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INVESTIGATION OF SOME SURFACE CHANGES OCCURRING AFTER BLEACHING TREATMENT ON AYOUS (*Triplochiton scleroxylon* K. Schum) WOOD

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Citation

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Abstract

Oxalic acid ($C_2H_2O_4$), hydrogen peroxide (H_2O_2), and sodium hydroxide (NaOH) chemicals are widely used in the bleaching industry. This research examined alterations in color parameters, glossiness values, and the whiteness index (*WI**) values following the application of bleaching agents, namely $C_2H_2O_4$ and H_2O_2 + NaOH solutions, on ayous (*Triplochiton scleroxylon* K. Schum) wood. A control group was established to compare the treated surfaces. The results indicate that variance analyses revealed significant differences across all tests concerning the type of bleaching chemical used. The application of bleaching chemicals resulted in increases in *WI** values in both directions. The ΔE^* values were determined to be 2.21 when using the $C_2H_2O_4$ chemical and 12.01 with the H_2O_2 + NaOH chemicals. It was determined that glossiness values decreased in both directions at 60 and 85 degrees. In addition, increases were observed in L^* and h^o values, while decreases were obtained in C^* and a^* values. It was observed that the surface properties of ayous wood changed with the chemicals used in the study.

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INVESTIGATION OF SOME SURFACE CHANGES OCCURRING AFTER BLEACHING TREATMENT ON AYOUS (*Triplochiton Scleroxylon* K. Schum) WOOD

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1. Introduction

Wood finishing involves a combination of processes like sanding, scraping, and planning to achieve a smooth surface for subsequent treatments. Following surface preparation, a range of finishes is applied, including varnishes, lacquers, and paints. Adhesives of various types are employed for bonding wood pieces together. Varnishes and lacquers are utilized to impart a glossy surface to the wood. Anti-bacterial paints serve to safeguard wood against bacterial decay. UV stabilizers and protectants are utilized to shield wood from sunlight. Wastewater generated from wood coating activities typically originates from these processes and the cleaning of process equipment (Badve et al., 2013). Color is an attribute of visual interpretation that is defined by the spectral makeup of light that is reflected off surfaces (Sandoval-Torres et al. 2010). Brightness is commonly described as the quality accountable for the glossy or shiny aspect of a coating. Assessing brightness becomes pivotal in scenarios necessitating the aesthetic allure of a coated varnish (Khanna and Kumar, 2008). Whiteness encompasses more than just lightness, which is measured by CIE Y values or CIE L^* values. Lightness, hue, and colorfulness-determined by CIE a^* and b^* values in the CIELAB space-all play a role in the perception of whiteness (Luo et al., 2009).

Color lightening methods can be categorized into oxidation-based and reduction-based color lightening techniques. Bleaching should only be undertaken when absolutely essential, as it has the potential to detract from the inherent beauty and lively aesthetic of solid wood or wood veneers. Color fading refers to the depletion of natural pigments in wood due to the action of different oxidation and reduction substances (Kurtoğlu, 2000). The aesthetic appeal of wood is influenced by its hue, grain pattern, sheen, and the techniques used for bleaching, filling, staining, and applying clear coatings. Given the vast array of color combinations and tones present in wood, offering exhaustive descriptions of all color variations is impractical. Nonetheless, the sapwood of many species tends to be light-colored, with some approaching near-whiteness (Forest Products Laboratory, 2000). The bleaching process carried out to remove lignin provides nearly permanent whiteness but is expensive (Shmulsky and Jones, 2011).

In the literature, there are reports of bleaching treatments conducted on various wood species using different bleaching agents [balau red (*Shorea guiso*) (Peker et al., 2024), bulletwood (*Manilkara bidentata* (A.DC.) A. Chev.) (Peker et al., 2023a), movingui (*Distemonanthus benthamianus*) (Peker et al., 2023b), Japanese larch (*Larix kaempferi*) and Mongolian oak (*Quercus mongolica*) (Park et al., 2022), satinwood ceylon (*Chloroxylon swietenia* DC) (Ayata and Çamlıbel, 2023), bamboo (Nguyen et al., 2019), ilomba (*Pycnanthus angolensis* Exell) (Ayata and Bal, 2023), okoumé (*Aucoumea klaineana*) (Çamlıbel and Ayata, 2024a), birch (Yamamoto et al., 2017), canelo (*Drimys winteri* J.R. Forst. & G. Forst.) (Peker, 2023a), birch (Liu et al., 2015), oak, birch, Norway maple, European larch (Möttönen et al. 2003), olon (*Zanthoxylum heitzii*) (Peker and Ayata, 2023), lotofa (*Sterculia rhinopetala*) (Peker, 2023b), cocobolo (*Dalbergia retusa* Hemsl.,) (Çamlıbel and Ayata, 2024b), black locust (*Robinia pseudoacacia* L.) (Peker and Ulusoy, 2023), linden (*Tilia tomentosa* - Moench.) (Çamlıbel and Ayata, 2023a), basralocus (*Dicorynia guianensis* Amshoff) (Ayata and Bal, 2024), maritime pine (Mehats et al., 2021), ekop (*Tetraberlinia bifoliolata* Haum.) (Çamlıbel and Ayata, 2023b), birch (Mononen et al. 2005), and izombé (*Testulea gabonensis*) (Peker et al., 2023c).

