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THE EFFECT OF SANDING ON THE WETTABILITY AND SURFACE QUALITY OF IMBUIA, RED OAK AND PINE WOOD VENEERS

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ABSTRACT

The finishing quality of wood products depends on the material's surface and its intrinsic properties. Dynamic wettability is a simple and efficient way to understand the behavior of materials related to solid-liquid interactions according to theoretical and practical perspectives. Thus, we sought to investigate the wettability of imbuia (*Ocotea* spp.), red oak (*Quercus* spp.), and pine (*Pinus elliottii*) woods and its effects before and after sanding. Through the sessile drop technique, we evaluated contact angle and work of adhesion. Sanding changed the samples' surface quality due to the decrease in contact angle and the increase in the work of adhesion. In addition, the droplet spreading and adsorption observed on the surface of the woods are an indicator of wettability. Pine and red oak had their dynamic contact angle reduced by up to 43 %. However, imbuia was less susceptible to the effects of sanding, since it was found to be a more hydrophobic species; thus, this wood has a more stable surface in terms of dynamic wettability. This may be a result of the effect of low molecular weight compounds on the surface of imbuia wood. The preparation of the wood surface depends on a synergy between the finishing processes and the chemical composition of the surface. Therefore, the results found can indicate which coatings are more suited to these woods.

Keywords: Contact angle, hydrophobicity, hydrophilicity, sanding, wood surface.

INTRODUCTION

The wettability of wood is an important parameter to determine how the properties of a given wood's surface react to liquid (Siebra *et al*. 2020). Wettability allows us to analyze the influence of several processes applied to wood, such as the effects of machining (Jankowska *et al*. 2018, Rolleri *et al*. 2016), thermal modification (Chu *et al*. 2016, Lopes *et al*. 2018, Santos and Goncalves 2016), film deposition by plasma technique (Cademartori *et al*. 2016, 2017, Fang *et al*. 2016 Peng and Zhang 2019), and varnish coatings (Darmawan *et al*. 2018; Fonte *et al*. 2019).

Additionally, wettability is typically measured via contact angle; the smaller the contact angle, the higher the surface wettability and vice versa (Fang *et al*. 2016; Wang *et al*. 2017). The sessile drop method is one of the most common alternatives for measuring the contact angle through the use of goniometers (Sinderski 2020). When a droplet is deposited on the surface of a solid, the instantaneous contact angle is formed and the droplet expands over the surface (spreading). Simultaneously, the liquid is adsorbed until it no longer penetrates or propagates, resulting in the equilibrium contact angle (Wei *et al*. 2012). When this angle lies at $\theta = 0°$, the liquid acts as a film, fully wetting the surface; at $\theta < 90°$, the wetting of the surface is preferred; and at $\theta > 90°$, the wetting is not preferred and the liquid remains as a droplet upon the surface (Agrawal *et al*. 2017. Siebra *et al*. 2020, Yuan and Lee 2013).

The surface properties of wood such as morphology, roughness, specific area, permeability, and chemical composition can influence the thermodynamics of the material and, consequently, the wettability (Santos and Garcia 2019, Tshabalala 2005). A phenomenon linked to the wettability of wood and its aforementioned properties is surface inactivation caused by overdrying. Overdrying leads to exudation of extractives to the surface, reorientation of wood surface molecules, and closure of large micropores in cell walls, leading to oxidation and loss of hydroxyl sites (Christiansen 1990, 1991). On the other hand, the exposure of wood to the environment without any surface modification processes, such as weathering agents, also causes surface inactivation, as found for the wettability of Norway spruce (*Picea abies*) wood (Nussbaum 1996).

In 1804, Young developed a method to measure the contact angle to investigate the surface roughness of materials. Such methodology uses the angle between the liquid-air interface and the solid surface (Xu 2016). The determination of the static contact angle, linked to the interfacial surface tensions between solid-air, solid-liquid, and liquid-air, is given by Young's Equation (Mantanis and Young 1997, Xu 2016, Young 1804).

