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Drying and physical properties of rubber wood impregnated with silver nanoparticles

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Sabrina Mayer de Almeida[1]
José Henrique Camargo Pace[2]
Jonnys Paz Castro[3]
Glaycianne C. Vieira dos Santos[4]
Carlos Eduardo Silveira da Silva[5]
João Vicente de F. Latorraca[6]*

[1, 2, 3, 4, 5, 6] Universidade Federal Rural do Rio de Janeiro (UFRRJ), Rodovia BR 465, Km 07, 23.890-000, Seropédica, Rio de Janeiro, Brasil.

*** Corresponding Author:**
E-mail: joaolatorraca@gmail.com

ABSTRACT: Rubber wood can be used after latex exploration however, the high contents of carbohydrates contribute to its low biological durability, making natural drying impossible. Wood treatment with silver nanoparticles can improve physical, mechanical and biological properties, catalyze the drying process, reduce hygroscopicity, and increase dimensional stability and biological resistance. The objective of this research was to evaluate the effects of impregnation of silver nanoparticles and vaporization on the drying rate, volumetric, radial and tangential contractions and the anisotropy coefficient of *Hevea brasiliensis* wood. Samples from two clones (PB311-MDF180 and TP875) were subjected to a vaporization process for 24 hours to increase permeability, also to an application of vacuum (750 mmHg) to remove vessels and pits obstructions, and subsequently to impregnation with silver nanoparticles (22 ppm). The variables were monitored (every 15 minutes until the samples reached 12 % moisture) of the mass loss and dimensions of the pieces submitted to drying in an oven (65 °C). In general, the treatments with previous application of 30 and 60 minutes of vacuum followed by impregnation of silver nanoparticles (I30 and I60, respectively) had the best performance. Thus, the impregnation with silver nanoparticles provides significant gains in drying time and dimensional stability of rubber wood.

KEYWORDS
Hevea brasiliensis
Nanotechnology
Volumetric contraction

PALAVRAS-CHAVE
Hevea brasiliensis
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RESUMO: *A madeira de seringueira pode ser utilizada após a exploração do látex, entretanto, os altos teores de carboidratos contribuem com sua baixa durabilidade biológica, inviabilizando a secagem natural. O tratamento da madeira com nanopartículas de prata pode melhorar as propriedades físicas, mecânicas e biológicas, catalisar o processo de secagem, reduzir a higroscopicidade, aumentar a estabilidade dimensional e resistência biológica. O objetivo deste trabalho foi avaliar os efeitos da impregnação de nanopartículas de prata e da vaporização sobre a taxa de secagem, as contrações volumétrica, radial e tangencial e o coeficiente de anisotropia da madeira de Hevea brasiliensis. Amostras de dois clones (PB311-MDF180 e TP875) foram submetidas a um processo de vaporização por 24 horas para aumento da permeabilidade, à aplicação de vácuo (750 mmHg) para desobstrução de vasos e pontoações, e posteriormente, à impregnação com nanopartículas de prata (22 ppm). As variáveis foram monitoradas (a cada 15 minutos até as amostras atingirem 12 % de umidade) quanto à perda de massa e das dimensões das peças submetidas à secagem em estufa (65 °C). Em geral, os tratamentos com prévia aplicação de 30 e 60 minutos de vácuo seguidos de impregnação de nanopartículas de prata (I30 e I60, respectivamente) obtiveram os melhores desempenhos. Assim, a impregnação de nanopartículas de prata proporciona ganhos significativos no tempo de secagem e na estabilidade dimensional da madeira de seringueira.*

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1 Introduction

Brazil has a large variety of forest species with potential for sustainable exploitation, such as a rubber tree (*Hevea brasiliensis* Willd.ex.A.Juss. Muell. Arg), a forest species native to the Amazon, with approximately 11 varieties known (Faria *et al.*, 2019). At the end of the latex production period, between 25 and 30 years, there is a significant supply of rubber tree wood (Faria *et al.*, 2019), which drives the wood industry due to the possibility of application in the manufacture of furniture, panels and as internal components in civil construction (Junior *et al.*, 2015). The manufacture of Laminated Veneer Lumber (LVL), for example, from commercial stands or unconventional native woods such as rubber trees, has been the focus of research in Brazil due to its potential in structural (construction) and non-structural wood applications, as furniture and floors (Faria *et al.*, 2020).

Despite having good workability characteristics related to gluing, machining and insertion of nails and screws (Faria *et al.*, 2019; 2020), rubber tree wood has low resistance to attack by xylophagous organisms (Martins *et al.*, 2019), it is then used as a source of low-cost raw material for energy purposes (Junior *et al.*, 2015). However, when associating it with a preservative treatment, there is the possibility of application as an alternative wood to those conventionally used (Faria *et al.*, 2019).

