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Scientific Article

Effect of drying air temperature on the physical properties of macauba kernels (*Acrocomia aculeata*)

Efeito da temperatura do ar de secagem nas propriedades físicas de amêndoas de macaúba (*Acrocomia aculeata*)

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ABSTRACT - The aim of this study was to evaluate the influence of moisture and drying temperature on the physical properties of macauba kernels. The experiment was set up in a split-plot design, with drying temperature (60 °C, 70 °C, 80 °C, and 90 °C) assigned to the plots and moisture (4.3%, 5.3%, 6.0%, 7.0%, and 8.9% b.u.) assigned to the subplots, in completely randomized design (CRD) with nine replications for the variables (C_i, E, D_g, A_p, S, ρ_u, ε, and Ψ) and four replications for the variable ρ_a. During the drying process, the geometric diameter, sphericity, roundness, projected and surface area, apparent specific mass, and total porosity were evaluated. These variables were analyzed according to drying temperature and moisture. Reducing the misture of macauba kernels led to an increase in geometric diameter and projected and surface area and to a reduction in roundness. Increasing the drying temperature led to a reduction in geometric diameter, sphericity, roundness, and projected area and surface area. The linear model fitted well the geometric diameter, roundness, and projected area and surface area of the macauba kernels for all drying temperatures and moistures. The quadratic model fitted well the phenomena of sphericity, total porosity, and apparent specific mass and unit-specific mass. It was concluded that the physical characteristics of macauba kernels are affected by varying drying temperatures and moistures. These data can be used to size the equipment for the main post-harvest operations.

Keywords: *Acrocomia aculeata*. Dehydration. Moisture. Post-harvest.

RESUMO - Objetivou-se avaliar a influência do teor de água e temperatura de secagem nas propriedades físicas de amêndoas de macaúba. O experimento foi instalado em esquema de parcela subdividida, tendo nas parcelas as temperaturas de secagem (60 °C, 70 °C, 80 °C e 90 °C) e nas subparcelas os teores de água (4,3%; 5,3%; 6,0%; 7,0% e 8,9% b.u.), no delineamento inteiramente casualizado (DIC), com nove repetições para as variáveis (Ci, E, Dg, Ap, S, ρu, ε e Ψ) e quatro repetições para a variável ρa. Durante o processo de secagem foram avaliados o diâmetro geométrico, esfericidade, circularidade, área projetada e superficial, a massa específica aparente e a porosidade total. Estas variáveis foram analisadas em função da temperatura de secagem e do teor de água. A redução do teor de água das amêndoas de macaúba proporcionou aumento no diâmetro geométrico, na área projetada e superficial e redução na circularidade. O aumento na temperatura de secagem promoveu redução no diâmetro geométrico, esfericidade, circularidade, área projetada e superficial. O modelo linear representou satisfatoriamente o fenômeno de diâmetro geométrico, circularidade, área projetada e superficial das amêndoas de macaúba, para todas as temperaturas de secagem e teores de água. Já o modelo quadrático representou satisfatoriamente o fenômeno de esfericidade, porosidade total e massa específica aparente e unitária. Conclui-se que diferentes temperaturas de secagem e teores água afetam as características físicas das amêndoas de macaúba. Os dados, poderão subsidiar o dimensionamento de equipamentos para as principais operações de pós-colheita.

Palavra-chave: *Acrocomia aculeata.* Desidratação. Teor de água. Pós-colheita.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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INTRODUCTION

Oil crops are an important source of raw material for obtaining oils that are used in various industrial sectors, such as food production, cosmetics, pharmaceuticals, biofuels, and lubricants (EVARISTO et al. 2016a; CARVALHO et al., 2022). The increase in the demand for vegetable oils, combined with sustainable supply in the current context of climate change, is a major challenge (TILAHUN, GROSSI; FAVARO, 2020). The introduction of new oilseed species can mitigate these problems (SILVA et al., 2022).

Brazil has a large diversity of plant species from which oils can be extracted, and the production of oils from oil palm trees has emerged as an alternative to oils from seeds and grains. Potential palm trees include the macauba tree [*Acrocomia aculeata* (Jacq.) Lodd. ex Mart] (AGUIEIRAS et al., 2014; SIMIQUELI et al., 2018; TILAHUN; GROSSI; FAVARO, 2020). This palm is widely distributed from southern Mexico to southern Brazil (RESENDE et al., 2020). It is widely present in Brazilian ecosystems, including the Cerrado and the Atlantic and Amazon Forests. The macauba fruit is drupe-shaped, spherical, and brown. It has a fibrous shell (epicarp), an oleaginous pulp (mesocarp), a nut (endocarp), and an oil-rich kernel (SILVA et al., 2020; SILVA et al., 2017). It is an emerging source for the production of high-quality oils from its pulp and kernel (SILVA et al., 2021). The oils in the kernel and pulp have great industrial value, both for the food and energy sectors (RESENDE et al., 2020).