According to the previous statement, new theories have emerged, such as Wenzel's and Cassie–Baxter's. Wenzel was one of the first authors to study the relationship between contact angle and roughness through the liquid-solid interface area (Sinderski 2020). According to Wenzel, rough surfaces tend to increase wettability, meaning that the rougher the surface of a material is, the more wettable the material tends to be (Wenzel 1936). Therefore, rougher surfaces tend to be more hydrophilic. In Wenzel’s equation, the contact angle is measured as the product of the roughness ratio (ratio of the area of a rough or real surface to the area of a surface considered flat or geometric) and the cosine of Young's contact angle (Sarkar and Kietzig 2013, Wenzel 1936, Xu 2016). According to the Cassie and Baxter equation, rough surfaces tend to form air pockets between the grooves of materials (Cassie and Baxter 1944, Sacilotto and Ferreira 2016), resulting in hydrophobicity and a larger contact angle. The apparent contact angle is expressed as a function of Young's contact angle and the solid fraction, which is the fraction of the solid surface encompassed by the liquid (Sarkar and Kietzig 2013).

Therefore, it is important to investigate wettability considering the interaction between species, their intrinsic properties, and the way wood is manufactured. The methodology applied to measure wettability parameters can help to adapt the surface treatment/coating.

In this context, this study seeks to assess the influence of sanding on the surface quality of wood samples of imbuia (*Ocotea* spp.), red oak (*Quercus* spp.), and pine (*Pinus elliottii*) by determining the wettability parameters via the sessile drop method, using distilled water as the liquid medium.

MATERIALS AND METHODS

Material

The wood veneers used were from imbuia (*Ocotea* spp.), red oak (*Quercus* spp.), and pine (*Pinus elliottii*) woods. These samples were tangentially cut as veneers (0,060 m x 0,013 m) and placed in a climate chamber at 20 °C and 65 % relative humidity until they reached equilibrium moisture content for the analysis of wettability variables. We estimated bulk density at 12 % RH as 630 kg/m³ ± 0,06 kg/m³ for Imbuia, 554 kg/m³ ± 0,03 kg/m³ for Red Oak, and 508 kg/m³ ± 0,08 kg/m³ for Pine.

Surface wettability

The surface wettability of the wood veneers was determined on a Kruss DSA25 digital goniometer using the sessile drop method. This method consisted of depositing 5 µL distilled water droplets on the surface of the wood veneers. The kinetics of droplet behavior was investigated 5 s, 10 s, and 15 s after they were deposited on the surface of the veneers. The wettability parameters measured were Contact Angle (CA) and Work of Adhesion (WoA). We determined the wettability parameters of the raw and sanded veneers for each of the three species. We sanded the veneers with a 220-grit sandpaper.

Extractive content

We analyzed this parameter in cold and hot water using the T 207 cm-08 (TAPPI 2008) standard, and in ethanol-toluene using the T 204 cm-17 (TAPPI 2017) standard. We determined the extractive content in triplicate for each species.

Data analysis

Initially, the variance was assessed for homogeneity through Bartlett's test. Subsequently, we performed an Analysis of Variance (ANOVA) in the Completely Randomized Design (CRD) followed by Tukey's Range Test at a 5 % probability of error. This was applied considering the combined and individual analysis between species and sanding as treatments.

RESULTS AND DISCUSSION

Isolated species and sanding analysis and wettability variables

Considering the analysis of the treatments according to their variables, 5 s after the release of the droplet on the surface of the wood substrates, the species (Table 1) were not significant for the CA variable by Tukey's test (p ≥ 0,05) when comparing imbuia and red oak, and imbuia and pine. The WoA also was not significant, as shown by the results for the three species studied.

Table 1: Assessment of wettability parameters for each species.

Species	CA (°)	WoA (mN/m)
Imbuia	57,43 ab (± 11,14)	110,24 a (± 11,97)
Red Oak	63,27 a (± 13,29)	103,90 a (± 15,49)
Pine	46,53 b (± 26,29)	117,56 a (± 25,58)

CA: Contact angle; WoA: Work of adhesion. Variables measured in 5 s. Means followed by the same letter vertically do not differ statistically by Tukey's Test at 5 % probability of error.