Green rubber tree wood has from 1.05 to 2.29 % of total sugars and kiln-dried about 7.53 to 10.17 % of starch (Kadir; Sudin, 1989). The high levels of carbohydrates present in parenchymal cells contribute to low biological durability, making them susceptible to termite and fungal attacks. Thus, natural drying is unfeasible, and therefore, drying in an oven must be used in order to obtain dry wood with the least amount of defects in the shortest possible time.

The drying of wood is related to the movement of free and hygroscopic water, caused by the transfer of heat to its interior. The drying process aims to reduce moisture in order to reach the equilibrium content in less time, maintaining its dimensional stability. According to Rezende *et al.* (2015) and Baranski (2017), the main advantages of this process in relation to natural drying are the reduction of time, the control of the drying rate and the reduction in the incidence of defects such as cracks and warping.

Studies related to the application of treatments that aims to help the drying process and/or improve the physical properties of wood are increasing (Rezende *et al.*, 2015; Pace *et al.*, 2019; Taghiyari *et al.*, 2019). Vaporization consists of the application of steam heated to high temperatures and relative humidity for a certain period. This technique can act to reduce growth tensions, increase permeability, reduce dimensional stability, wood sterilization, reduce moisture gradients and drying time, as well as promote an increase in the drying rate (Rezende *et al.*, 2015).

Another possible technology is nanotechnology, which is related to the production of new materials with innovative properties, from matter at the nanometer scale (< 100 nm) (Borges *et al.*, 2018). The use of nanoparticles (NPs) and metal oxides in wood has been reported in several studies, especially NPs of copper, silver, gold, boron and zinc and aluminum oxides (Borges *et al.*, 2018; Papadopoulos; Kyzas, 2019).

In general, nanocompounds are easier to penetrate into the cell walls of wood, are rarely leached and have greater natural durability (Can *et al.*, 2019). Treatment with NPs can promote increases in the physical, mechanical and biological properties of wood, reduction of hygroscopicity and increase in dimensional stability, in addition to the possible application as a catalyst (Papadopoulos; Kyzas, 2019).

The use of silver nanoparticles can favor the penetration of heat to internal parts of the wood due to its good thermal conductivity (Taghiyari, 2012). Vaporization and vacuum prior to impregnation with silver NPs can enhance their action and, thus, favor drying and reduce the volumetric contraction of the material (Pace *et al.*, 2019).

Therefore, the main goal of this research was to evaluate the effects of impregnation of silver nanoparticles and vaporization on the drying rate, volumetric, radial and tangential contractions and anisotropy coefficient of the wood of two clones of *Hevea brasiliensis*.

2 Material and methods

Sampling Method

Two clones of *Hevea brasiliensis*, PB311-MDF180 and TP875, approximately 20 years old, from a plantation located in the municipality of Igrapiúna/BA (13°48'51"S, 39°8'54"W), with spacing of 2.5 x 8.0 m were used. The area is characterized by maximum and minimum temperatures of 28.9 and 20.7 °C, respectively, and average annual precipitation, analyzed between 2005 and 2015, of 1751.3 mm, with a rainy period between February and July (166 mm on average) and less rainy from August to January (48 mm on average).

Two trees were used, one of each clone, and the first log was selected, corresponding to the first three meters, which were then unfolded into boards, with the aid of a vertical band saw. After the primary break-down, samples measuring 2 x 2 x 13 cm (width x thickness x length) were made, which were later reduced to two sizes. For the evaluation of the physical properties and drying of the wood, samples with dimensions of 2 x 2 x 10 cm were used and, for the determination of the average penetration of silver nanoparticles, samples paired to the above were used with a dimension of 2 x 2 x 2 cm. Posteriorly, they were submitted to treatments according to the experimental design. Other informations related to the logs used in this research are described in Table 1.

Table 1. Complementary information of the *Hevea brasiliensis* clone trees used in the experiment.

Tabela 1. Informações complementares das árvores dos clones de *Hevea brasiliensis* utilizados no experimento.

Code	Clone	Average DBH (cm)	Average height (m)
PB	PB311-MDF180	28.01	15
TP	TP875	27.37	14

DBH = diameter at breast height (1.30 m from the ground).

DAP = diâmetro a altura do peito (1,30 m em relação ao solo).

Experimental design

The experimental design consisted of six treatments per clone, each containing 12 samples. The control consists of untreated samples. Treatments I30 and I60 consisted of samples submitted to application of 30 and 60 minutes of vacuum, respectively, and subsequent impregnation of silver nanoparticles for 6 hours. Treatments I30-VAP24 and I60-VAP24 for samples submitted to vaporization for 24 hours, application of 30 and 60 minutes of vacuum, respectively, and subsequent impregnation of silver nanoparticles for 6 hours. The VAP24 treatment for samples submitted to vaporization for 24 hours without impregnation of silver nanoparticles (Figure 1).

