

Surface Characteristics of Selected Wood Species after Treatment with Tannin and Ammonia Vapor

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GRAPHICAL ABSTRACT



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Effects of ammonia vapor and tannin treatments were studied relative to the properties of wood. The color change, surface roughness, and surface hydrophobicity of Persian oak (*Quercus persica*), Persian walnut (*Juglans regia* L.), Oriental beech (*Fagus orientalis* Lipsky), and Siberian pine (*Pinus sibirica*) were evaluated after treatments for 8 and 24 h. The color difference (ΔE^*) values increased with prolonged exposure, with the highest changes observed in tannin-treated samples exposed to ammonia vapor for 24 h. Pronounced color changes were observed in Siberian pine samples, while beech and oak showed moderate color shifts. Walnut exhibited a more complex response, with an initial increase in yellowness followed by stabilization. Surface roughness measurements demonstrated a significant increase, particularly in maximum height (R_z), indicating substantial modifications to the wood surface. The most significant increase in roughness was observed in the samples treated with ammonia vapor and tannin after 24 hours of exposure, regardless of species type, although oak and walnut showed more controlled alterations. The surface hydrophobicity of the samples was increased after treatment, with the highest contact angle values after treatment for 24 h. This study highlights the potential of tannin and ammonia vapor treatments for improving the aesthetical and surface properties of wood.

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Keywords: Ammonia vapor treatment; Tannin; Wood color; Surface roughness; Contact angle

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INTRODUCTION

Wood has been subject to various finishing treatments for surface protection, improving its aesthetic properties, and providing an attractive appearance. Traditional wood finishing methods include the application of stains, varnishes, oils, and waxes, for enhancing the attraction of natural color of wood and its grains while offering some level of surface protection (Petric 2024). However, these methods often face limitations, such as susceptibility to wear, reduced durability under environmental exposure, and a tendency to fade or discolor over time (Teacă *et al.* 2019). Ammonia vapor treatment is another traditional approach to darken the color of the wood, and makes it more attractive for the furniture industry (Allen 1984; Kropat *et al.* 2020).

Unlike other chemical or water-based systems, ammonia vapor has the major advantage of not affecting the grain patterns and easily evaporating from the wood surfaces (Allen 1984). Weigl *et al.* (2009) treated 38 different wood species with ammonia and found a considerable color change in the black locusts, and minor changes in the black walnut. Miklečić *et al.* (2012a,b) reported that oak (*Quercus robur* L.) underwent a more rapid and pronounced initial color change following ammonia vapor treatment compared to other species such as maple, larch, and spruce. This accelerated color transformation is attributed to the high tannin content in oak, which reacts strongly with ammonia. However, despite these initial changes, the long-term color stability of ammonia-treated oak improved significantly after 16 and 32 days of exposure to ultraviolet (UV) light, as the chemical interactions between ammonia and tannins enhanced resistance to UV-induced discoloration. The fumigation of *Betula alnoides* with ammonia resulted in an obvious color change and also decreased surface wettability (Zeng *et al.* 2022). It is generally believed that ammonia vapor reacts with the natural compounds of wood, such as tannins, and darkens its color (Miklečić *et al.* 2012a, b; Stachowiak-Wencek *et al.* 2020; Zeng *et al.* 2022). However, this may not be the case for all wood species, like the ones with low tannin contents.