The results shown in Table 1 reflect how the intrinsic properties of each species may influence the behaviors of the variables (Amorim *et al.* 2013, Gardner *et al.* 1991, Pereira *et al.* 2017, Piao *et al.* 2010, Santos and Garcia 2019, Tshabalala 2005).

Furthermore, the effects of sanding for each species resulted in a significant change in most of the wettability variables (p < 0,05), as shown in Table 2. We observed a decrease of around 25 % in CA, and an increase of around 18 % in WoA.

Table 2: Assessment of wettability variables as a result of sanding.

Treatment	CA (°)		WoA (mN/m)	
Without sanding	67,48 a (± 18 ,58)	25,10 % ↓	98,48 b (± 21,16)	18,11 % ↑
With sanding	50,54 b (± 14,77)		116,32 a (± 12,60)	

CA: Contact angle; WoA: Work of adhesion. ↓: Percentage Reduction; ↑: Percentage Increase. Variables measured in 5 s. Means followed by the same letter vertically do not differ statistically by Tukey's Test at 5 % probability of error.

Rougher surfaces possess better moistening properties due to the behavior of the surface energies of solid and liquid interfaces. The wet area under the droplet has a low surface energy when compared to the solid interface on rough surfaces (Wenzel 1936). This favors a better spreading of the droplet on the substrate surface. Sinderski associates Wenzel’s idea of interface energy behavior to the sanding process, which according to him, modifies the surface energy properties, thus changing the contact angle (Sinderski 2020).

Surface inactivation is another factor that influences the wettability of wood (Cademartori *et al.* 2016). Wood components are bound together by molecular forces and wood binding sites become open and unstable when subjected to weather immediately after machining. These sites are subsequently taken over by contaminants and/or dust and become less viable for certain adhesives because of the resulting surface inactivation (Aydin and Demirkir 2010, Forbes 1998).

Sanding is a treatment that removes this inactive layer and improves surface properties. In a previous study, Jankowska and coauthors found that European oak (*Quercus robur*) did not require additional treatments prior to finishing. Though the found wettability was more significant with the sawing and flat slicing operations, sanding made the wood surface smoother, which favored the exposure of its hydrophilic sites (hydroxyl groups). Consequently, the contact angle for water decreased and the wettability increased. (Jankowska *et al.* 2018)

The sanding treatment applied to each species amplified the surface energy and favored the exposure of hydroxyl sites on the surface of the materials, which increased their wettability rate.

Therefore, we observed that the properties inherent to wood and the effect of sanding significantly influenced surface wettability. Thus, the best way to more accurately understand the influence of each of the effects is through the interaction between them.

The relationship between wood species and sanding treatments and their effect on wettability variables

The mean comparison of the variables added to the low percentages of reduction in CA and of increase in WoA, showed that the behavior of the droplet on the substrate surface after sanding was not significant ($p \geq 0,05$) for imbuia wood. Table 3 shows the behavior of the wettability variables for 5 s. We observed the opposite behavior for red oak and pine woods. In terms of percentage, pine wood presented the greatest change in absolute values of the wettability parameters.

Table 3: Assessment of the wettability variables within 5 seconds as a combination of species and sanding.

Species and treatment	CA (°)		WoA (mN/m)	
Imbuia without sanding	61,04 a (± 10,86)	10,13 % ↓	106,46 a (± 11,84)	6,08 % ↑
Imbuia with sanding	54,86 a (± 10,98)		112,93 a (± 11,73)	
Red Oak without sanding	77,62 a (± 15,00)	26,41 % ↓	87,26 b (± 18,39)	27,24 % ↑
Red Oak with sanding	57,12 b (± 5,99)		111,03 a (± 6,19)	
Pine without sanding	68,20 a (± 30,35)	46,23 % ↓	96,01 b (± 33,85)	32,65 % ↑
Pine with sanding	36,67 b (± 18,08)		127,35 a (± 13,63)	

CA: Contact angle; WoA: Work of adhesion. ↓: Percentage Reduction; ↑: Percentage Increase. Variables measured in 5 s. Means followed by the same letter vertically do not differ statistically by Tukey's Test at 5 % probability of error.