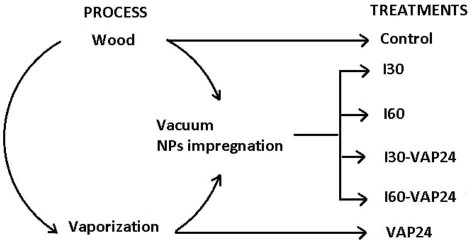

Figure 1. Overall scheme of treatments used. Treatments: Control - untreated samples; I30 - application of 30 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I60 - application of 60 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I30-VAP24 - vaporization for 24 hours, and application of 30 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; I60-VAP24 - vaporization for 24 hours, and application of 60 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; and VAP24 - vaporization for 24 hours.

Figura 1. Esquema global dos tratamentos utilizados. Tratamentos: Controle - amostras sem tratamento; I30 - aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60 - aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I30-VAP24 - vaporização por 24 horas, aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60-VAP24 - vaporização por 24 horas, aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; e VAP24 - vaporização por 24 horas.

Wood vaporization

The vaporization process was carried out in an experimental horizontal autoclave with a capacity of approximately 0.18 m³ with temperature and pressure control for 24 continuous hours. The steam was generated with the aid of a boiler with a capacity of 8 kg h^{-1} and a flow rate of 60 kg h^{-1}. The maximum temperature and humidity used were 96±5 °C and 90±5 %, respectively.

The humidity was monitored with the aid of a digital hygrometer, with a variation of 2 % in moisture and 0.5 °C in temperature. The steam release valve was kept closed whenever the relative humidity inside the autoclave was greater than 95 %.

Impregnation of silver nanoparticles

The colloidal suspension of silver nanoparticles was provided by the Brazilian company KHEMIA Nanoparticles LTDA, with a concentration of 22 ppm, containing nanoparticles with sizes between 5 and 20 nm, without the presence of surfactants and without the formation of precipitates. The impregnation process took place in steamed and non-vaporized woods. It was carried out in a desiccator measuring 45 x 40 x 50 cm (width x height x length) with an attached vacuum pump.

The application of vacuum occurred in two distinct periods, 30 and 60 minutes under negative pressure of 750 mmHg. Then, the impregnation was carried out by simple immersion for a period of 6 continuous hours in the samples with and without initial vacuum and vaporization, except for the Control and VAP24 treatments.

Subsequently, the samples were weighed with the aid of an analytical balance with precision of 0.01 g to obtain the mass, the respective volumes were measured with a caliper with a precision of 0.001 mm and then kept in an oven (65±5 °C) to start the drying process.

Wood drying

The drying process was carried out on samples measuring 2 x 2 x 10 cm, in an oven with forced ventilation at a temperature of 65±5 °C. During the drying process, the samples were constantly weighed with the aid of an analytical balance with a precision of 0.01 g and measurement of the dimensions using a caliper with a precision of 0.001 mm, at 15-minute intervals. The registration of the respective masses and dimensions was carried out until they reached 12 % moisture content. To obtain anhydrous wood, the samples were dried at 103±5 °C.

Wood drying rate

The wood drying rate was determined from the mass loss recorded for each treatment (Equation 1) and evaluated through the analysis of the total drying rate (total DR), capillary (capillary DR) and diffusion (diffusion DR), in order to individually contemplate the drying behavior before and after the fiber saturation point (FSP).

$$DR = \frac{M}{t*ES} \quad \text{(Equation 1)}$$

Where: DR = drying rate for a given humidity range (g $cm^{-2}h^{-1}$); M = mass of water removed from the wood (kg); t = drying time (h); ES = evaporation surface (cm²).

The evaporation surface, in square centimeters (cm²), was obtained through equation 2, considering the area of a rectangular prism for the sample.

$$ES = 2(a * b + a * c + b * c) \quad \text{(Equation 2)}$$

Where: ES = evaporation surface (cm²); a, b, c = measurements of the axes of the prismatic sample (cm).

Physical properties of wood

In order to determine the physical properties of the wood, samples measuring 2 x 2 x 10 cm were used. Wood density was calculated in the untreated samples (control) after the drying process, for both clones, following NBR 7190 (ABNT, 1997). The averages total, radial and tangential volumetric contractions and the anisotropy coefficient for each treatment were determined by means of linear measurements of each sample, measured every 15 minutes until reaching a humidity of 12 %. The volumetric variation of the samples was measured according to equation 3:

$$\Delta V = \frac{Vsat - Vdry}{Vdry} * 100 \quad \text{(Equation 3)}$$

Where: ΔV = volumetric variation for a given humidity range (%); V_{sat} = saturated wood volume (cm³); V_{dry} = wood volume after drying for a certain time (cm³).