In Brazil, macauba is usually harvested between September and January. This could be an obstacle for the industry, as processing would be limited to a short period of the year, thus resulting in industrial inactivity over a long period of the year (SILVA et al., 2019). In view of the above, the storage conditions of this product are crucial. Temperature and humidity are the most important factors in determining post-harvest life (EVARISTO et al., 2016b).

The main preservation method used worldwide for agricultural products is drying (KUMAR; KARIM; JOARDDER, 2014; SAMADI et al., 2014). Reducing the amount of water in the material reduces the biological activity and physicochemical changes that occur in the post-harvest period (CARVALHO et al., 2022). Knowledge of the physical properties of agricultural products is of fundamental importance for the development and optimization of equipment for post-harvest (MARTINS et al., 2017a). According to Ramashia et al. (2018), the knowledge of the physical properties of agricultural products are essential for reducing costs and preserving them during post-harvest.

Although the drying process of macauba fruit is well known (SILVA et al., 2017; SILVA et al., 2020), there is no information in the literature about the effects of different drying temperatures on the physical properties of macauba kernels. Therefore, the objective was to evaluate the effects of mositure and drying temperature on the physical properties of macauba kernels.

MATERIAL AND METHODS

Fruit harvest and study site

The macauba fruits were collected from plants grown in a natural population in the municipality of Acaiáca (20° 45'36"S, 44°15'W), Minas Gerais, Brazil. The region's climate is humid subtropical (Cwa) with cold, dry winters and hot, rainy summers. These plants were identified, georeferenced, and monitored. The fruits were harvested when they were physiologically ripe (beginning of yellowing of the mesocarp and natural abscission).

The fruits were stored in the laboratory for 20 days at approximately 25 °C. This specific storage lenth was chosen to allow oil to accumulate in the kernels, because studies conducted by Evaristo et al. (2016c) showed that macauba fruits accumulate oil over this length of time.

Drying process

After 20 days of storage, the fruits were pulped to obtain the kernels. The macauba fruit kernels were dried in an atmosphere conditioning unit (model Aminco-Aire 150/300 CFM, Aminco) equipped with temperature control devices. The air flow was kept constant at approximately 4 m^3 min^{-1} m^{-2}. Removable trays with screened bottoms were placed inside the equipment to allow air to pass through the sample. The macauba fruit kernels were dried under four drying air conditions: 60 ºC, 70 ºC, 80 ºC, and 90 ºC. The samples were weighed periodically until they reached a moisture of 4.3%; 5.3%; 6.0%; 7.0%, and 8.9% on a wet basis (b.u.).

The experiment was set up in a split-plot design, with drying temperatures (60 °C, 70 °C, 80 °C, and 90 °C) assigned to the plots and moisture (4.3%, 5.3%, 6.0%, 7.0%, and 8.9% b.u.) assigned to the subplots, in a completely randomized design (CRD) with nine replications for the variables C_i, E, D_g, A_p, S, ρ_u, ε, and Ψ and four replications for the variable ρ_a.

Physical characterization of macauba kernels

Shape and size

Biometry was analyzed by roundness (C_i), sphericity (E), projected area (A_p) and surface area (S), which were calculated based on the measurements of the characteristic dimensions, for each moisture (ten repetitions), obtained using a digital caliper with a resolution of 0.01 mm.

C_i, E, geometric diameter (Dg), and S were calculated using equations proposed by Mohsenin (1986). A and S (in mm^2) were calculated by analogy with a sphere of the same D_g.

Apparent specific mass (ρ_a) and unit-specific mass (ρ_u)

Kernel ρ_a, expressed in kg /m^3, was determined using a polyvinyl chloride (PVC) cylinder, 24.5 cm in diameter and 24.5 cm high, in four repetitions (PRADHAN et al., 2008). The values of ρ_a were determined based on the ratio between kernel mass and volume.