Papp and Csiha studied 4 wood species, Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), Silver birch (*Bétula pendula*), and Sessile oak (*Quercus petraea*). These woods were submitted to the same sanding process with 13 types of grit size. The authors found that Norway spruce and Sessile oak showed a higher contact angle due to high extractive content when compared to Silver birch and European beech, which showed a low contact angle (Papp and Csiha 2017).

Based on these results, we determined the extractive content of the species through extraction conducted in cold water, hot water, and ethanol-toluene. As described in Table 4, Imbuia wood showed higher extractive content values in cold water (9 %), hot water (20 %), and ethanol-toluene (9 %), unlike what we observed for red oak (around 4 %, 14 %, and 6 %) and pine (around 4 %, 13 %, and 5 %).

Table 4: Average values of extractives' content in cold water, hot water and ethanol-toluene.

Species	Extractive content in cold water (%)	Extractive content in hot water (%)	Extractive content in ethanol-toluene (%)
Imbuia	8,73 (± 0,0009)	19,96 (± 0,0042)	9,08 (± 0,0191)
Red Oak	4,18 (± 0,0018)	14,02 (± 0,0072)	6,78 (± 0,0104)
Pine	3,51 (± 0,0022)	13,11 (± 0,0032)	4,67 (± 0,0082)

As we analyzed the results (Table 4), we observed differences in the content of extractive materials since different species have different quantities of extractives. Another factor that may influence the results is that each solvent has a certain selectivity. For example, cold water extracts inorganic components, tannins, sugars, gums, and dyes; hot water extracts the components mentioned above and starch; and the ethanol: toluene mixture (1 : 2 v/v) extracts waxes, fats, resins, phytosterols, sterols, polyphenols, non-volatile hydrocarbons, low molecular weight carbohydrates, salts, and other water-soluble substances (TAPPI 2008; 2017; Wastowski 2018). Therefore, due to the nature of these chemical compounds, water has a higher hydrophilic favorability, and ethanol-toluene a higher favorability for hydrophilic and lipophilic components.

Sanding removes the inactive layer present on the wood surface that forms due to various phenomena such as surface oxidation and contamination, and migration of extractives (Aydin and Demirkir 2010, Christiansen 1991). This inactive layer modifies the energy properties of the surface (Sinderski 2020) and influences the effects of wettability. However, when analyzing the extractive content in cold water, hot water, and ethanol-toluene, imbuia wood showed a higher percentage of extractives than red oak and pine. That is, even after sanding and removing the inactive surface layer, the extractive content of Imbuia wood was higher than the other species. Consequently, due to the low percentage of the wettability variables (CA and WoA), the degree of repellency was higher for Imbuia rather than for Red Oak and Pine (Table 3).

Therefore, the high content of extractives does not necessarily mean that the material has high hydrophobicity since these compounds have particular chemical properties. These chemical compounds are present in the cell wall and consist mainly of fats, fatty acids, phenols, terpenes, steroids, resin acids, rosin, waxes, and other minor organic compounds. Such types of extractives may have different levels of polarity that influence wettability properties (Rowell *et al.* 2005). In a study with Alder (*Subcordate alnus*) and Ironwood (*Zelkova carpinifolia*), Ghofrani and coauthors found that wood whose extractive materials were removed with ethanol and hot water had an increased surface wettability compared to wood whose extractives were not removed (Ghofrani *et al.* 2016).

Compared to red oak, pine wood has better droplet adsorption and spreading because of the effects of machining shown in Table 3. This is due to the reduction of the contact angle and the increase of the work of adhesion. Thus, we assume that the removal of the inactive layer by sanding and the low extractive content may have affected the hydrophilicity of the pine. However, as mentioned before, we cannot state whether the quantity of extractives favors wettability or not due to their chemical nature.

Although sanding modifies the wettability properties of wood, this treatment was not a significant factor for Imbuia, probably due to its high extractive content compared to those of other species.