Tannins, which are polyphenolic compounds, play a significant role in influencing the surface and optical properties of wood (Missio *et al.* 2020). In plants, galls are abnormal growths that develop in response to environmental factors, fungi, or insects, with the compositions of mainly tannins and other polyphenolic compounds (Mehdi Karami *et al.* 2019). The gall mazouj is commonly found on oak species (*Quercus* spp.) and is caused by interactions with cynipid wasps (*Andricus* spp.). Both existing tannin types, such as hydrolyzable and condensed tannins, protect wood surfaces from photodegradation and discoloration by forming complexes with wood components and absorbing UV. However, their effects differ based on their chemical structure. Hydrolyzable tannins, which break down into simpler phenolic compounds, are more reactive and can form UV-absorbing chromophores, reducing the degradation of wood pigments (Pizzi 2019). Conversely, condensed tannins are more resistant to hydrolysis and contribute to surface durability, making wood less prone to oxidation and long-term discoloration (Missio *et al.* 2020). Mazouj galls that are found in the oak forests in western Iran, mainly comprise condensed tannins and proanthocyanidins (Mehdi Karami *et al.* 2019). Tannins can react chemically with treatment chemicals, further modifying the wood texture and visual characteristics by intensifying its natural hues and improving color stability (Tondi *et al.* 2013; Zeng *et al.* 2022). Although tannins are known to influence the optical and surface properties of wood, the effect of artificially increasing tannin concentrations on these properties remains underexplored. Therefore, this study aimed to investigate the effect of tannin and ammonia vapor treatments modification on the color, surface roughness, and wettability of wood species with varying natural tannin contents. By selecting Oriental beech (*Fagus orientalis* Lipsky) and Siberian pine (*Pinus sibirica*) as low tannin-containing species, walnut (*Juglans regia* L.) as a moderate tannin-containing species, and oak (*Quercus persica*) as a high tannin-containing species, this research sought to determine whether tannin enhancement improves surface quality and aesthetic properties across different wood types. The findings are expected to provide insights into the potential of tannin and ammonia treatments as natural wood surface modifiers for improving properties and aesthetical appearance in furniture and decorative applications.

EXPERIMENTAL

Materials

Persian oak (*Quercus persica*), Persian walnut (*Juglans regia* L.), Oriental beech (*Fagus orientalis* Lipsky), and Siberian pine (*Pinus sibirica*) wood samples, measuring $10 \times 5 \times 1$ cm³, were used. The beech and pine samples were obtained from a local sawmill in the northern forest region of Iran, while the walnut and oak samples were sourced from oak forests in the western part of Iran. All samples were selected from clear sections of the boards, free of knots and visible defects. The species were chosen based on their tannin contents. According to Bernabé-Santiago *et al.* (2013) and Shubkin *et al.* (2021), the respective tannin contents in walnut and oak are 2.5% and 9.4%, while pine and beech represented the low tannin content species with a range from about 0.02% in beech to about 0.12% in pine (Scalbert 1992). The mazouj galls were collected from an oak forest in the Khoram Abad city, located in western Iran. The tannin extraction in water was carried out by milling mazouj galls to a fine powder passing the 32-mesh sieve. Then 80 g of the oven-dried (103 °C for 24h) powder was mixed in a volumetric flask with 1000 mL of distilled water at room temperature for 24 h. The extracted tannin was then collected by removal of the impurities using filter paper.

Surface Treatments

The samples were initially surface treated with manual application of extracted tannin solution using surface brushing and then dried at 24 °C for 24 h. Then, ammonia treatments were carried out in a $100 \times 100 \times 90$ cm³ chamber by exposing the samples to 400 ml of ammonium hydroxide (25% concentration) for 8 h and 24 h at 20 °C. Three replicates were prepared per treatment condition. The samples from each wood species were labeled as control, ammonia vapor-treated for 8 h (A8), ammonia vapor-treated for 24 h (A24), tannin- and ammonia-treated for 8 h (TA8), and tannin- and ammonia-treated for 24 h (TA24). The samples were then conditioned at 20 °C and 65% relative humidity following DIN 50014:2018 standard for two weeks before any further measurements.