It has been observed in the literature that ayous wood has not been bleached using $C_2H_2O_4$ and H_2O_2 + NaOH bleaching chemicals. To provide a brief overview of this wood species:

According to reports, ayous wood pulp has potential for producing paper of medium quality (Louppe et al. 2008). In the United Kingdom, "ayous (*Triplochiton scleroxylon* K. Schum)" timber finds application in pattern making, skirting, furniture, and shelf construction. It is capable of taking a fine polish and should be seasoned before use (Boulton and Price, 1931). Although ayous wood is lightweight, its strength values are notable owing to its density (Bosu and Krampah, 2005).

In ayous wood, the thermal conductivity value was determined as 0.14 W/m.K, lignin content was 32.40%, water extraction was 2.28%, cellulose content was 40.40%, pentosan content was 17.00%, silica content was 0.019%, ash content was 2.19%, and ethanol extraction was 1.99% (Gérard et al., 2019). Weight losses for *Poria placenta* were 42%, for *Irpex lacteus* were 56%, for *Gloeophyllum trabeum* were 24%, and for *Trametes versicolor* were 61% (Nzokou et al., 2003). Shore D hardness was 37.65 HD, air-dried density was 384 kg/m^3, and Janka hardness values were 21.01 N/mm^2, 17.87 N/mm^2, and 28.69 N/mm^2 in tangential, radial, and tangential directions, respectively. Nail holding resistance values were 4.69 N/mm^2, 4.39 N/mm^2, and 4.41 N/mm^2 in tangential, radial, and tangential directions, respectively (Ayata, 2020).

In this study, certain surface changes resulting from the bleaching of ayous wood were investigated. The aim of this study was to enable the emergence of a new situation in terms of the applications of ayous wood with the results obtained from this study.

2. Materials and Methods

2.1. Material

2.1.1. Wood Material

In this research, ayous (*Triplochiton scleroxylon* K. Schum) wood was employed as the primary material. The wood was obtained from a reliable commercial supplier to ensure top quality and had dimensions measuring 100 x 100 x 16 mm. In adherence to these selection criteria, the specimens were prepared according to the protocols outlined in ISO 554, (1976). Prior to the bleaching procedure, the test samples underwent sanding with grits 80, 120, and 180, followed by surface cleaning using compressed air.

2.1.2. Bleaching Chemicals

In the study, single-component [oxalic acid ($C_2H_2O_4$): liquid, colorless, odorless, pH value 2.0±0.5] and two-component [pH value 7, liquid, odorless, colorless, soluble, solvent water, hydrogen peroxide (H_2O_2): component A and sodium hydroxide (NaOH): component B, in a ratio of 2:1] chemicals were utilized.

2.2. Method

2.2.1. Application of Bleaching

The chemicals were applied to the wooden surfaces using a sponge with the brushing technique, as a single layer.

2.2.2 Determination of Glossiness Values, Color Parameters, and Whiteness Index (*WI**) Properties

Glossiness assessments were carried out using the ETB-0833 model gloss meter device at three different angles (20°, 60°, and 85°) in both perpendicular and parallel directions to the fibers, in accordance with ISO 2813 (1994) specifications. The Whiteness Meter BDY-1 device was utilized to determine the whiteness index (*WI**) values in both parallel and perpendicular directions to the fibers, following the ASTM E313-15e1 (2015) standard. The color alteration of samples was measured using a CS-10 (CHN Spec, China) device based on the CIELAB color system and ASTM D 2244-3 (2007) standard [CIE 10° standard observer; CIE D65 light source, illumination system: 8/d (8°/diffuse illumination)]. The evaluations of total color difference were determined according to DIN 5033 (1979) standards. [undetectable (<0.2), very weak (0.2 - 0.5), weak (0.5 - 1.5), distinct (1.5 - 3.0), very distinct (3.0 - 6.0), strong (6.0 - 12.0), and very strong (> 12.0)]. Explanations for Δ*C**, Δ*a**, Δ*b**, and Δ*L** are detailed in Table 1, based on Lange (1999) guidelines.