The relationship between wood species and sanding and their effect on dynamic wettability variables

Considering the dynamic behavior of the droplet, we evaluated the wettability variables for periods of up to 15 s (Figures 1 and 2). When comparing the process of the treatments applied to each species, sanding, and the dynamic behavior of the droplet, we found that sanding changes the surface properties of the woods studied, as discussed in section 3.1. These changes occur throughout the 5 s, 10 s, and 15 s intervals. However, the changes in the wettability variables were more significant for red oak and pine (Figure 1).

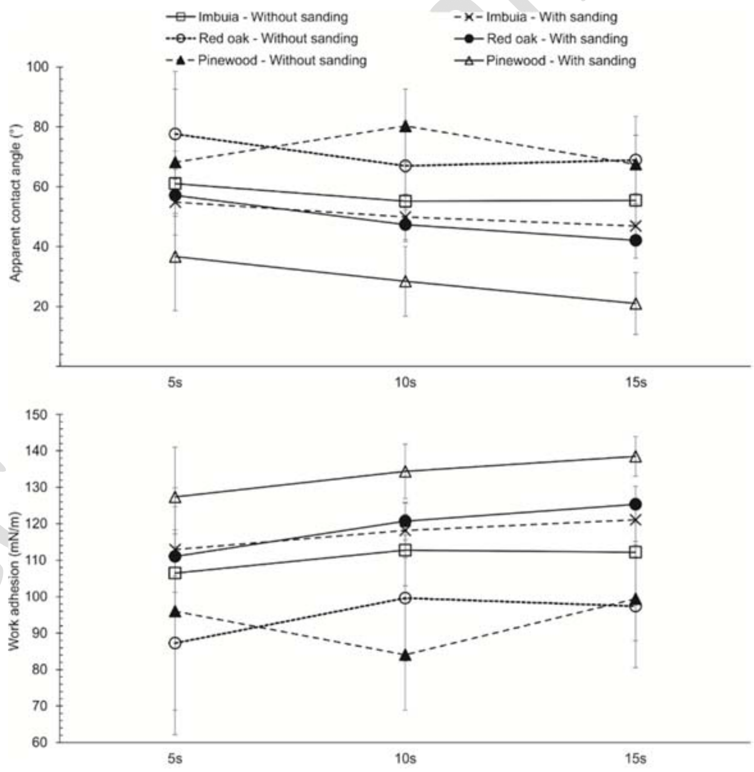

Figure 1: Kinetics of the contact angle and work of adhesion of the treated woods according to time after droplet deposition.

Considering the dynamic behavior of the droplet over 15 s, we observed that droplets on the surface of red oak and pine woods tend to spread along the fibers and be adsorbed.

This effect is evidenced by the approximate increase in WoA (13 % and 9 %), which inversely contribute to a decrease in CA (26 % and 43 %).

As evidenced previously, sanding significantly changes the wettability variables measured for each time interval and the dynamic behavior in the materials analyzed, especially red oak and pine. Therefore, we observed that the removal of the surface inactivation layer changed the surface energy of the wood of the species subjected to sanding and exposed hydroxyl sites. Consequently, red oak and pine showed a higher tendency to hydrophilicity.

However, sanding did not have a major effect on imbuia, which showed a reduction of 15 % in CA and an increase of 7 % in WoA. This difference can be explained by the higher extractive content of imbuia compared to those of other species. Therefore, as discussed previously, imbuia showed a higher degree of repellency to water on its surface.

CONCLUSIONS

Sanding changed the surface quality of the samples by decreasing CA and increasing WoA. In addition, regarding the dynamic behavior of the droplet over 15 s, we observed droplet spreading and adsorption on the surface of the woods. Therefore, sanding made the surface of wood veneers more wettable. Imbuia wood, however, showed less significant results after sanding compared to red oak and pine. The low interference of machining on imbuia wood may have occurred because of the high extractive content and resulted in a higher hydrophobicity on the wood surface.

AUTHORSHIP CONTRIBUTIONS

L. A. C.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing-Original draft, Writing - Review & Editing, Visualization, Project administration; B. D. M**.** Data Curation; M. E. B. C.: Writing - Review & Editing; A. L. M.: Writing - Review & Editing; U. K.: Writing - Review & Editing; P. H. G. D. C.: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration.

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