Penetration of silver nanoparticles

Penetration of silver nanoparticles was performed in specimens with dimensions of 2 x 2 x 2 cm, using 4 samples per treatment. The samples treatments followed the procedures mentioned above and the determination of the average penetration of the silver NPs solution was obtained through the difference between the mass before and after the immersion of the pieces (Equation 4).

$$P = \frac{M_{after} - M_{before}}{M_{after}} * 100 \quad \text{(Equation 4)}$$

Where: P = average penetration of silver nanoparticles (%); M_{after} = mass of wood obtained after impregnation (g); M_{before} = mass of air-conditioned wood before impregnation (g).

Statistical analysis

For the drying rate, the statistical prerequisites of normality of residues (Shapiro-Wilk, 5 % of significance) and homogeneity of variance (Bartlett, 5 % of significance) were met and, therefore, the methods of parametric analysis were adopted (ANOVA), with a completely randomized design. Tukey test was used to compare means at the 95 % confidence level, whenever the null hypothesis was rejected.

For physical properties, the non-parametric Kruskal-Wallis test (95 % of probability) was applied to compare the mean ranks, as the data did not follow a normal distribution (Lillefors test). After this test, the analysis was carried out using the Dunn test, to compare the means (95 % of probability).

3 Results and Discussion

Wood density and penetration of silver nanoparticles

The results revealed similarity between the basic density values for the PB and TP clones (0.512 and 0.516 g cm-^{3}, respectively). However, there was a small variation in bulk density, 0.546 g cm-^{3} for CP and 0.565 g cm-^{3} for TP.

There was also a gain in mass in the specimens subjected to treatments of vaporization and impregnation of NPs (Table 2). Both clones had higher percentage penetration of silver NPs in treatment I60, 56.88 and 60.06 %, for PB and TP respectively. The lowest percentages were found in I30 (clone PB), 52.01 %, and I60-VAP24 (clone TP), 51.75 %.

Table 2. Complementary Average penetration (± standard deviation) of the silver nanoparticles solution per treatment.

Tabela 2. Penetração média (± desvio padrão) da solução de nanopartículas de prata por tratamento.

Treatment	Average penetration (µg)	
	PB311-MDF180	TP875
I30	108.30(9.88)	82.78(4.07)
I60	125.07(2.84)	90.64(3.37)
I30-VAP24	109.12(7.24)	86.85(7.26)
I60-VAP24	109.89(8.09)	74.42(5,22)

Values in parentheses correspond to standard deviation. Treatments: I30 - application of 30 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I60 - application of 60 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I30-VAP24 - vaporization for 24 hours, and application of 30 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; I60-VAP24 - vaporization for 24 hours, and application of 60 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours.

Valores entre parênteses correspondem ao desvio padrão. Tratamentos: I30 - aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60 - aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I30-VAP24 - vaporização por 24 horas, aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60-VAP24 - vaporização por 24 horas, aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas.

According to the classification of the Instituto de Pesquisas Tecnológicas (IPT, 1985), low density woods have a basic density less than or equal to 0.50 g cm^{-3}; medium density woods have values between 0.50 and 0.72 g cm^{-3} and; high density woods, values above 0.72 g cm^{-3}. Thus, the clones used in this experiment are considered medium density wood.

Rubber wood density can vary between 0.470 and 0.640 g cm^{-3}, according to age and position in the shaft (Majumdar *et al.*, 2015). Juvenile wood can present a basic density of 0.550 g cm-^{3} and bulk density, at 12 % of moisture, of 0.614 g cm^{-3} (Matan; Kyokong, 2003). The low variability between basic densities can be considered an advantage when using rubber in certain industrial processes, for example, in the manufacture of wood-based panels (Junior *et al.*, 2015).

There is an inversely proportional relationship between wood density and retention of silver NPs (Moya *et al.*, 2017), and it is possible to verify an increase in retention in the sapwood (Pařil *et al.*, 2017). There may be penetration into pit membranes and cell walls, depending on the dimensions and species used (Pařil *et al.*, 2017).

Another important aspect is that the empty-cell impregnation method can remove part of the suspension of nanoparticles from the wood (Taghiyari *et al.*, 2013a), reducing its amount inside the samples. This information collaborates with the impregnation method used in this study, full cell, which possibly favored the retention of the solution inside the wood.

The contrast between the clones behavior is possibly related to their anatomical, physical and/or chemical characteristics, associated with the time of application of vacuum and vaporization of the samples. Vacuum may have contributed to the penetration of the silver NPs solution due to the possible unblocking of anatomical elements, however, vaporization for 24 hours may not have been sufficient to effectively increase the permeability of the wood and favor the entry of nanoparticles into the samples.

Wood drying

When comparing the clones, it was found that there was not statistical difference in the rates of total drying, capillarity and diffusion however these parameters were significantly different between treatments (Figure 2).