Color Changes

Color changes were determined according to the ASTM D2244–16 (2016) using the CIELab system to analyze color variations in wood samples treated with ammonia vapor and tannin. Measurements were conducted with a 3NH NR110 colorimeter, performing five readings per control and treated samples. The transverse orientation was utilized to assess the color changes observed in each sample. The sensor head diameter was 4 mm, and measurements were taken under D65 illuminant conditions. In the CIELab color system, L^* represents lightness, a^* represents chroma from green to red, and b^* represents chroma from blue to yellow. These values were used to calculate differences (ΔL^* , Δa^* , and Δb^*) and the total color difference (ΔE^*) between treated and control wood samples. The average degree of color change following three replicates was calculated using Eq. 1 (Ghavidel *et al.* 2021),

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where ΔE^* is the overall color change and ΔL^* , Δa^* and Δb^* are the differences in L^* , a^* and b^* coordinates, respectively.

Surface Roughness

A portable stylus profilometer, the Mitutoyo Surftest SJ-201, was employed for surface roughness analysis. The device consists of a main unit and a pick-up unit equipped with a skid-type diamond stylus featuring a 5 μm tip radius and 90° tip angle. The stylus runs at a constant speed of 0.5 mm/s on the surface for a sampling length of 8 mm. A linear displacement of the stylus in a direction perpendicular to the surface is then converted into an electrical signal by using a linear displacement transducer. The signals are amplified and then converted into digital form. Using the measurements in digital form, several parameters such as average roughness (R_a), mean peak-to-valley height (R_z), and root mean square roughness (R_q) were obtained. The samples were analyzed parallel to the longitudinal direction of the wood. The profilometer stylus traversed both earlywood and latewood to obtain representative surface roughness measurements across the grain structure. Three replicates of each wood sample with different treatments were measured, and the averages were calculated. The roughness measurement procedure followed ISO 4287 (1997), which defines roughness parameters and evaluation methods.

Contact Angle Analysis

The contact angle test followed the NF EN 828 (2013) method. Deionized water (5 microliters per droplet) was used for the tests, and measurements were taken immediately after dispensing. For each sample, contact angles at five randomly chosen points were measured on tangential sections of each block using a contact angle testing device equipped with a digital microscope camera (HD resolution: 1920×1080 pixels). Digimizer software was employed for accurate angle measurements, and the left and right contact angle data were averaged for each collection time. Each wood sample underwent measurement in five replicates across different treatments, with subsequent calculation of the average values.

Statistical Analysis

Statistical analyses were conducted using IBM SPSS version 26 (IBM Corporation, New York, USA). One-way analysis of variance (ANOVA) was employed at a significance level of 0.05, followed by Duncan's multiple-range test to assess significant differences among the samples.

RESULTS AND DISCUSSION

Color Changes

Different color indicators, such as L^* , a^* , b^* , ΔL^* , Δa^* , Δb^* , and ΔE^* were measured in the specimens as a function of surface treatments (Tables 1 and 2). The L^* parameter, indicating lightness, slightly decreased in all wood samples after treatment. Miklečić and co-workers (2012a) reported that the L^* parameter was the most significant factor influenced by ammonia vapor treatment in all examined wood species, including oak, maple, spruce, and larch. This resulted in a significant increase of the a^* parameter after treatments, which is associated with the chroma from green to red. The b^* parameter, corresponding to chroma from blue to yellow, was similar between A8 and A24 treated samples but significantly increased in TA8 and TA24 treated samples. The variations in color parameters (L^* , a^* , and b^*) observed in the treated wood samples might be due to the chemical modification of wood surfaces induced by the ammonia vapor and tannin treatments.

Table 1. Color Parameters in Treated Samples with Ammonia Vapor and Tannin after 8 and 24 Hours

