass, and knowledge of the porosity is important for the development of fans, engine power and the drying and aeration systems.

The behavior of the physical properties of coffee is significantly different from that of most agricultural products due to the grain structure (endocarp or parchment). These differences are present even before drying. Due to the presence of the endocarp, an air layer forms between the grain and the endocarp. This characteristic, which has also been observed in castor beans, may lead to differences in the drying process and its consequences (heat and mass transfer, drying rate, shrinkage, diffusivity, etc.). Also, the parchment can modify the behavior of the physical properties in relation to moisture content. Couto *et al*. (1999) reported that the coffee density increases with increasing moisture content. The opposite behavior is observed in most agricultural products.

By evaluating the drying process of agricultural products, sorption isotherms can be obtained. Moisture sorption isotherms for bulk solids describe the equilibrium relationship between the *X* and the RH of the surrounding environment, which is equal to a_w at the equilibrium state. Moisture sorption isotherms are a useful tool for understanding the moisture relationship of a material and its stability problems. The sorption isotherm of granular bulk solids of biological origin provides information about moisture changes during storage. This information is useful for successful transportation over long distances. According to Ayranci and Duman (2005), the sorption isotherms are an important element of the theory of drying and provide information regarding the design of drying equipment and in the study of the storage of dehydrated food.

Mathematical models used to construct the sorption isotherms are capable of predicting the EMC of the grain. However, no model is capable of predicting the EMC over all T and RH ranges. Consequently, these models must be studied for each product and air condition to determine which model is best for predicting the EMC of the product in certain air conditions.

Recent research has studied parchment alteration during drying (Borém *et al.*, 2008), heat and mass transfer during drying (Hernández-Díaz *et al.*, 2008), the thermal properties (Chandrasekar and Viswanathan, 1999; Pérez-Alegría and Ciro-Velásquez, 2001) and the physical properties of coffee grains (Chandrasekar and Viswanathan, 1999). No previous research has investigated the effects of the parchment on the drying process and the physical properties of coffee grains. The goal of the present work was to evaluate the effect of the parchment on the drying process and the physical properties of the coffee grain. These properties were correlated with the composition of the parchment of the coffee grains, providing information for future analyses of the thermodynamic properties, thermal properties and heat and mass transfer.

Material and methods

The present work was conducted in the Laboratory of Physical Properties and Quality Evaluation of Agricultural Products at the National Grain Storage Training Center-CENTREINAR, Federal University of Viçosa, Viçosa, MG, Brazil.

The coffee grain used (*Coffea arabica* L. cv. Catuai Amarelo) was from Viçosa, MG, Brazil. The grains were manually harvested, and the immature, deteriorated or damaged fruits were eliminated to obtain a homogeneous and high-quality sample.

After harvesting, a portion of these fruits were manually pulped with the parchment intact, and the endocarp was removed from the other batch. These treatments were named PP (pulped coffee with parchment) and PR (parchment removed from the pulped coffee). The samples were weighed using an analytical balance with 0.01 g of precision. The percentage of the grain coffee mass represented by the parchment was obtaining by mass difference.

The initial *X* of both batches was 150% dry basis (d.b.). The coffee grain *X* was determined by drying in an oven at 105 ± 1°C for a 24 h period in triplicate according to the seeds analysis standard of Brazil (Brazil, 1992).

Thin-layer drying treatment was applied in a factorial scheme of 4 × 5 with four T levels (20, 35, 45 and 55°C) and five air RH levels (30, 40, 50, 60 and 80%) until the product reached equilibrium humidity at the specified air conditions.

Hygroscopic equilibrium

The desorption method used was the dynamic technique or gravimetric method, in which the material is brought into equilibrium with air at fixed T and RH, and the EMC of the material is measured.

The environmental conditions for the performance of the tests consisted of a T-controlled chamber manufactured by Aminco (model Aminco-Aire 150/300 CFM). Removable perforated trays containing 50 g of the product were placed inside the equipment to allow air to pass through the samples. Air flow was monitored with an anemometer with rotating blades and maintained around 10 $m^{-3}\ min^{-1}\ m^{-2}$. The T and air RH were monitored with a psychrometer installed next to the trays containing the samples.