Table 1: The definitions of Δ*a**, Δ*C**, Δ*b**, and Δ*L** (Lange 1999)

Test	Positive Description	Negative Description
Δ*b**	More yellow than the reference	Bluer than the reference
Δ*L**	Lighter than the reference	Darker than the reference
Δ*a**	Redder than the reference	Greener than the reference
Δ*C**	Clearer, brighter than the reference	Duller, matte than the reference

The total color differences were determined using the formulas below.

$$\Delta a^* = [a^*_{bleached}] - [a^*_{control}] \quad (1)$$
$$\Delta L^* = [L^*_{bleached}] - [L^*_{control}] \quad (2)$$
$$\Delta b^* = [b^*_{bleached}] - [b^*_{control}] \quad (3)$$
$$\Delta E^* = [(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2]^{1/2} \quad (4)$$
$$C^* = [(a^*)^2 + (b^*)^2]^{1/2} \quad (5)$$
$$\Delta C^* = [C^*_{bleached}] - [C^*_{control}] \quad (6)$$
$$h^o = \arctan [b^*/a^*] \quad (7)$$
$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2} \quad (8)$$

2.2.3. Statistical Analysis

Statistical analysis was performed using statistical software, examining the measurement data from the study. This process included calculating identifying the maximum and minimum mean values, standard deviations, computing measurement values related to the mean, conducting variance analyses, establishing homogeneity groups, and determining percentage (%) change rates.

3. Results

Table 2 shows the recorded data for color parameters (a^*, b^*, C^*, h^o, and L^*).

Table 2: Measurement results for color parameters (a^*, b^*, C^*, h^o, and L^*)

Test	Bleaching Chemical Type	N	Mean	Change Ratio (%)	*HG*	Standard Deviation	Mini-mum	Maxi-mum	Coefficient of Variation
L^*	Control	10	64.65	-	C**	0.46	63.87	65.37	0.71
	$C_2H_2O_4$	10	66.69	↑3.16	B	0.63	66.01	67.69	0.94
	H_2O_2 + NaOH	10	75.43	↑16.67	A*	0.44	75.00	76.13	0.59
a^*	Control	10	7.73	-	A*	0.28	7.26	8.07	3.68
	$C_2H_2O_4$	10	7.02	↓9.18	B	0.26	6.69	7.51	3.71
	H_2O_2 + NaOH	10	3.44	↓55.50	C**	0.14	3.28	3.79	4.06
b^*	Control	10	24.03	-	B	0.32	23.36	24.34	1.33
	$C_2H_2O_4$	10	24.49	↑1.91	A*	0.54	23.92	25.57	2.20
	H_2O_2 + NaOH	10	20.98	↓12.69	C**	0.52	20.31	22.13	2.48
C^*	Control	10	25.35	-	A*	0.52	24.46	26.34	2.04
	$C_2H_2O_4$	10	25.27	↓0.32	A	0.79	23.68	26.57	3.13
	H_2O_2 + NaOH	10	21.25	↓16.17	B**	0.54	20.57	22.46	2.52
h^o	Control	10	72.16	-	C**	0.43	71.60	72.86	0.60
	$C_2H_2O_4$	10	74.01	↑2.56	B	0.46	73.04	74.41	0.62
	H_2O_2 + NaOH	10	80.68	↑11.81	A*	0.18	80.27	80.84	0.23
N: Number of Measurements, *HG*: Homogeneity Group, *: Lowest Value, **: Highest Value									

Table 3 presents the results for the total color differences (ΔE^*).

Table 3: Results for the total color differences

Bleaching Chemical Type	ΔL^*	Δa^*	Δb^*	ΔC^*	ΔH^*	ΔE^*	Color Change Criteria (DIN 5033, 1979)
$C_2H_2O_4$	2.04	-0.72	0.45	-0.07	0.84	2.21	Distinct (1.5 - 3.0)
H_2O_2 + NaOH	10.78	-4.29	-3.06	-4.09	3.31	12.01	Very Strong (> 12.0)

Table 4 outlines the measured glossiness values.