Treatments	Pine			Beech			Walnut			Oak		
	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*
Control	82.24 (± 0.37)a	8.15 (± 0.08)a	22.19 (± 0.25)a	70.91 (± 0.9)a	9.48 (± 0.25)a	17.61 (± 0.5)a	59.14 (± 0.58)a	10.1 (± 0.34)a	17.71 (± 0.1)a	55.92 (± 0.98)a	10.56 (± 0.27)a	18.7 (± 0.49)a
A8	81.71 (± 0.21)a	8.42 (± 0.30)a	22.61 (± 0.5)a	70.07 (± 1.65)a	8.79 (± 0.23)a	16.63 (± 0.72)a	56.41 (± 0.91)a	9.37 (± 0.64)a	16.94 (± 0.96)a	53.99 (± 0.95)a	9.41 (± 0.08)a	18.55 (± 0.21)a
A24	79.49 (± 1.16)a	8.71 (± 1.16)a	23.34 (± 0.32)a	70.53 (± 0.61)a	9.02 (± 0.25)a	17.34 (± 0.24)a	54.75 (± 0.08)b	8.73 (± 0.13)b	15.14 (± 0.3)b	54.63 (± 1.51)a	9.21 (± 0.19)a	18.75 (± 0.12)a
TA8	62.72 (± 1.22)b	14.33 (± 0.02)b	28.98 (± 0.46)b	58.13 (± 1.35)b	13.24 (± 0.24)b	25.62 (± 0.16)b	49.72 (± 0.49)c	11.92 (± 0.21)c	22.28 (± 0.52)c	51.05 (± 0.65)b	11.04 (± 0.36)a	23.04 (± 0.81)b
TA24	61.94 (± 0.98)b	14.94 (± 0.51)b	29.82 (± 0.6)b	55.40 (± 0.48)b	13.28 (± 0.25)b	25.31 (± 0.47)b	46.68 (± 0.9)c	11.75 (± 0.24)c	22.01 (± 0.22)c	48.05 (± 0.43)b	10.81 (± 0.08)a	22.5 (± 0.27)b

Different letters in a column indicate significant differences between samples at $p < 0.05$ level.

Table 2. Color changes of treated wood samples with ammonia vapor and tannin after 8 and 24 Hours

Treatments	Pine				Beech				Walnut				Oak			
	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*	ΔE^*	ΔL^*	Δa^*	Δb^*	ΔE^*
A8	-0.53 (± 0.52)a	0.27 (± 0.37)a	0.41 (± 0.72)a	1.00 (± 0.67)a	-0.84 (± 0.77)a	-0.68 (± 0.42)a	-0.97 (± 0.89)a	1.62 (± 1.03)a	-2.72 (± 1.36)a	-0.72 (± 0.89)a	-0.77 (± 1.06)a	3.35 (± 1.03)a	-1.93 (± 0.13)a	-1.15 (± 0.18)a	-0.15 (± 0.51)a	2.31 (± 0.18)a
A24	-2.75 (± 1.05)b	0.56 (± 0.37)b	1.14 (± 0.45)b	3.08 (± 1.09)b	-0.38 (± 0.86)b	-0.45 (± 0.50)b	-0.27 (± 0.65)b	1.31 (± 0.33)a	-4.38 (± 0.52)b	-0.80 (± 1.29)a	-2.56 (± 0.36)b	5.29 (± 0.48)b	-2.29 (± 1.44)a	-1.35 (± 0.24)a	0.04 (± 0.55)b	3.01 (± 0.86)a
TA8	-19.52 (± 0.87)c	6.18 (± 0.11)c	6.78 (± 0.70)c	21.59 (± 0.56)c	-12.78 (± 1.88)c	3.76 (± 0.50)c	8.01 (± 0.38)c	15.62 (± 1.28)b	-9.41 (± 0.27)c	1.82 (± 0.48)b	4.57 (± 0.45)c	10.63 (± 0.45)c	-4.86 (± 1.30)b	0.48 (± 0.40)b	4.33 (± 0.81)c	6.63 (± 1.07)b
TA24	-20.30 (± 1.32)c	6.79 (± 0.60)c	7.62 (± 0.84)d	22.72 (± 1.64)d	-15.51 (± 1.37)d	3.80 (± 0.29)c	7.70 (± 0.47)c	17.76 (± 0.94)c	-12.45 (± 1.29)d	1.65 (± 0.38)b	4.30 (± 0.31)c	13.29 (± 1.22)d	-7.87 (± 0.55)c	0.25 (± 0.31)c	3.79 (± 0.62)c	8.74 (± 0.77)c

Different letters in a column indicate significant differences between samples at $p < 0.05$ level.