The trays containing the product were periodically weighed during drying. Hygroscopic equilibrium was reached when the mass variation of the containers remained constant for three consecutive readings.

The relationship between the EMC data and the RH and T for coffee was evaluated using the following models: Chung-Pfost (Pfost *et al.*, 1976), modified Henderson (Thompson, 1972), Oswin (Oswin, 1946)

Table 1. Mathematical models utilized to predict the hygroscopicity phenomenon of coffee (*Coffea arabica* L.) cultivar 'Catuaí Amarelo'

Model designation	Model	
Chung-Pfost	$EMC = a - b \cdot \ln\left[-\left(T + c\right) \cdot \ln\left(RH\right)\right]$	[1]
Guggenheim-Anderson-de Boer (GAB)	$EMC = a \cdot b \cdot c \cdot RH \Big/ \left[\left(1 - b \cdot RH\right) \cdot \left(1 - b \cdot RH + b \cdot c \cdot RH\right)\right]$	[2]
Modified Henderson	$EMC = \left\{\ln\left(1 - RH\right) \Big/ \left[-a \cdot \left(T + b\right)\right]\right\}^{1/c}$	[3]
Oswin	$EMC = \left(a + b \cdot T\right) \Big/ \left[\left(1 - RH\right) / RH\right]^{1/c}$	[4]

EMC: equilibrium moosture content, %d.b. a,b,c: parameters of the models. T: temperature, °C. RH: relative humidity, decimal.

and Guggenheim-Anderson-de Boer – GAB (Anderson, 1946). These models are presented in Table 1.

The experimental data were interpreted with the Quasi-Newton method of non-linear regression analysis using the program STATISTICA 8.0®. The models were selected based on the mean relative percent deviation (P), the standard error (SE) and the determination coefficient (R^2):

$$SE = \sqrt{\frac{\sum_{i=1}^{n}\left(Y - \hat{Y}\right)^2}{DF}} \qquad [5]$$

$$P = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{\left|Y - \hat{Y}\right|}{Y}\right) \qquad [6]$$

where DF is the degrees of freedom of the model; P is the mean relative percent deviation in%, n is number of observed data; SE is the standard error in decimal; Y is observed value; and $\hat{Y}$ is the value estimated by the model.

According to Mohapatra and Rao (2005), P values below 10% indicate a good fit of the model to the data for practical purposes.

True and bulk density

The true density (ρ_t) is the relationship between the mass and the volume of a single grain. The true density can be determined through the liquid dislocation method (Moreira *et al.*, 1985). To utilize this method, a liquid that has minimum penetration at the grain pores must be used. In a comparative study of the volume completion efficiency of various liquids for the determination of the ρ_t of an agricultural grain, Moreira *et al.* (1985) concluded that soybean oil, which is easy to obtain and economically accessible, can be used as a substitute for toluene. Coffee grains from both batches were immersed in soybean oil, and the grain volume (V) was obtained from the volume of displaced oil. The grain density was determined by dividing the grain mass by the measured grain volume five times.

The bulk density (ρ_b; also known as the hectoliter weight) is the relationship between the mass of grain, including the empty spaces, and its respective volume. The ρ_b was determined using a hectoliter balance with a one liter capacity five times.

Porosity

The symbol ε refers to the existing relationship between the volume of empty spaces in the granular mass of the products and the total volume occupied by this granular mass. This property of the grain can be obtained by correlating the bulk and true densities. The formula method of Mohsenin (1986) was used to calculate the grain ε:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \cdot 100 \qquad [7]$$

where ρ_b is the bulk density in kg m^{-3}; ρ_t is the true density in kg m^{-3}; and ε is the porosity in%.