The ρ_u, expressed in kg/ m^{-3}, was determined by the ratio between the mass and volume of each kernel, in nine repetitions for each moisture. To determine the volume, the macauba kernels were considered as having a triaxial spheroid shape and their characteristic dimensions and orthogonal axes were measured using a digital caliper with a resolution of 0.01 mm.

After determining their characteristic dimensions, the volume (V) of the kernels was determined as proposed by Mohsenin (1986).

Total porosity (ε)

Total porosity (expressed as percentage) was determined indirectly from the unit-specific mass and apparent specific mass results, as proposed by Mohsenin (1986).

Unit volumetric shrinkage index (Ψ)

The unit volumetric shrinkage index of the macauba kernels associated with moisture reduction was determined by the ratio between kernel volume for each percentage of moisture and the initial volume. The experimental data for Ψ were adjusted to the mathematical models described by the expressions listed in Table 1.

Table 1. Models tested for modeling the unit volumetric shrinkage index.

Model name	Models	
Bala and Woods modified	$\Psi = 1 - A\{1 - \exp[-B(M - M_0)]\}$	(1)
Corrêa et al. (2004)	$\Psi = 1/A + B\exp(M)$	(2)
Exponential	$\Psi = A\ exp\ (BM)$	(3)
Linear	$\Psi = A + BM$	(4)
Polynomial	$\Psi = A + BM + {}^{CM2}$	(5)
Rahman	$\Psi = 1 + \beta\ (M - M_0)$	(6)

M = moisture, decimal b.s.; M_0 = initial moisture, decimal b.s.; *A*, *B*, *C* = parameters that depend on the product; and β = unit volumetric contraction coefficient, dimensionless.

Statistical analysis

The data was analyzed using regression analysis (response surface methodology). The models were chosen based on the significance of the regression coefficients at 5% probability using Student's t-test, the coefficient of determination, and the potential to explain the biological phenomenon. The SigmaPlot software (SPSS, 2001) was used to obtain the regression equations and plot the graphs.

RESULTS AND DISCUSSION

This is the first study in the literature to compile data on the effects of moisture and drying temperature on the physical properties of macauba kernels. Agricultural products show significant changes in their physical properties, including size and shape, when subjected to conditions capable of modifying their moisture (OBA et al., 2019). Understanding these physical properties is of paramount importance for the execution and planning of post-harvest stages (MARTINS et al., 2017a).

Analysis of the shape of macauba kernels

Geometric diameter

The three-dimensional response surface graph was generated to show the effects of moisture and temperature on the geometric diameter of the macauba kernel (Figure 1). The average values for the geometric diameter of the macauba kernel for both parameters (moisture and temperature) showed significant linear effects ($P < 0.05$) and ($P < 0.01$), respectively.

A reduction in the geometric diameter of the kernel was observed with decreasing moisture . As the temperature increased, the geometric diameter decreased. A reduction of 2.14% in geometric diameter was obtained with the reduction in moisture, at a temperature of 60 °C. At 70 °C, there was a reduction of 1.96% with moisture reduction. Overall, there was an uneven reduction in geometric diameter, as well as an uneven reduction with increasing drying temperature.