These treatments likely transformed the surface properties and composition of wood, thereby influencing how light was absorbed and reflected. The increase in a^* values indicates a shift towards reddish hues, likely resulting from chemical reactions that modify natural wood pigments or surface attributes. The fluctuations in b^* values, especially notable in TA8 and TA24 treated samples, may signify shifts towards more yellowish tones, potentially influenced by how tannin and ammonia interact with lignin and other wood components.

In pine wood, ΔE^* values were 1.0, 3.1, 21.6, and 22.7 after the treatments of A8, A24, TA8, and TA24. For beech, these values were 1.6, 1.3, 15.6, and 17.7, while for walnut, they were 3.3, 5.3, 10.6, and 13.3. Oak exhibited ΔE^* values of 2.3, 3.0, 6.6, and 8.7 for the same treatments. The overall trend showed an increase in ΔE^* with prolonged treatment times, likely due to the enhanced bonding of stabilizing compounds within the wood structure (Čermák and Dejmal 2013; Weigl *et al.* 2009). As presented in Table 2, ammonia vapor and tannin treatments resulted in significant color alterations, with pine exhibiting the most pronounced changes, characterized by a substantial decrease in ΔL^* and notable increases in Δa^* and Δb^* . This effect was especially evident in the TA24 treatment, which led to the highest overall color change (ΔE^*). Beech and oak also darkened visibly, with increased redness and yellowness, particularly in the TA treatments. Walnut displayed a more complex color response, with an initial increase in yellowness that slightly decreased with prolonged ammonia exposure. This complexity can be attributed to the chemical composition of walnut, which includes moderate levels of tannins, flavonoids, and other extractives that react differently with ammonia compared to high-tannin species like oak (Zeng *et al.* 2022). These observations align with the findings of Yaşar *et al.* (2024), who reported that tannin treatment intensified the red and yellow hues while significantly reducing lightness (L^*) in pine and walnut wood, resulting in a darker, richer appearance. The observed color transformations in ammonia- and tannin-treated wood can be explained by several chemical reactions occurring at the surface. Tannins can react with ammonia to form ammonium tannate complexes, which influence the oxidation state of tannins and modify the light absorbance and reflectance from the wood surface (Pizzi 2019). Ammonia also interacts with lignin, altering its color, while both ammonia and tannin contribute to oxidation reactions that impact the appearance of wood (Miklečić *et al.* 2012b). Simultaneously, ammonia vapor reacts with wood extractives, either modifying existing pigments or forming new color compounds, further influencing the final appearance of the treated wood (Miklečić *et al.* 2012b; Šprdlík *et al.* 2016). Figure 1 further supports this correlation, showing that longer exposure times (24 h) resulted in more pronounced color changes across all species. The decrease in L^* values confirms this darkening effect, consistent with previous findings indicating that tannin-based modifications enhance wood coloration while maintaining its natural grain (Yasar *et al.* 2024). The low tannin content in pine (Fig. 1a-e) makes it more responsive to ammonia treatment, as the absence of natural tannins allows for proportionally stronger chemical interactions with externally introduced tannins. This results in more pronounced color changes compared to species with naturally higher tannin levels. Conversely, walnut (Fig. 1k-o) and oak (Fig. 1p-t), with moderate and high natural tannin content, underwent more controlled color transformations, while beech (Fig. 1f-j), with low tannin content, exhibited intermediate changes. The application of tannin seems to regulate the surface reaction with ammonia in a more predictable way by intensifying the color change, particularly in species with initially low tannin levels, such as beech and pine.