Results

Based on statistical parameters, the GAB model was the only model that represented the hygroscopic phenomenon satisfactorily. Table 2 shows the parameters of the

Table 2. Fitted parameters of the Guggenheim-Anderson-de Boer (GAB) model to the observed data of pulped coffee with parchment (PP) and pulped coffee grain without parchment (PR) for cultivar 'Catuaí Amarelo' and their respective determination coefficients (R^2), mean relative percent deviations (*P*) and standard error (*SE*) values, for each temperature studied

Coffee	Temperature (°C)	Parameters[1] a	b	c	R^2 (%)	*P*	*SE*
PP	20	7.9487	0.6787	12.2661	95.86	4.14	1.40
	35	13.4313	0.4733	3.0941	97.04	4.70	1.45
	45	4.7789	0.8016	11.4115	98.56	3.95	0.93
	55	197.4336	0.2436	0.2036	96.37	7.38	1.58
PR	20	83.3489	0.0105	27.5201	96.86	2.94	1.17
	35	9.1407	0.5970	4.8817	95.65	5.74	1.71
	45	11.4954	0.4764	3.5902	97.26	4.67	1.28
	55	285.2771	0.1927	0.1960	96.91	8.60	1.44

[1] a,b,c: parameters of the model.

GAB model fitted to the observed data and the R^2, *P* and *SE* values for PP (pulped coffee with parchment) and PR (parchment removed from pulped coffee) coffee grains.

The desorption isotherms constructed using the equations of the GAB model fitted to temperatures of 20, 35, 45 and 55°C are shown at Figure 1.