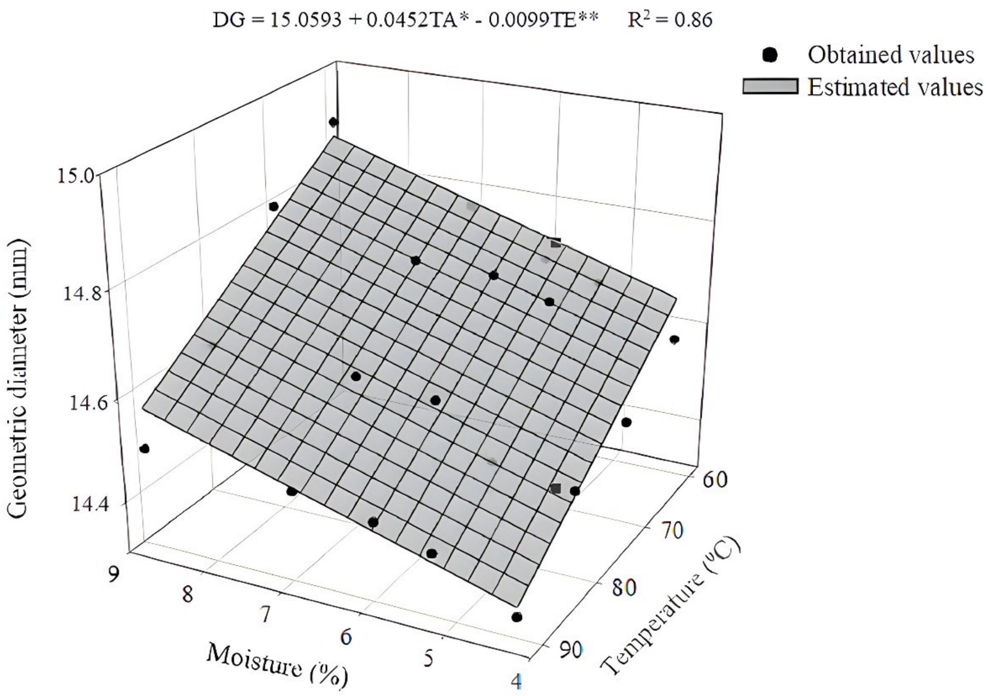

Figure 1. Geometric diameter (mm) of macauba fruit kernels as a function of moisture and temperature. * Significant at 5% and ** Significant at 1% by the t-test.

These results show that the geometric dimensions of macauba kernels, like most agricultural products, shrink unevenly during the drying process, as was observed by Araujo et al. (2014) in peanut kernels.

Sphericity

Sphericity expresses the characteristic shape of a given solid in relation to a sphere, indicating the degree of approximity of the product to a sphere, while roundness expresses the characteristic shape of a given solid in relation to a circle (PAIXÃO et al., 2020). Figure 2 shows the response surface constructed from the model obtained for the sphericity of the macauba kernel. According to the equation, moisture had no effect, either linear ($P > 0.1$) or quadratic ($P > 0.1$). The temperature factor had a linear ($P < 0.1$) and quadratic ($P < 0.1$) effect.

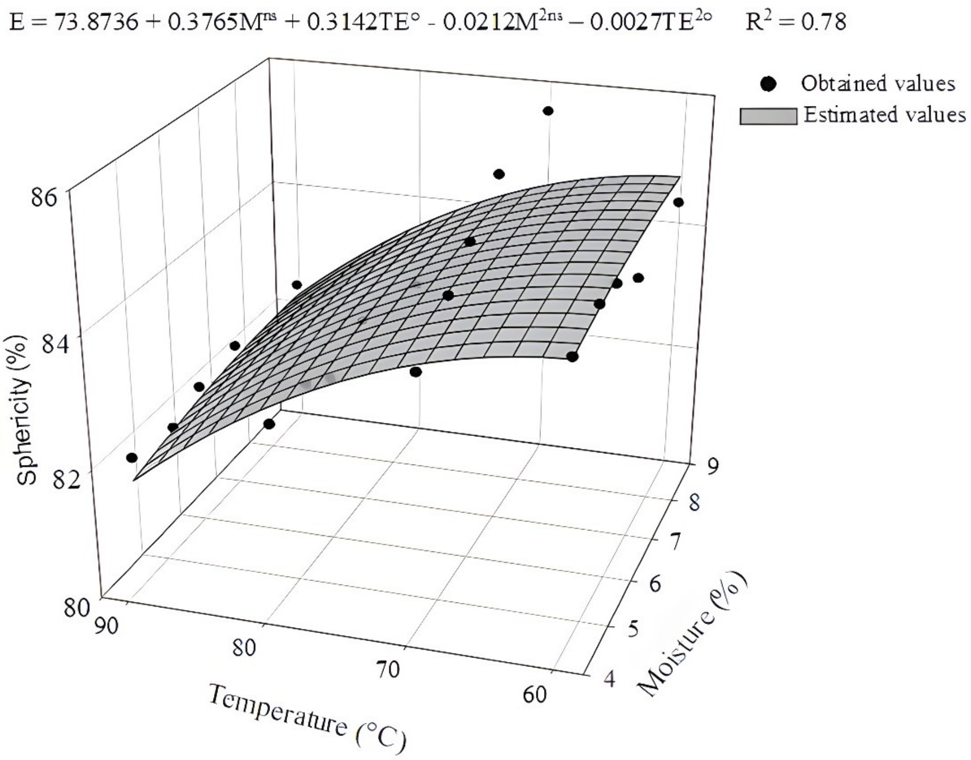

Figure 2. Sphericity (%) of macauba fruit kernels as a function of moisture and temperature. ° Significant at 10% and ^{ns} Not significant by the t-test.