Table 4: Measurement results for glossiness values

Test	Bleaching Chemical Type	N	Mean	Change Ratio (%)	*HG*	Standard Deviation	Mini-mum	Maxi-mum	Coefficient of Variation
⊥20°	Control	10	0.40	-	B**	0.00	0.40	0.40	0.00
	$C_2H_2O_4$	10	0.41	↑2.50	B	0.09	0.30	0.50	21.36
	H_2O_2 + NaOH	10	0.50	↑25.00	A*	0.00	0.50	0.50	0.00
⊥60°	Control	10	1.86	-	A*	0.15	1.70	2.10	8.09
	$C_2H_2O_4$	10	1.28	↓31.18	C**	0.10	1.20	1.40	8.07
	H_2O_2 + NaOH	10	1.68	↓9.68	B	0.13	1.50	1.80	7.84
⊥85°	Control	10	0.45	-	A*	0.14	0.30	0.60	30.09
	$C_2H_2O_4$	10	0.10	↓77.78	B**	0.00	0.10	0.10	0.00
	H_2O_2 + NaOH	10	0.10	↓77.78	B**	0.00	0.10	0.10	0.00
∥20°	Control	10	0.40	-	B**	0.00	0.40	0.40	0.00
	$C_2H_2O_4$	10	0.40	0.00	B**	0.00	0.40	0.40	0.00
	H_2O_2 + NaOH	10	0.46	↑15.00	A*	0.05	0.40	0.50	11.23
∥60°	Control	10	2.17	-	A*	0.16	2.00	2.40	7.54
	$C_2H_2O_4$	10	1.76	↓18.89	B**	0.21	1.60	2.00	11.74
	H_2O_2 + NaOH	10	1.79	↓17.51	B	0.09	1.70	1.90	4.89
∥85°	Control	10	0.45	-	A*	0.14	0.30	0.60	30.09
	$C_2H_2O_4$	10	0.18	↓60.00	B	0.10	0.10	0.30	57.38
	H_2O_2 + NaOH	10	0.10	↓77.78	B**	0.00	0.10	0.10	0.00
N: Number of Measurements, *HG*: Homogeneity Group, *: Lowest Value, **: Highest Value									

Table 5 illustrates the obtained values for whiteness index (*WI**).

Table 5: Measurement results for whiteness index (*WI**) values

*WI** ⊥	Control	10	22.82	-	B**	0.47	22.50	23.70	2.05
	$C_2H_2O_4$	10	23.06	↑1.05	B	0.44	22.60	23.60	1.89
	H_2O_2 + NaOH	10	33.28	↑45.84	A*	0.45	32.80	33.80	1.35
*WI** ∥	Control	10	15.26	-	C**	0.38	14.90	16.20	2.51
	$C_2H_2O_4$	10	19.46	↑27.52	B	0.14	19.30	19.70	0.73
	H_2O_2 + NaOH	10	30.18	↑97.77	A*	0.15	29.90	30.30	0.51
N: Number of Measurements, *HG*: Homogeneity Group, *: Lowest Value, **: Highest Value									

The Table 6 presents the analysis of variance outcomes for color parameters (*a**, *b**, *C**, *h*°, and *L**), glossiness values, and whiteness index (*WI**) values.

Table 6: Analysis of variance results for color parameters (*a**, *b**, *C**, *h*°, and *L**), glossiness values, and whiteness index (*WI**) values

Bleaching Chemical Type					
Test	Sum of Squares	df	Mean Square	F Value	Sig.
*L**	655.814	2	327.907	1221.444	0.000*
*a**	105.582	2	52.791	941.013	0.000*
*b**	72.928	2	36.464	164.752	0.000*
*C**	109.728	2	54.864	139.420	0.000*
h°	401.300	2	200.650	1387.159	0.000*
⊥20° glossiness	0.061	2	0.030	11.870	0.000*
⊥60° glossiness	1.763	2	0.881	52.184	0.000*
⊥85° glossiness	0.817	2	0.408	66.818	0.000*
∥20° glossiness	0.024	2	0.012	13.500	0.000*
∥60° glossiness	1.045	2	0.522	20.321	0.000*
∥85° glossiness	0.673	2	0.336	34.793	0.000*
*WI** (⊥)	713.059	2	356.529	1751.509	0.000*
*WI** (∥)	1183.883	2	591.941	9270.543	0.000*
*: Significant					

4. Discussion

Increases of 3.16% with $C_2H_2O_4$ and 16.67% with H_2O_2 + NaOH were obtained in the L^* parameter. Samples treated with the H_2O_2 + NaOH solution exhibited the highest L^* value (75.43), while the control experiment samples showed the lowest value (64.65) (Table 2). In the literature, the bleaching process with $C_2H_2O_4$ and H_2O_2 + NaOH chemicals were reported to increase the L^* values in bulletwood (Peker et al., 2023a), movingui (Peker et al., 2023b), ilomba (Ayata and Bal, 2023), olon (Peker and Ayata, 2023), canelo (Peker, 2023a), lotofa (Peker, 2023b), and black locust (Peker and Ulusoy, 2023) woods.