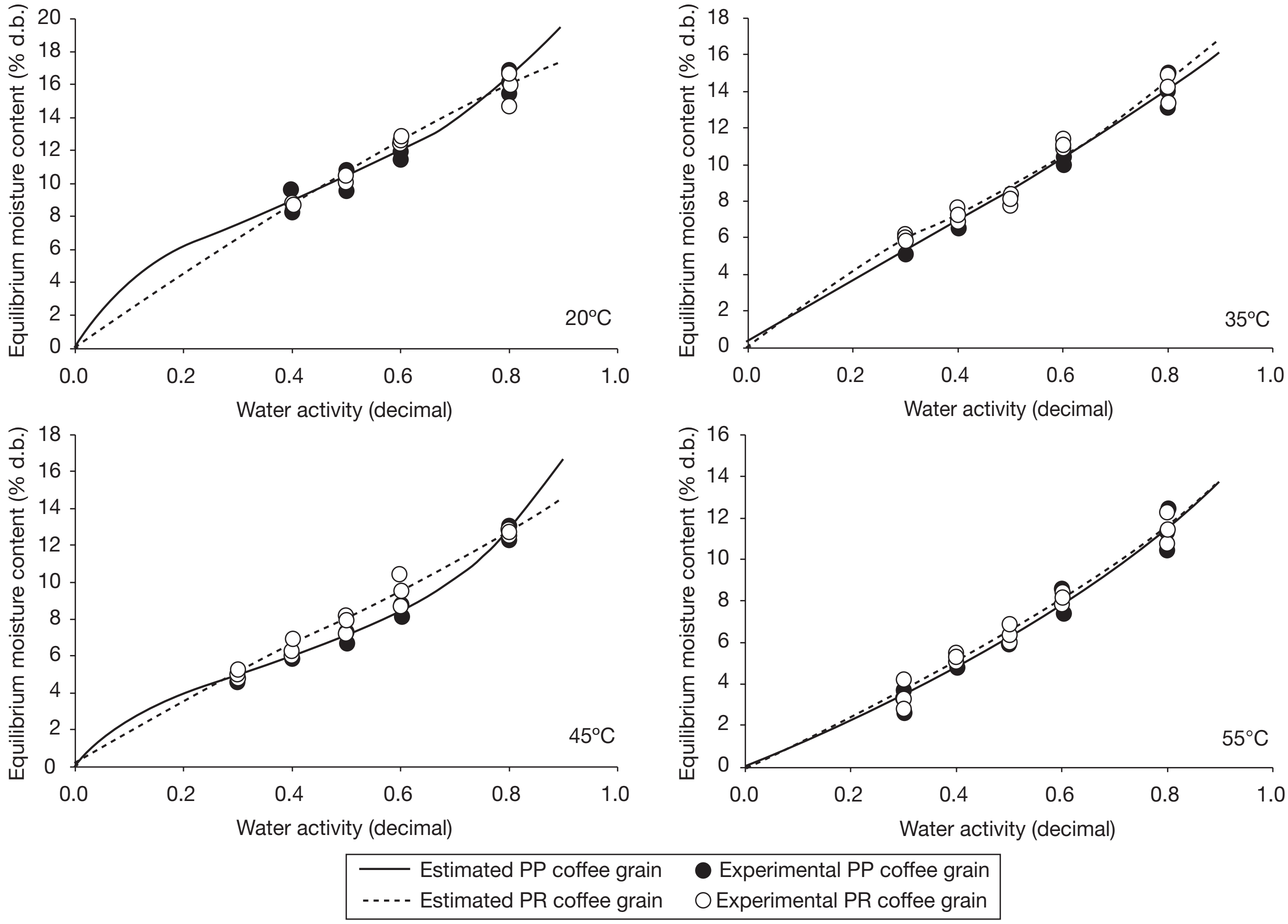

Figure 1. Desorption isotherms of the coffee grains with (PP) and without (PR) parchment estimated by the GAB model for several temperatures.

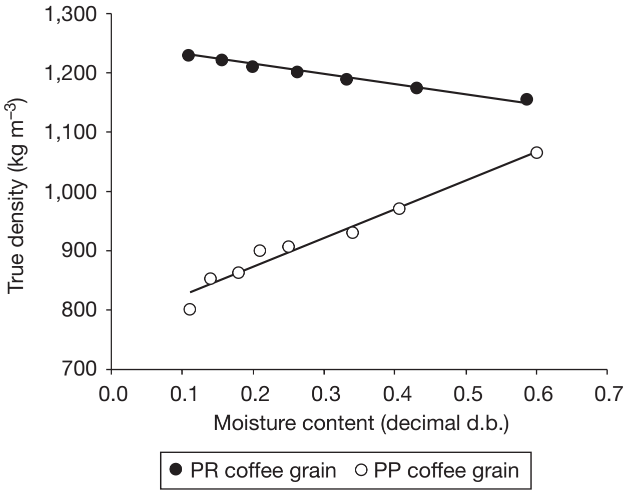

Figure 2. True density of the coffee grains with (PP) and without (PR) parchment as a function of the moisture content.

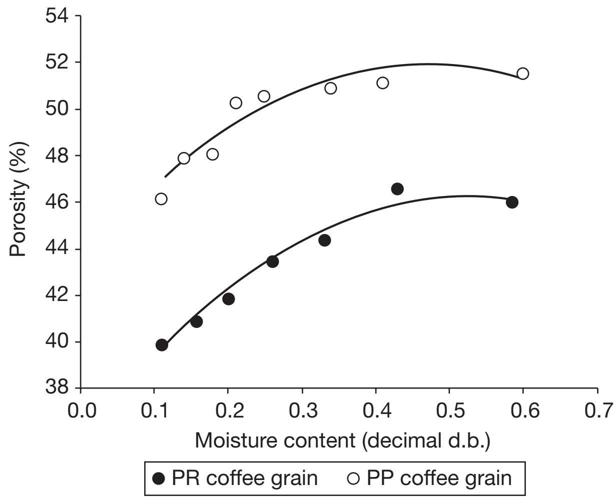

Figure 4. Porosity of the pulped coffee grains with (PP) and without (PR) parchment as a function of the moisture content.

Figure 2 presents the ρ_t variations with X for the PP and PR coffee. The ρ_t ranged from 1,234.67 to 1,154.13 kg m^{-3} and from 802.78 to 1,064.99 kg m^{-3} for the PR and PP coffee, respectively. The ρ_t of the PR coffee tended to decrease as X increased.

Figure 3 represents the ρ_b of the PP and PR grain coffee for different X. The ρ_b ranged from 533.56 to 393.26 kg m^{-3} and from 448.62 to 518.58 kg m^{-3} for the PR and PP coffee, respectively.

Figure 4 shows the ε obtained from Equation [7] for the PP and PR coffee grains as a function of X.