The sphericity of the macauba kernels decreased with increasing drying temperature. With moistures of 6.0%, 5.5%, and 4.3%, the greatest reductions in sphericity were seen with an increase in temperature, 2.74%, 3.09%, and 2.70%, respectively. The lowest average sphericity values were obtained at 90 °C and the lowest experimental sphericity value (81.95%) was observed when the kernels were dried to a moisture of 5.3%. These results show that the sphericity of macauba kernels is more affected when they are dried at higher temperatures. This behavior may be related to the high rate of water removal under these drying conditions. As the temperature rises, the level of molecular vibration of water molecules increases, thus contributing to faster water diffusion.

Sphericity values below 80% mean that agricultural products cannot be classified as spherical (ARAUJO et al., 2014). Therefore, regardless of the drying temperature and moisture tested in this study, all the experimental sphericity values were higher than 80%, so the product tends to be classified as spherical. During drying at 90 °C the kernels cracked, which decreased the average sphericity values. This phenomenon probably facilitates the removal of water from the product. Oliveira et al. (2013) studied morphometric changes in soybeans during the drying process and also found cracks in the beans when subjected to a temperature of 90 °C.

Roundness

Figure 3 shows the experimental and estimated roundness values of macauba kernels. It was shown, through the equation, that moisture and drying temperature had linear effects ($P < 0.01$). Figure 3 shows a reduction in the average roundness values with increasing drying temperatures. Macauba kernel roundness showed the greatest reduction (2.87%), relative to the initial value, in moisture ranging between 8.9% and 4.8% and at a drying temperature of 60 °C.