Fig. 1. Visual evaluation of control and treated wood samples with ammonia vapor and tannin

Surface Roughness

The surface roughness of the wood samples after treatments is presented in Fig. 2. The roughness parameters include R_a (average roughness), R_z (maximum height of the roughness profile), and R_q (root mean square roughness), which provide insights into the surface texture alterations of wood samples subjected to various chemical treatments. In pine samples, the R_a and R_q values were slightly increased after treatments (Fig. 2a), while a more pronounced increase was observed in R_z with an average value of $30.05 (\pm 1.16)$. The R_z increased significantly with each treatment groups, especially TA24 in average value of $30.05 (\pm 1.16)$, indicating a substantial increase in the maximum height of the roughness profile. A similar pattern was detected in the beech, walnut and oak samples with a slight increase in R_a and R_q values and a substantial increase of R_z , particularly after TA24 treatment (Fig. 2b-d). Across all wood types, the maximum height of the roughness profile (R_z) was obtained after treatments involving both tannin and prolonged ammonia vapor exposure (TA24). This indicates that the combination of tannin and ammonia vapor had a pronounced effect on the surface of the wood. Pine exhibited the most notable increase in R_z after TA24 treatment, suggesting a rougher surface. Beech and oak showed moderate increases in R_a and R_q , but more significant increases in R_z , indicating that while the overall surface roughness increased, the peak-to-valley heights in the roughness profile were more affected. Oak displayed the highest increase in R_z by TA24 treatment, which

could be attributed to its unique chemical composition, such as extractives that react differently to the combined chemical treatments, resulting in a highly uneven surface texture (Laina *et al.* 2017; Thoma *et al.* 2015). Using aqueous solutions may naturally lead to grain raising and a rougher surface on wood. Specifically, when water is applied, wood fibers can swell and lift, resulting in a coarser texture (Landry *et al.* 2013). This phenomenon is primarily due to the hygroscopic nature of wood and the different swelling behaviors of earlywood and latewood (Luo *et al.* 2024). Following the drying process, the surface roughness may increase further as the swollen fibers can become fixed in a raised position. Moreover, ammonia treatment is known to elevate the equilibrium moisture content of wood (Onisko and Matejak 1971), which could intensify the grain-raising effect. The increased moisture content softens the wood fibers, rendering them more prone to deformation and raising during the drying process that follows. Ammonia treatment could lead to notable chemical and structural modifications on the wood surfaces. It alters the cellulose crystal structure, produces acetamide, and impacts ester linkages as well as side chains of hemicelluloses and syringyl lignin (Yamashita *et al.* 2018). During exposure to ammonia, carboxylate groups form ammonium salts, aldehydic, and ketonic groups generate imines, and ester groups convert into amides (Pawlak and Pawlak 1997).