Table 3 provides the fitted regression equations and their respective determination coefficients for the observed ρ_t, ρ_b and ε as a function of the X of the coffee grain, T and RH.

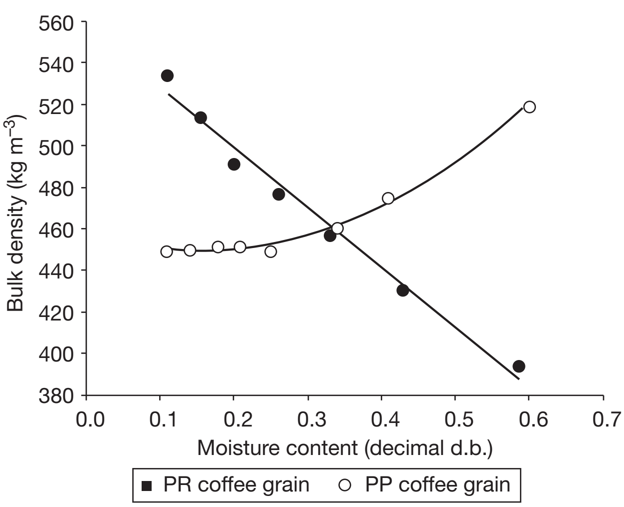

Figure 3. Bulk density of the coffee grains with (PP) and without (PR) parchment as a function of the moisture content.

Discussion

Four mathematical models were used to describe the hygroscopicity of the PR and PP coffee grains. According to the statistical parameters used, the GAB model best fit the experimental data.

The EMC values of the PP and PR coffee were similar at all T (Fig. 1). However, the lowest variation among the products was at 55°C, indicating that a rupture of the parchment probably occurred during the drying process at this T. This rupture led to a similar behavior of the products. This trend was also observed by Borém *et al.* (2008), who reported that above 50°C of drying T, cellular disorganization of the parchment occurs.

The resemblance of the results of both products is due to the parchment, which experienced an important mass and volume loss. Because of its composition, the parchment is a non-hygroscopic product and consequently does not affect the EMC. The parchment only affects the time at which the equilibrium will occur.

According to Chen (2000), adsorption or desorption of moisture is a complex phenomenon and depends on the carbohydrate, sugar, protein, fiber and mineral contents of the product. However, no difference in the behavior of the desorption isotherms of the PP and PR coffee was observed, indicating that the constituents of the parchment did not interfere during the drying process or affect the final X.

Table 3. Regression equations and their respective determination coefficients (R^2) for the true density (ρ_t), the bulk density (ρ_b) and the porosity (ε) of pulped coffee grain with (PP) and without (PR) parchment as a function of the moisture content (X) during the desorption process for cultivar 'Catuaí Amarelo' (*Coffea arabica* L.)

Coffee	Physical property	Equation	R^2 (%)
PP	True density	$\rho_i = 484.03X + 776.1$	96.81
	Bulk density	$\rho_b = 346.56X^2 - 103.96X + 456.63$	99.47
	Porosity	$\varepsilon = 39.93X^2 + 37.03X = 43.21$	89.48
PR	True density	$\rho_i = -169.34X + 1{,}248.6$	98.37
	Bulk density	$\rho_b = -288{,}55X + 556.33$	98.50
	Porosity	$\varepsilon = 37.83X^2 + 40.43X + 35.52$	97.86

Parchment consists of 24.40% lignin, 66.65% carbohydrates and 8.95% fiber (Braham and Bressani, 1979). Lignin provides firmness, impermeability and resistance to microbiological and mechanical attacks to vegetal tissues. Heat and mass transfers between the environment and the grain are difficult because of lignin. The parchment is a rigid material, and during the drying process, the PP coffee maintains its original volume. However, the mass of the grain decreases due to dehydration.

Removing the parchment of the coffee grain reduces the grain mass by approximately 20% and the grain volume by approximately 40%. This decrease may explain the observed phenomenon demonstrated at Figure 2 because the ρ_t of the PR coffee was higher than that of the PP coffee.