There was a significant increase in the total wood drying rate of the two rubber tree clones submitted to treatments I30 and I60. At I30, the averages obtained were 0.700 and 0.721 g cm-^{2}h^{-1}, and at I60 they were 0.724 and 0.711 g cm-^{2}h^{-1}, for the TP and PB clones, respectively. On the other hand, the vaporization for 24 hours (VAP24) and its combination with the impregnation of silver NPs (I30-VAP24 and I60-VAP24) promoted a decrease in this variable.

It was found that the impregnation with NPs and the vaporization of the wood contributed to the increase in the capillary drying rate. The TP clone showed considerable improvement in treatment I60, 1.171 g cm-^{2}h^{-1}, followed by treatments I30, I30-VAP24 and I60-VAP24, 1.100, 1.070 and 1.022 g cm-^{2}h^{-1}, respectively. PB clone obtained the best results in treatments I30, I60 and, unlike the previous clone, VAP24, with averages of 1.239, 1.350 and 1.238 g cm-^{2}h^{-1}, respectively.

In the diffusion drying rate, the treatments with more expressive results used the previous application of vacuum and the impregnation of NPs and, consequently, those that used wood vaporization had a decrease in this variable. TP clone obtained 0.044 and 0.046 g cm-^{2}h^{-1}, and PB clone, 0.045 and 0.046 g cm-^{2}h^{-1}, for I30 and I60 respectively.

Some rubber tree clones may have vessels obstructed by tyloses close to the medulla, increased frequency of vessels in the region close to the cambium, prismatic calcium oxalate crystals (Santos *et al.*, 2019), as well as a texture moderately coarse to even (Majumdar *et al.*, 2015). Therefore, despite the similarity between basic density and total TS, anatomical characteristics and even compounds inherent to each clone may have contributed to the difference between the mean penetration values of silver NPs.

Clearly, the impregnation of silver nanoparticles exerted a greater influence on the total and diffusion drying rates. Its deposition on the surface of the vessel element walls and on the fiber wall ultrastructure can promote an increase in the wood drying rate and contribute to the hygroscopic water output (Pace *et al.*, 2019). It can also favor heat transfer to inner layers by reducing the moisture gradient (Taghiyari *et al.*, 2012; 2013a; 2013b; Taghiyari; Malek, 2014), improve permeability, due to extractive dissolution, breakage and collapse of drill plates and tyloses, which act as physical obstacles blocking the flow of liquids (Ghorbani *et al.*, 2012; Taghiyari *et al.*, 2013b; 2014; 2015).

Thus, silver NPs act as catalysts for the process of diffusing heat from the surface to the interior of the wood enhancing its transfer between the walls and lumens cell, making the hygroscopic water output faster, with the lowest energy expenditure. As well as the low hygroscopicity of silver linked to changes in the hygroscopic properties of the cell wall and the reduction in extractives and carbohydrates, due to heat treatment, can help to reduce water absorption by wood cells.

It was also found that in the capillarity TS of the TP clone, vaporization combined with the impregnation of NPs contributed to the increase in the permeability of the wood due to the leaching of the content of the vessel elements, with the release of free water from the cell cavities and with the transfer of heat in the wood, thus increasing the drying rate. Therefore, possibly the wood of this clone has some obstruction in the large transport structures, such as tyloses, due to the greater difficulty in losing water present in the capillaries. On the other hand, the isolated application of impregnation or vaporization on the wood of the PB clone would be sufficient to favor the release of free water.

The vaporization process can facilitate the hygroscopic water output from the wood and promote changes in its chemical composition, such as a reduction in the total extractives and carbohydrate content, which in turn can influence the hygroscopic properties of the cell wall (Pace *et al.*, 2019) and, consequently, the permeability of the wood.

As the temperature increases, changes are observed in the wood, such as darkening, movement of extractives from the interior to the surface of the sample, reduction of water absorption and density, increased biological durability, among others (Owoyemi; Iyiola, 2016). However, the application of high temperatures can result in reduced permeability due to breakage and accumulation of tyloses along the vessel elements, blocking the flow of liquids (Taghiyari *et al.*, 2015).

Consequently, the results showed that in none of the clones the isolated application of vaporization was