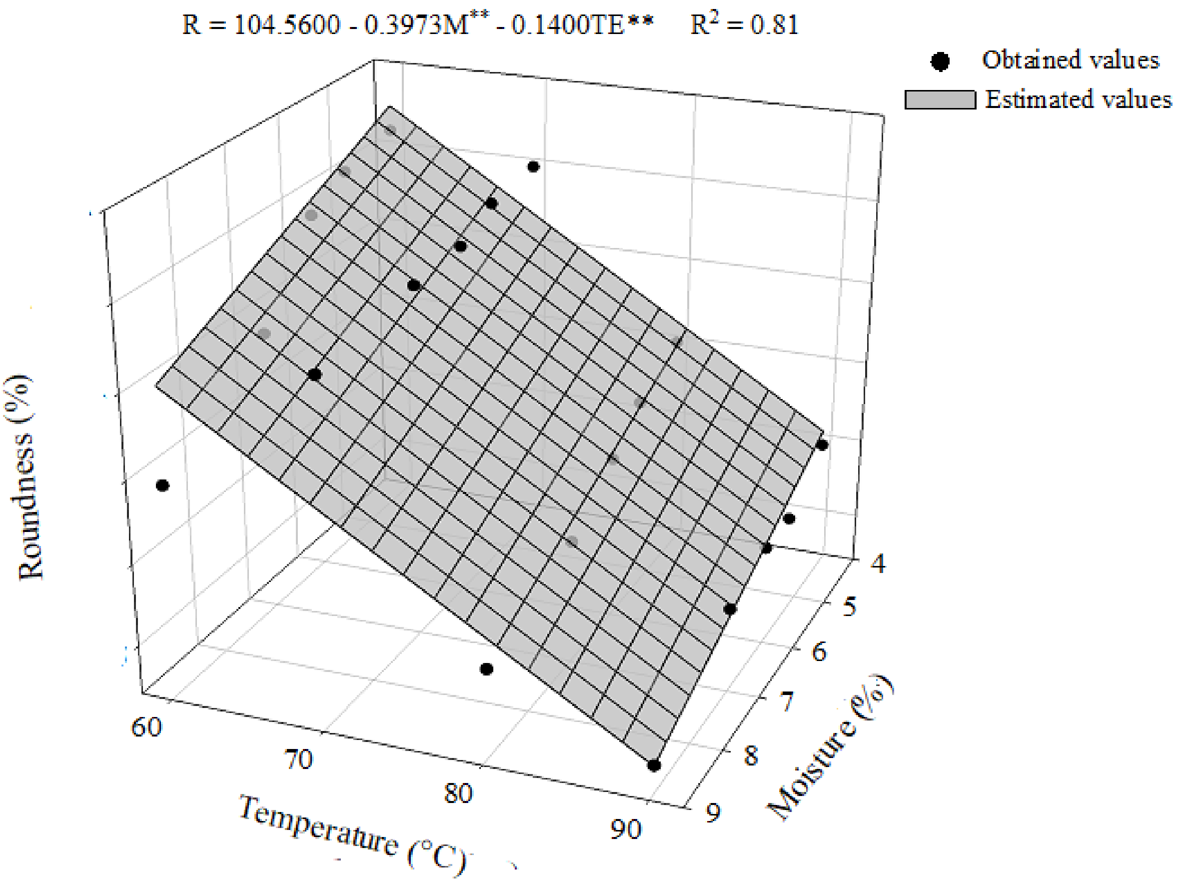

Figure 3. Roundness (%) of macauba fruit kernels as a function of moisture and temperature. ** Significant at 1% by the t-test.

Roundness decreased with decreasing kernel moisture during drying. Similar results were obtained by Siqueira, Resende and Chaves (2012) in their study of the shape and size of jatropha fruits during drying under five air conditions (45, 60, 75, 90, and 105 ºC). Although there was a significant reduction in kernel roundness with temperature and moisture, this reduction was small. This behavior was also shown by Araujo et al. (2014) in the analysis of the physical properties of peanuts during drying.

Projected area and surface area

Three-dimensional response surface graphs were generated to show the effect of moisture and temperature on the projected area and surface area of the macauba kernel (Figure 4). Both moisture and temperature had a significant linear effect on the average values of the projected area and surface area of the macauba kernel.

Figure 4 shows that the experimental values for the projected area (Figure 4A) and surface area (Figure 4B) of the macauba kernels decreased linearly with decreasing moisture and with increasing drying temperature. The reduction in the projected and surface areas of agricultural products due to the decrease in moisture is related to the reduction in volume during the drying process (PAIXÃO et al., 2020).

Greater reductions in projected area (around 3.60%) and surface area (around 3.35%) were obtained by reducing moisture from 8.9% to 4.3% at a temperature of 60 °C. There was a small reduction in the average values of both the projected and surface areas with decreasing moisture and increasing temperature. This behavior was also reported by Botelho et al. (2016) in their analysis of the physical properties of coffee during the drying process. This small reduction during drying was probably due to the physical nature of the product, which makes it difficult to lose water during the process and, consequently, prevents drastic reductions in the projected and surface areas.

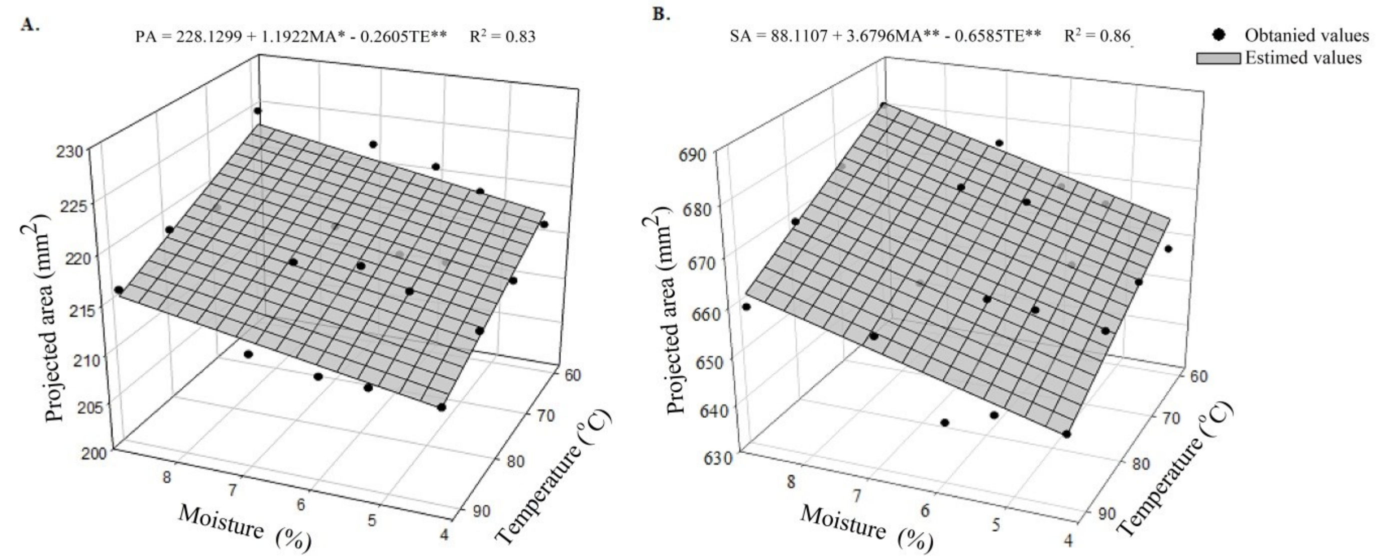

Figure 4. Projected area (A) and surface area (B) of macauba fruit kernels as a function of moisture and temperature. * Significant at 5% and ** Significant at 1% by the t-test.