The trend of the PR coffee shown in Figure 2 can be explained by the parchment removal because the grain itself is a hygroscopic material that swells with an increase in the water availability. During this swelling, the mass does not increase proportionally because of the low values of ρ_t. Unlike PR coffee, PP coffee tends to decrease with a decrease in X. Because parchment is not a hygroscopic product due to its constitution, the volume does not alter significantly during drying, although the grain mass decreases. With an increase in the X of the product, the ρ_t tends to be equal for both products.

Different behaviors of the products were observed in Figure 2. The PR coffee has a lower slope (less values variation) than PP coffee. The PP coffee had a higher variation in the magnitude of ρ_t during the drying process because that grain, which has no parchment, is more susceptible to shrinkage during the drying process, and the relationship between the mass and the volume is approximately constant for different values of X. The ρ_t can be used to design separation or cleaning processes based on the density differences between the product and the water.

Bulk density of agricultural products generally increases with a decrease in the X of the product. This rise depends on the percentage of grain that is damaged, the initial X, the T reached during drying, the final X and the grain cultivar (Brooker *et al.*, 1992). This phenomenon was observed for the PR coffee but not for the PP coffee, indicating that the parchment affects the behavior of the ρ_b. This behavior was also observed by Ribeiro *et al.* (2001), who studied several coffee varieties and concluded that, for PP coffee of the cultivar «Catuai», the ρ_b increases with an increase in the X of the product. Chandrasekar and Viswanathan (1999) report that this increase of ρ_b when X increases is due to the no expansion characteristic of the parchment, which allows only mass increases with an increase in X.

At elevated X values, the mass of the PP grain coffee is higher than that of the PR coffee. The absence of the parchment provides the PR coffee with a lower mass and volume, resulting in a much lower value of ρ_b. During the process of achieving hygroscopic equilibrium, X decreases due to the new T and RH conditions. This process accentuates the PR coffee shrinkage. The PP coffee experiences a lower volume alteration during the drying process because of the presence of the parchment. This variation is explained by the water loss of the product.

Below an X of 0.3 d.b for the PP coffee, the ρ_b remains close to constant. This result can be explained by the presence of the parchment, which provides a physical obstacle to water loss and does not shrink. The ρ_b can be used as an indicator of the quality during of stored agricultural products. A decrease in the ρ_b indicates a reduction in the overall quality of the grain (Mpotokwane *et al.*, 2008).

PP coffee has higher porosity than PR coffee because of the elevated percentage of volume provided by the parchment. The arrangement of the PP grains leads to a large number of empty spaces. The porosity of both products tends to increase when the moisture content increases and reaches a maximum value of around 0.5 d.b. of moisture content. This phenomenon was also observed by Couto *et al.* (1999). This result is caused by the higher volume of the product at elevated moisture contents. The amount of empty volume is smaller when the moisture content is elevated. With a decrease in the moisture content, the product experiences a reduction of its volume (shrinkage). Consequently, the arrangement of the grains changes, decreasing the amount of empty volume and forming a more compact mass with lower porosity. The porosity is important in air flow and heat flow studies (Mohsenin, 1986); for calculating the rate of aeration and cooling; for drying and heating; and for the design of heat exchangers and similar equipment (Asoegwu *et al.*, 2006; Corrêa *et al.*, 2007).

All physical properties investigated (bulk density, true density and porosity) were influenced by the presence of the parchment. The true density values of pulped coffee without parchment (PR) were higher than those of pulped coffee with parchment (PP). The bulk density decreased when the moisture content decreased for the PP coffee grain, and the opposite effect was observed for the PR coffee. The porosity increased when the moisture content increased for both products and reached a maximum value when X was 0.5 d.b..

The equilibrium moisture content (EMC) increased with decreasing temperature. The magnitude of the EMC at each a_w value did not differ between the PP and PR coffees. Thus, the drying process is mainly controlled by the air drying conditions. Even though the parchment is a physical barrier to moisture loss, it does not affect the final moisture content of the coffee. The drying rate and the physical properties are influenced by the presence of the parchment on the coffee grain.

Based on statistical parameters, the GAB model was the model that best represented the hygroscopic phenomenon of the PP and PR coffees.

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