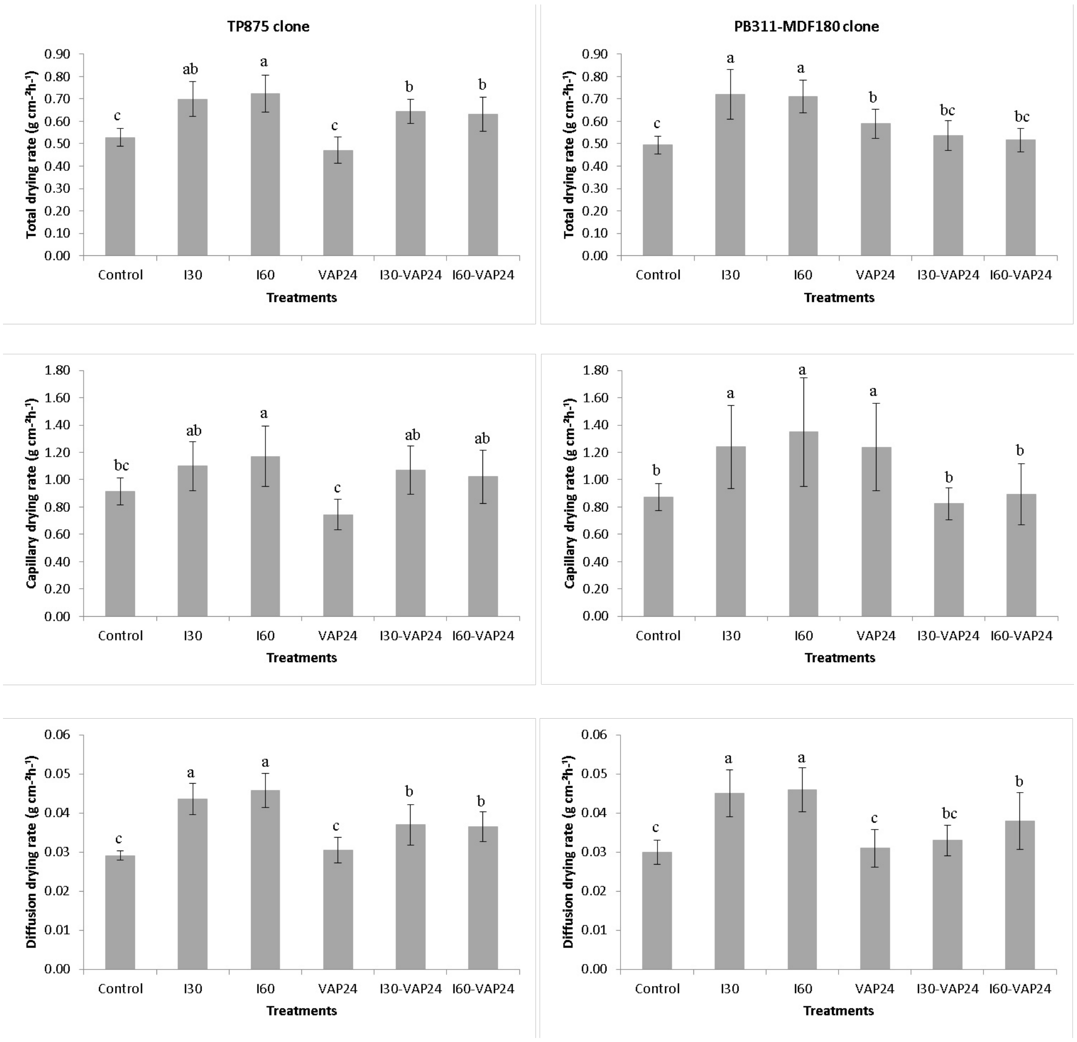

Figure 2. Rate of total drying, capillarity and diffusion (± standard deviation) of clones TP875 and PB311-MDF180, of *Hevea brasiliensis* wood. Graphics on the left for clone TP875 and on the right for clone PB311-MDF180. Treatments: Control - untreated samples; I30 - application of 30 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I60 - application of 60 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I30-VAP24 - vaporization for 24 hours, and application of 30 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; I60-VAP24 - vaporization for 24 hours, and application of 60 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; and VAP24 - vaporization for 24 hours. Letters a, b, c denote statistical differences between treatments, analyzed by column (Tukey, p> 0.05).

Figura 2. Taxa de Secagem Total, de Capilaridade e de Difusão (± desvio padrão) dos clones TP875 e PB311-MDF180, da madeira de *Hevea brasiliensis*. Gráficos à esquerda correspondem ao clone TP875 e à direita ao clone PB311-MDF180. Tratamentos: Controle - amostras sem tratamento; I30 - aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60 - aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I30-VAP24 - vaporização por 24 horas, aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60-VAP24 - vaporização por 24 horas, aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; e VAP24 - vaporização por 24 horas. As letras a, b, c denotam diferenças estatísticas entre os tratamentos, analisadas por coluna (Tukey, p> 0,05).

enough to improve the drying rates, to the point of replacing the impregnation with silver nanoparticles. In this case, treatments I30 and I60 obtained the most satisfactory results, reaffirming that silver NPs were essential to increase the drying rates evaluated. It is also possible to say that the diffusion drying rate has a greater influence on the total drying rate, when compared to capillarity drying rate, which is proven by the optimization of the water output from the wood due to the action of nanoparticles.