The lowest result for the a^* parameter was found on samples treated with the H_2O_2 + NaOH solution (3.44), while the highest was obtained in the control experiment samples (7.73). Decreases of 9.18% with $C_2H_2O_4$ and 55.50% with H_2O_2 + NaOH were found in the a^* value (Table 2). In the literature, it has been reported that satinwood ceylon (Ayata and Çamlıbel, 2023), lotofa (Peker, 2023b), and black locust (Peker and Ulusoy, 2023) woods subjected to bleaching with $C_2H_2O_4$ and H_2O_2 + NaOH chemicals exhibited increases in the a^* parameters.

The lowest result for the b^* parameter was determined on samples treated with the H_2O_2 + NaOH solution (20.98), while the highest result was detected in samples treated with $C_2H_2O_4$ (24.49). In the b^* test, a decrease of 1.91% was observed with $C_2H_2O_4$, and an increase of 12.69% was found with H_2O_2 + NaOH (Table 2). The studies on bleaching revealed that the application of $C_2H_2O_4$ led to an enhancement in the color of satinwood ceylon (Ayata and Çamlıbel, 2023), ilomba (Ayata and Bal, 2023), olon (Peker and Ayata, 2023), lotofa (Peker, 2023b), black locust (Peker and Ulusoy, 2023), and linden (Çamlıbel and Ayata, 2023a) wood species. Conversely, the use of H_2O_2 + NaOH resulted in a decrease in color for the same wood species.

The samples treated with the H_2O_2 + NaOH solution exhibited the lowest result for the C^* parameter (21.25), whereas the highest result was observed in the control experiment samples (25.25). In terms of C^* value, decreases of 0.32% with $C_2H_2O_4$ and 16.17% with H_2O_2 + NaOH were recorded (Table 2). In studies conducted on bleaching, decreases in the C^* values were reported in satinwood ceylon (Ayata and Çamlıbel, 2023) and black locust (Peker and Ulusoy, 2023) woods treated with bleaching agents $C_2H_2O_4$ and H_2O_2 + NaOH.

The h^o parameter reached its peak value in samples treated with the H_2O_2 + NaOH solution (80.68), whereas the lowest value was recorded in the control experiment samples (72.16). An increase of 2.56% was noted with $C_2H_2O_4$, and 11.81% with H_2O_2 + NaOH in the h^o value (Table 2). In previous studies, it has been noted that the h^o values increased in satinwood ceylon (Ayata and Çamlıbel, 2023), movingui (Peker et al., 2023b), ilomba (Ayata and Bal, 2023), izombé (Peker et al., 2023c), ekop (Çamlıbel and Ayata, 2023b), canelo (Peker, 2023a), olon (Peker and Ayata, 2023), and lotofa (Peker, 2023b) woods treated with bleaching agents $C_2H_2O_4$ and H_2O_2 + NaOH.

After the application of both solutions, ΔL^* values (lighter than the reference) were obtained positively, while ΔC^* values (duller, matte than the reference) and Δa^* values (greener than the reference) were determined negatively. Additionally, Δb^* values were found to be positive with $C_2H_2O_4$ (more yellow than the reference) and negative with H_2O_2 + NaOH (bluer than the reference). The ΔE^* values were calculated to be 2.21 with the $C_2H_2O_4$ chemical and 12.01 with the H_2O_2 + NaOH chemicals. When examining the outcomes based on color alteration criteria, it becomes evident that while the $C_2H_2O_4$ chemical resulted in a distinct (1.5 - 3.0) criterion, the H_2O_2 + NaOH chemical yielded a much stronger effect, meeting the very strong (> 12.0) criterion (Table 3).

Glossiness measurements conducted at 60 and 85 degrees in both directions indicated decreases with both bleaching solutions. Likewise, the control experiment group samples yielded the highest results at these degrees and directions (Table 4).