Analysis of apparent specific mass and unit-specific mass

Figure 5 shows the response surfaces constructed from the models obtained for the apparent specific mass (Figure 5A) and unit-specific mass (Figure 5B) of the macauba kernel. According to the equations, moisture had no linear (P > 0.1) or quadratic (P > 0.1) effect on either variable, whereas temperature had a linear (P < 0.01) and quadratic (P < 0.01) effect on both variables.

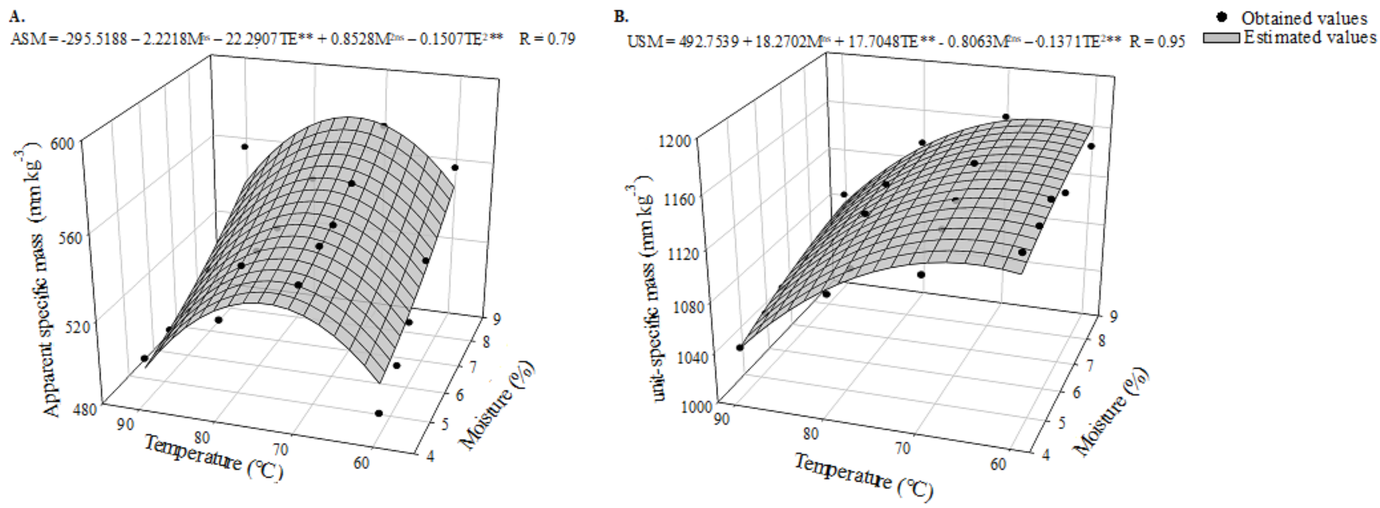

Figure 5. Apparent specific mass (A) and unit-specific mass (B) of macauba fruit kernels as a function of moisture and temperature. ** Significant at 1% and ^{ns} Not significant by the t-test.

There was a trend of small reduction in the apparent specific mass and unit-specific mass of macauba kernels with decreasing moisture. These results are probably due to the combined effects of the presence of empty spaces between the kernels and the reduced shrinkage of their dimensions. This behavior was also observed by Araujo et al. (2014) in peanut kernels and by Bande et al. (2012) in melon seeds.

With regard to the temperature factor, the highest and lowest apparent specific mass values for macauba kernels were obtained at 60 °C (556.89 kg/m^3 and 491.73 kg/m^3). The highest average value of unit-specific mass of macauba kernels (1162.40 kg/m^3) was reported when drying at 70 °C, while the lowest average value (1040.12 kg/m^3) was observed when drying at 90 °C. Knowing the apparent specific mass and unit-specific mass of agricultural products is important because the information provided helps sizing the silos and calculating transporters, separators, and classifiers for these products (ARAUJO et al., 2014).