Physical properties

In general, there was a reduction in the total volumetric contraction, however, despite the similarity between the basic densities, the clones showed similar results. PB clone obtained a significant reduction in volumetric contraction in treatments I30 and I60, with values of 7.54 and 8.45 % respectively. On the other hand, all treatments of the TP clone showed statistical difference in relation to the control, in addition to being associated with lower standard deviation values (Figure 3). The reduction in radial volumetric contraction of TP clone was observed in I30, VAP24 and I60-VAP24, with values of 3.12, 3.30 and 3.02 % respectively, while none of the treatments of PB clone showed a significant difference from the control. In the tangential volumetric contraction there was a reduction in I30 and I60 in PB clone and, in TP clone, all treatments differed from the control.

Regarding the anisotropy coefficient, although high values are expected in rubber trees, the results obtained were satisfactory. PB clone did not show any significant increase compared to the control, but TP clone showed a reduction in I60 and I30-VAP24. This fact may be related to the contribution of steam and NPs in improving the dimensional stability of wood.

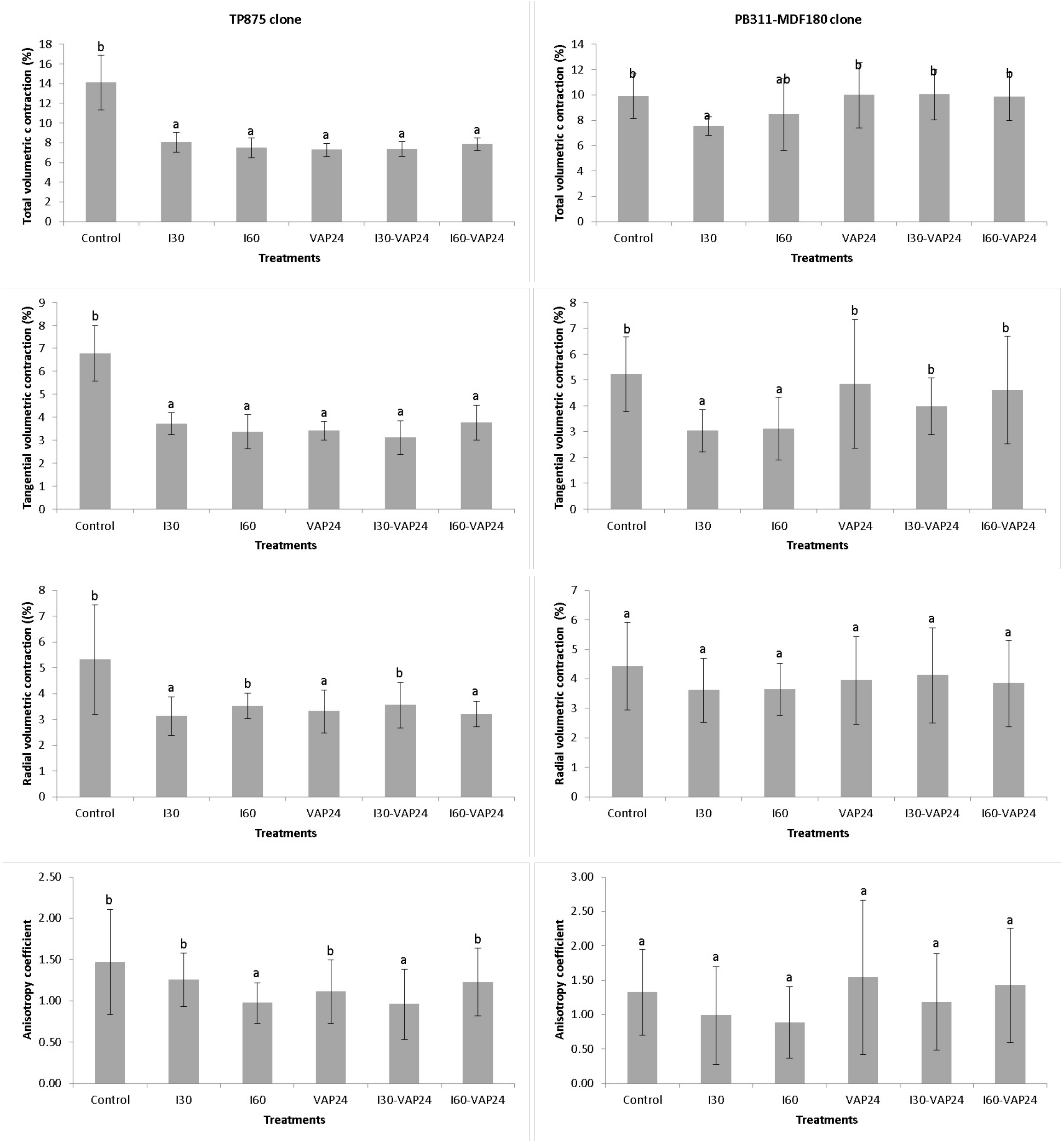

Figure 3. Total, tangential and radial volumetric contraction and anisotropy coefficient of the wood of two clones of *Hevea brasiliensis*. Graphics on the left for clone TP875 and on the right for clone PB311-MDF180. Treatments: Control - untreated samples; I30 - application of 30 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I60 - application of 60 minutes of vacuum and impregnation of silver nanoparticles for 6 hours; I30-VAP24 - vaporization for 24 hours, and application of 30 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; I60-VAP24 - vaporization for 24 hours, and application of 60 minutes of vacuum, and impregnation of silver nanoparticles for 6 hours; and VAP24 - vaporization for 24 hours. Letters a, b, c denote statistical differences of mean treatment posts, analyzed by column (Dunn, p> 0.05).