In both perpendicular (⊥) and parallel (∥) directions, the control experimental group exhibited the lowest WI^* values (⊥: 22.82 and ∥: 15.26). Conversely, the samples treated with the H_2O_2 + NaOH chemical solution yielded the highest WI^* values (⊥: 33.28 and ∥: 30.18). The WI^* ⊥ values exhibited increases of 1.05% and 45.84% with the $C_2H_2O_4$ and H_2O_2 + NaOH chemicals, respectively, while the WI^* ∥ values showed increases of 27.52% and 97.77%, respectively (Table 5).

The analysis of variance indicated that the factor representing the number of categories had a significant influence on the test results, as shown in Table 6.

5. Conclusion

Variance analyses were found to be significant across all tests. The WI^* values showed increases in both directions with the bleaching chemicals. It was noted that glossiness values declined in both directions at 60 and 85 degrees. Furthermore, there were increases in h^o and L^* values, while decreases were noted in a^* and C^* values.

Disclosure Statement

No potential conflict of interest was reported by the authors.

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APPLICATIONS OF NATURAL AND SYNTHETIC WAX BLENDS ON WOOD SURFACES OF MAGNOLIA (*Magnolia grandiflora* L.)

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Abstract

In this study, researchers investigated how surface properties, such as whiteness index (WI*) values, color parameters [total color differences (ΔE*), lightness (L*), red (a*) color tone, yellow (b*) color tone, chroma (C*) value, and hue (ho) angle], and glossiness values, were affected by wax applications with different coating layers on magnolia (*Magnolia grandiflora* L.) wood. A control group was set up, and the outcomes from samples with varying counts of wax layers were contrasted. The variance analyses conducted for the number of rocks factor in all tests were found to be significant. The ΔE* values were found to be 3.02 for the 1-layer application, 3.67 for the 2-layer application, and 4.80 for the 3-layer application. It was observed that as the number of layers increased in color parameters, the values of ho and L* decreased, while b*, C*, and a* values increased. Additionally, decreases in WI* values were detected in both directions (⊥ and ∥). It was observed that the waxes used in the study had a modifying effect on the selected surface properties of magnolia wood.

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APPLICATIONS OF NATURAL AND SYNTHETIC WAX BLENDS ON WOOD SURFACES OF MAGNOLIA (*Magnolia grandiflora* L.)

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1. Introduction

Wax is commonly a blend of organic compounds, frequently comprising elongated molecules. These molecules encompass hydrocarbons, esters derived from fatty acids, elongated chain alcohols, and similar constituents. The precise chemical makeup of wax is largely contingent upon its source, be it animal, plant, or mineral in origin (Regert et al. 2005; Peris-Vicente et al. 2006). Waxes play a role in establishing a tough and long-lasting shield on surfaces. This shield not only offers resilience but also establishes a waterproof barrier, shielding the surface from a range of external factors. They find extensive applications across furniture, upholstery, and plastic goods. In the realm of art, waxes serve as a crucial tool for creating resist paintings. Artists apply them selectively to areas where exposure to acid is undesirable, effectively protecting those regions from the potential corrosive effects of acid (Hammond et al., 1969).

The Magnolia genus, belonging to the Magnoliaceae family, consists of about 90 species of trees or shrubs. These are mainly found in temperate and tropical regions, with distribution extending across countries such as India, Malaysia, Japan, and China (Anonymous, 1996). *Magnolia grandiflora* L., commonly known as the Southern magnolia tree, is a tree reaching heights of 5-20 meters, native to the southeastern states of the United States and Mexico (Vázquez, 1990). When newly cut, the wood displays a white coloration; however, upon exposure to air, it undergoes a transformation to a brown hue (Elias, 1980). This tree exhibits remarkable resistance to wind and is suitable for use in shelterbelt plantings (Huxley, 1992).

Wood has a restricted range of uses; however, it can be employed in crafting furniture, paneling, cladding, commodities, and cabinets (Brown and Kirman, 1990). The timber is utilized in small amounts for fuel, basketry, crate construction, wooden crafts, and furniture making (Vines, 1982; Sargent, 1965). While the wood is hard and relatively dense, it lacks significant flexibility and durability (Vines, 1982). Wood stands as one of the foremost renewable construction materials. It can be easily molded, demands minimal energy during processing, and exhibits exceptional structural characteristics (Scheffer and Cowling, 1966).