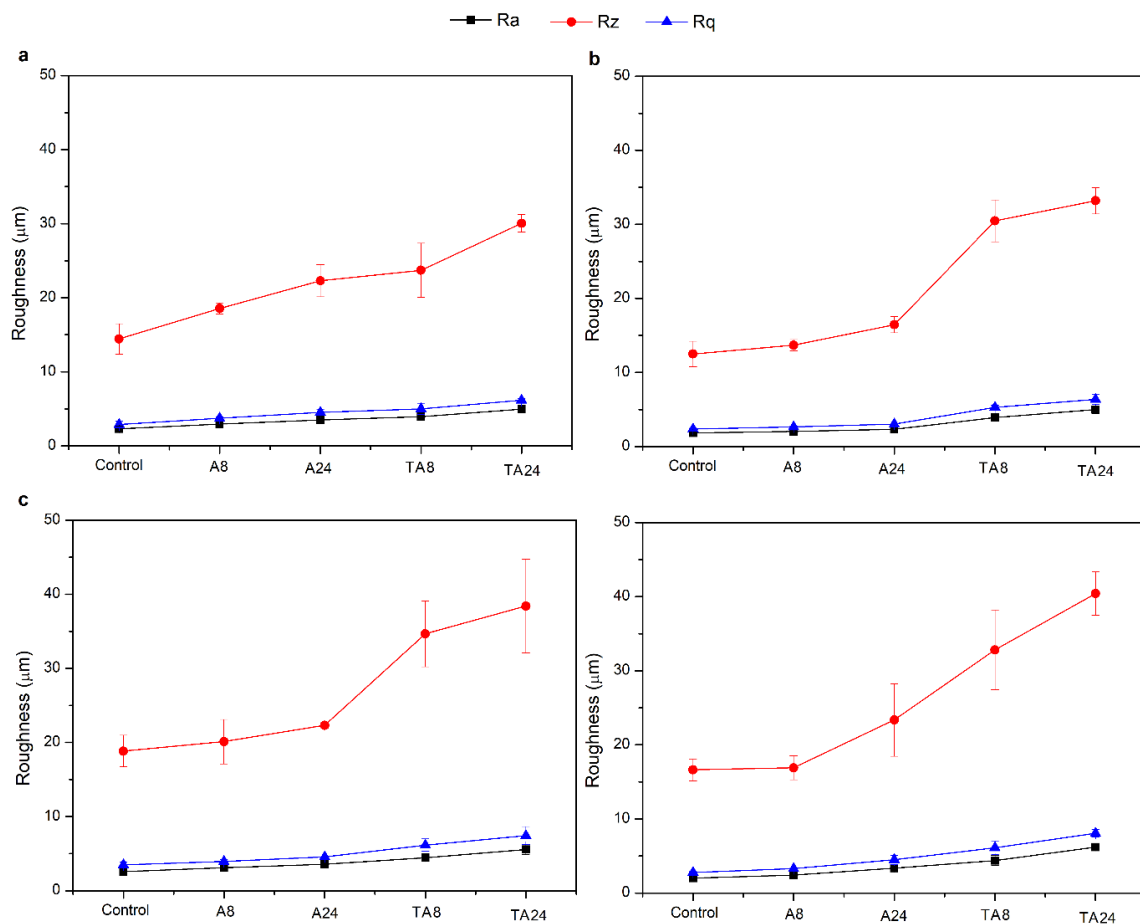


Fig. 2. Roughness measurements in control and treated samples of pine (a), beech (b), walnut (c) and oak (d)

Xylan degradation may also occur as a result of ammonia treatment, which could possibly lead to the migration of fractionated xylan to the inner surfaces of fiber cell walls (Yamashita *et al.* 2018), resulting in a more rough wood surface. Tannin-based treatments, on the other hand, can affect the fiber wall structure at micro and nano levels by plasticization of ray cells (Gurau *et al.* 2017). A similar finding was reported by Ozcifci *et al.* (2009), who treated spruce (*Picea orientalis*) and oak (*Quercus sessiliflora*) wood samples with a 25% ammonia solution. The authors claimed that the most significant increase in R_a occurred after ammonia treatment for both oak and spruce samples.

Contact Angle Analysis

In many wood applications, the interaction between wood and liquid is crucial, significantly affecting wood performance under various conditions (Moghaddam *et al.* 2016). The contact angle measurements of modified wood blocks were performed using the Easy Drop method to assess the wettability of the treated surfaces. Contact angle serves as an indicator of surface hydrophobicity, higher contact angle values correspond to lower wettability and increased hydrophobicity.

As shown in Fig. 3, almost identical contact angle values were obtained in all untreated samples, confirming their intrinsic hydrophilic nature. Treatment with ammonia vapor (AF8 and AF24) slightly increased surface hydrophobicity, while tannin-ammonia treatments (TA8 and TA24) resulted in the highest contact angle values.