Analysis of total porosity

Figure 6 shows the observed and estimated porosity values of macauba kernels as a function of moisture and drying temperature. The equation showed that mosture did not have a linear ($P > 0.1$) or quadratic ($P > 0.1$) effect, whereas temperature had a linear ($P < 0.01$) and quadratic ($P < 0.01$) effect.

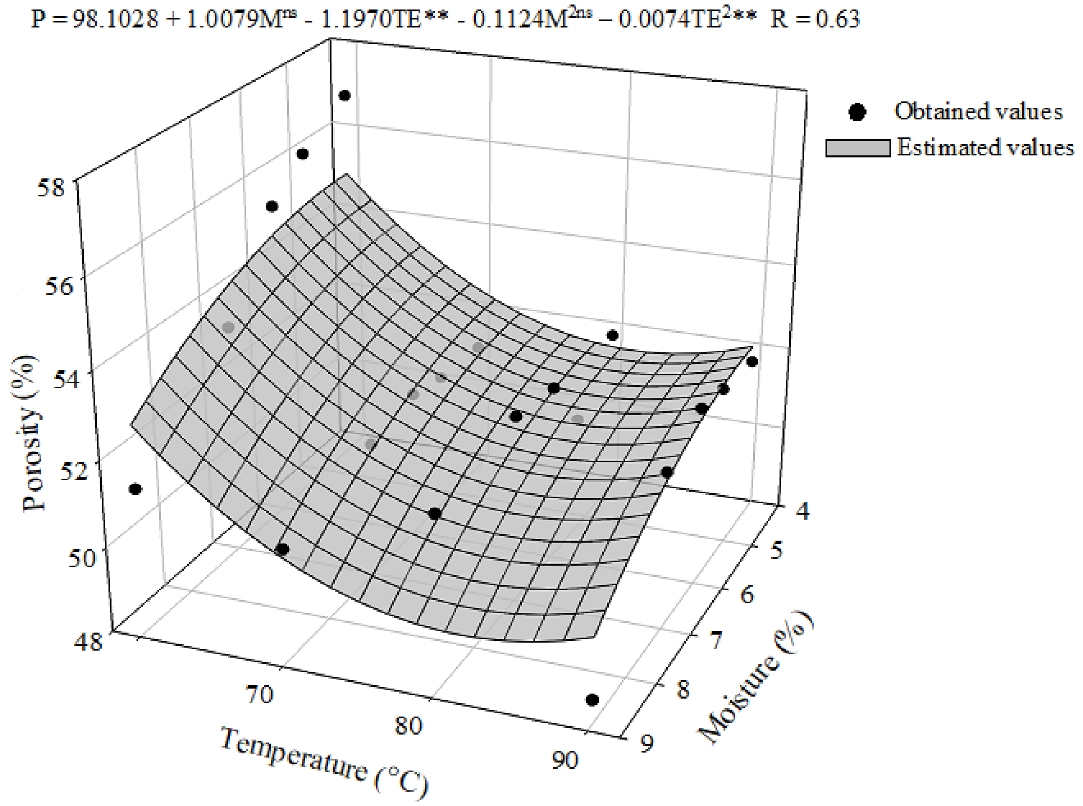

Figure 6. Total porosity (%) of macauba fruit kernels as a function of moisture and temperature. ** Significant at 1% and ^{ns} Not significant by the t-test.

Figure 6 shows that the values of total kernel porosity ranged from 48.6% to 56.9%, with moisture ranging between 8.9% and 4.8%. As moisture in the products decreases, its volume shrinks and, consequently, its mass becomes more compact, which reduces the intergranular spaces (MARTINS et al., 2017b). Porosity is the main factor that defines the resistance to the passage of air in the drying and aeration processes of agricultural products. In view of the above, the data on porosity obtained in these studies will serve to choose the drying temperature and the final moisture for the process.

The results obtained in this study confirm, for the first time, that drying temperature and moisture alter the physical properties of macauba kernels and, consequently, affect an entire planning of the post-harvest. It is important to point out that this study contributes to the development of further studies that determine the cost/benefit ratio of sizing the equipment for drying and storing this product.

CONCLUSION

Reducing the moisture of macauba kernels led to an increase in geometric diameter, projected area and surface area and a reduction in roundness. While the increase in drying temperature reduced the geometric diameter, sphericity, roundness, projected area and surface area. The correct drying temperature and moisture are factors that can affect the behavior of the physical properties of macauba kernels and can be an efficient tool in the post-harvesting of macauba kernels.

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