Magnolia wood had a fully dry density of 581.12 kg/m^3, tangential shrinkage of 6.16%, radial shrinkage of 4.66%, longitudinal shrinkage of 0.54%, volumetric shrinkage of 11.36%, fiber saturation point of 19.56%, moisture absorption after two weeks of 68.46%, bending strength of 85.56 N/mm^2, modulus of elasticity of 6375.66 N/mm^2, dynamic bending (shock) resistance of 0.378 kg/cm^2, tangential surface Janka hardness of 57.51 N/mm^2, radial surface Janka hardness of 49.50 N/mm^2, transverse surface Janka hardness of 62.73 N/mm^2 (Çavuş, 2019), and air-dry density of 647.00 kg/m^3, with screw holding capacity of 32.53 N/mm^2 on the radial surface, 38.40 N/mm^2 on the tangential surface, and 30.40 N/mm^2 on the transverse surface (Çavuş and Ayata, 2018).

In the literature, numerous studies have investigated the application of various wax treatments on wooden surfaces (Garai et al., 2005; Lesar et al., 2011; Avramidis et al., 2011; Wang et al., 2014; Yuqing et al., 2016; Humar et al., 2017; Akçay, 2020; Janesch et al., 2020; Yang et al., 2020; Niu and Song, 2021; Zhang et al., 2022; Arminger et al., 2022; Liu et al., 2022; Ning et al., 2022; Piao et al., 2022; Peker et al., 2024a, 2024b, 2024c). The changes in surface alterations between the applied wax and wooden material have been attempted to be explained using various tests in conducted studies. Nevertheless, there seems to be a notable gap in research concerning the surface alterations resulting from the application of different coating layers specifically on magnolia wood.

In this study, variations in surface properties resulting from wax applications with different coating layers were investigated on magnolia (*Magnolia grandiflora* L.) wood. The obtained results were believed to have made a significant contribution to the knowledge domain regarding both the researchers involved in the wax application study and the potential applications of this specific tree species.

2. Materials and Methods

2.1. Material

2.1.1. Wood Material

In this study, magnolia (*Magnolia grandiflora* L.) wood was utilized as the principal material. The wood was sourced from a reputable commercial supplier to ensure high quality and had dimensions of 100 x 200 x 15 mm. Following these selection criteria, the samples were prepared in accordance with the standards specified in ISO 554, (1976). Prior to bleaching, the test samples underwent sanding with grits 80, 120, and 180, followed by surface cleaning using compressed air.

2.1.2. Wax

In the research, a blend of natural and synthetic wax with oil (appearance: paste, odor: characteristic, color: neutral, solubility in water: dispersible but not soluble, dry residue: 30%, and pH value: 7.6) was employed.

2.2. Method

2.2.1. Application of Wax on Wooden Material Surfaces

In the study, oil with a mixture of natural and synthetic wax was applied to wooden material surfaces using a brush in 1, 2, and 3 layers.

2.2.2 Determination of Glossiness Values, Color Parameters, and Whiteness Index (*WI**) Properties

The use of Whiteness Meter BDY-1 device determined the whiteness index (*WI**) values in parallel and perpendicular directions to the fibers (ASTM E313-15e1, 2015). Glossiness tests were conducted using the ETB-0833 model gloss meter device at three different angles (20°, 60°, and 85°) in perpendicular and parallel directions to the fibers according to ISO 2813 (1994) standard. The color change of samples was measured using a CS-10 (CHN Spec, China) device based on the CIELAB color system and ASTM D 2244-3 (2007) standard [CIE 10° standard observer; CIE D65 light source, illumination system: 8/d (8°/diffuse illumination)]. The explanations for Δa*, ΔC*, Δb*, and ΔL* are outlined in Table 1 based on Lange (1999).

Table 1: The definitions of Δa*, ΔC*, Δb*, and ΔL* (Lange, 1999).

Test	Positive Description	Negative Description
Δb*	More yellow than the reference	More blue than the reference
ΔL*	Lighter than the reference	Darker than the reference
Δa*	Redder than the reference	Greener than the reference
ΔC*	Clearer, brighter than the reference	Duller, matte than the reference

Alternative criteria for comparing the visual assessment of the calculated ΔE* color difference are presented in Table 2 following DIN 5033, (DIN 1979) standards.

Table 2: Comparison criteria for ΔE* evaluation (DIN 5033 1979).