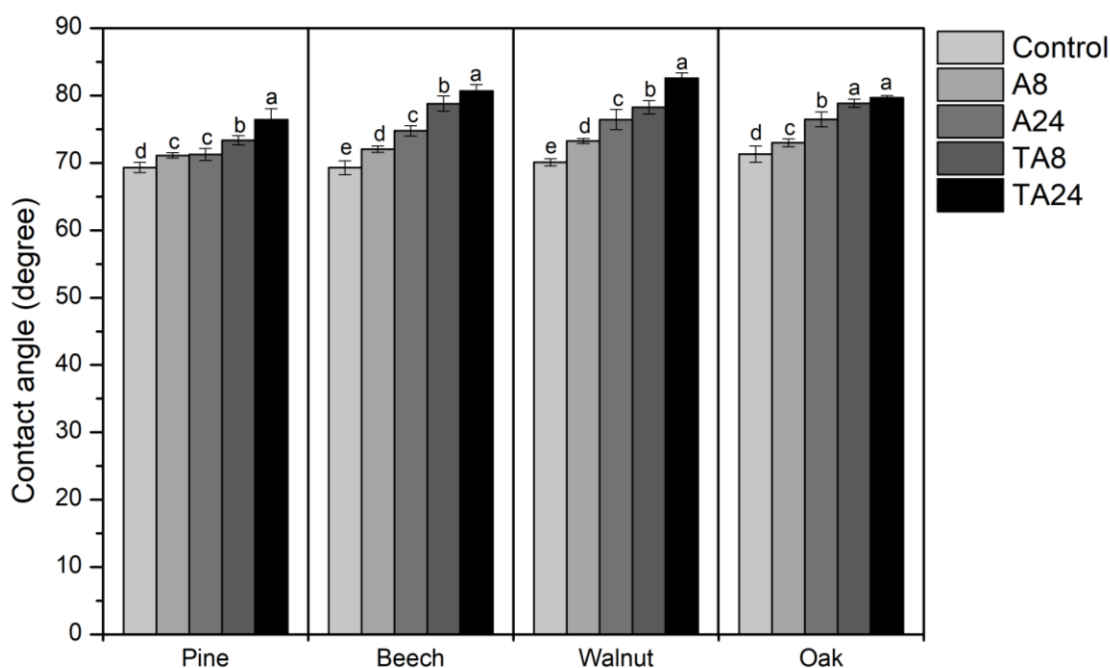


Fig. 3. The contact angle of water on control and treated wood with ammonia vapor and tannin. Different letters above the bars denote significant differences ($p < 0.05$). The statistical analysis was performed within the species and each treatment.

A similar trend was observed in all samples, with minor variations between species. Despite the observed increase in surface roughness (Fig. 2), all contact angle values remained below 90° , suggesting that the treated wood surfaces can still be classified as hydrophilic. This aligns with the Wenzel model (1936), which states that on hydrophilic

surfaces, an increase in roughness enhances water spreading, further reducing contact angle values. The combined effect of ammonia and tannin treatments likely induced chemical modifications in the wood surface, leading to a reduction in surface energy (Mariusz and Kowaluk, 2010). This suggests that while these treatments increase roughness, they do not introduce significant hydrophobicity, leaving the wood still susceptible to water. The increased hydrophobicity observed in TA-treated samples may be attributed to the formation of hydrophobic degradation products, resulting from chemical reactions between ammonia, tannins, and wood polymers. However, the overall hydrophilic nature of the treated wood, as indicated by contact angle values below 90°, suggests that while these modifications enhance water resistance, they do not render the surface hydrophobic.

These methods showed promise for applications in the furniture industry and other areas where robust and visually appealing wood products are needed. Future research should aim to optimize treatment parameters and assess the environmental impacts of these chemical methods to promote more sustainable wood enhancement practices.

CONCLUSIONS

1. The results of this study indicate that ammonia vapor and tannin treatments can significantly alter the optical and surface properties of various wood species.
2. Combining ammonia vapor with tannin was particularly effective for wood types with low natural tannin content, leading to notable color enhancements and better surface properties. These treatments not only darken the wood but also increase its redness and yellowness, giving it a more fashionable appearance.
3. The treatments enhanced surface roughness and hydrophobicity, suggesting improved durability and water resistance.

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