Figura 3. Contração volumétrica total, tangencial e radial e coeficiente de anisotropia da madeira de dois clones de *Hevea brasiliensis*. Gráficos à esquerda correspondem ao clone TP875 e à direita ao clone PB311-MDF180. Tratamentos: Controle - amostras sem tratamento; I30 - aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60 - aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I30-VAP24 - vaporização por 24 horas, aplicação de 30 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; I60-VAP24 - vaporização por 24 horas, aplicação de 60 minutos de vácuo e impregnação de nanopartículas de prata por 6 horas; e VAP24 - vaporização por 24 horas. As letras a, b, c denotam diferenças estatísticas dos postos médios dos tratamentos, analisadas por coluna (Dunn, p> 0,05).

The amount of water present in rubber tree wood interferes with weight, permeability, dimensional stability and strength (Majumdar *et al.*, (2015), but its removal above the fibers saturation point (FSP) does not affect the dimensions of the wood. Below the FSP, water molecules bound to cellulose and hemicelluloses are removed causing shrinkage proportional to the amount of water removed from the cell wall (Matan; Kyokong, 2003).

Vaporization can reduce the rigidity of cell walls and cause cell accommodation, due to a possible release of growth tensions by relaxing deformations through the momentary use of moisture and heat (Rezende *et al.*, 1988), as well as increasing the permeability of the wood due to the dissolution of carbohydrates present in the cell wall.

The behavior of rubber wood can vary according to the influence of different factors, such as age and position in the trunk. Majumdar *et al.* (2015) claim that the tangential contraction can be twice as large as the radial one, due to the restriction of the angle of the microfibrils in the cell wall and/or the physical organization of the cellulose chains.

According to Junior *et al.* (2015), the tangential contraction of rubber tree wood is 5.8 % and radial of approximately 2.7 %, varying according to the clone. Majumdar *et al.* (2015) obtained tangential contraction ranging from 4.02 to 6.10 % and, the radial one, from 2.03 to 3.20 %. Raia *et al.* (2018) obtained 7.62 % tangential and 0.72 % radial contraction for a height of 3.0 m in trees after the latex extraction period.

The anisotropy coefficient (AC) is obtained through the ratio between the tangential and radial contractions of the wood. It can vary according to the clone, with values between 2.2 and 2.3 (Junior *et al.*, 2015), as well as with the height of the tree, between 2.24 for 1.5 m and 2.12 for 3.0 m (Raia *et al.*, 2018). According to the classification of the anisotropy coefficient proposed by Durlo & Marchiori (1992), values between 1.2-1.5 are considered excellent; values from 1.5 to 2.0 classify the wood as normal; and above 2.0 as bad. Therefore, the results showed that the clones' woods can be classified as excellent, in contrast to what was previously reported in the literature.

Junior *et al.* (2015) state that after latex exploitation, the wood of some rubber tree clones can be used in small structures, in internal construction components, utilities, panels and furniture, and can replace wood from forest species, such as *Cedrela* spp., *Cedrelinga cateniformis*, *Vochysia* spp. and *Erisma uncinatum*. The same authors state that the physical performance of rubber tree wood is similar to that of the species *Tectona grandis* L.f. (Teak) and the mechanic the *Swietenia macrophylla* King (Mahogany).

4 Conclusion

The impregnation with silver nanoparticles significantly contributes to increasing the wood drying rate in all stages of the process, especially in the diffusion stage. Despite the similarity between the results, TP clone demonstrated that the increase in the drying rate in the capillary phase is independent of the previous vaporization of the wood. They also help to reduce the volumetric contraction of wood, which is more pronounced in tangential contraction. Vaporization alone did not improve the physical properties of rubber tree wood.

The use of silver NPs impregnation treatment of wood preceded by application of 30 min of vacuum (I30) is the most indicated, due to its effectiveness in reducing volumetric shrinkage and increasing the drying rate and the lowest energy expenditure to carry out the treatment.

Studies related to the anatomical structure and chemical composition of rubber wood and the characterization of nanostructures regarding morphology (size and geometrical shape), polydispersity (zeta potential), stability, toxicity and financial viability are recommended.

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