Visual	Total Color Difference
Undetectable	<0.2
Very Weak	0.2 - 0.5
Weak	0.5 - 1.5
Distinct	1.5 - 3.0
Very Distinct	3.0 - 6.0
Strong	6.0 - 12.0
Very Strong	> 12.0

The results of total color differences were determined using the following formulas.

$$\Delta a^* = [a^*_{\text{wax applied}}] - [a^*_{\text{control}}] \quad (1)$$

$$\Delta L^* = [L^*_{\text{wax applied}}] - [L^*_{\text{control}}] \quad (2)$$

$\Delta b^* = [b^*_{\text{wax applied}}] - [b^*_{\text{control}}]$ (3)
$\Delta E^* = [(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2]^{1/2}$ (4)
$C^* = [(a^*)^2 + (b^*)^2]^{1/2}$ (5)
$\Delta C^* = [C^*_{\text{wax applied}}] - [C^*_{\text{control}}]$ (6)
$h^o = \arctan [b^*/a^*]$ (7)
$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{1/2}$ (8)

2.2.3. Statistical Analysis

Statistical analysis was conducted utilizing a statistical software package and the study's measurement data. This involved computing standard deviations, determining maximum and minimum mean values, calculating measurement values associated with the mean, identifying homogeneity groups, conducting variance analyses, and determining percentage (%) change rates.

3. Results

The analysis of variance results for color parameters (a^*, b^*, C^*, h^o, and L^*) is provided in Table 3.

Table 3: Analysis of variance results for color parameters (a^*, b^*, C^*, h^o, and L^*)

Source	Test	Sum of Squares	df	Mean Square	F	Sig.
Number of Layer	L^*	53.376	3	17.792	12.078	0.000*
	a^*	5.553	3	1.851	43.418	0.000*
	b^*	69.555	3	23.185	60.099	0.000*
	C^*	73.946	3	24.649	61.155	0.000*
	h^o	7.686	3	2.562	15.753	0.000*
Error	L^*	53.032	36	1.473		
	a^*	1.535	36	0.043		
	b^*	13.888	36	0.386		
	C^*	14.510	36	0.403		
	h^o	5.855	36	0.163		
Total	L^*	203697.927	40			
	a^*	502.140	40			
	b^*	21337.849	40			
	C^*	21839.021	40			
	h^o	264669.499	40			
Corrected Total	L^*	106.408	39			
	a^*	7.087	39			
	b^*	83.444	39			
	C^*	88.456	39			
	h^o	13.541	39			

*: Significant

Table 4 presents the measurement results for color parameters (a^*, b^*, C^*, h^o and L^*).

Table 4: Measurement results for color parameters (a^*, b^*, C^*, h^o, and L^*)

Test	Wax Application	N	Mean	Change (%)	*HG*	*SS*	Minimum	Maximum	COV
L^*	Control	10	73.29	-	A*	1.18	71.34	75.19	1.61
	1-layer	10	70.99	↓3.14	B	1.42	67.93	72.32	2.00
	2-layers	10	70.82	↓3.37	B	1.19	68.82	71.83	1.68
	3-layers	10	70.28	↓4.11	B**	1.04	68.60	71.25	1.48
a^*	Control	10	2.99	-	D**	0.22	2.58	3.37	7.45
	1-layer	10	3.37	↑12.71	C	0.16	3.18	3.72	4.86
	2-layers	10	3.74	↑25.08	B	0.24	3.39	4.10	6.40
	3-layers	10	3.98	↑33.11	A*	0.19	3.46	4.15	4.83
b^*	Control	10	21.02	-	D**	0.71	20.09	22.48	3.37
	1-layer	10	22.93	↑9.09	C	0.64	21.63	23.81	2.78
	2-layers	10	23.62	↑12.37	B	0.65	22.63	24.57	2.75
	3-layers	10	24.63	↑17.17	A*	0.46	23.54	25.20	1.87
C^*	Control	10	21.23	-	D**	0.72	20.25	22.73	3.39
	1-layer	10	23.18	↑9.19	C	0.65	21.87	24.06	2.79
	2-layers	10	23.91	↑12.62	B	0.67	22.87	24.91	2.80
	3-layers	10	24.95	↑17.52	A*	0.48	23.79	25.52	1.92
h^o	Control	10	81.90	-	A*	0.51	81.17	82.68	0.63
	1-layer	10	81.63	↓0.33	A	0.26	80.96	81.96	0.32
	2-layers	10	81.01	↓1.09	B	0.44	80.47	81.67	0.55
	3-layers	10	80.83	↓1.31	B**	0.35	80.43	81.63	0.43
N: Number of Measurements, *SS*: Standard Deviation, *HG*: Homogeneity Group, COV: Coefficient of Variation, *: Lowest Value, **: Highest Value									

The variance analyses related to the glossiness values are shown in Table 5.

Table 5: Analysis of variance results for glossiness values

Source	Test	Sum of Squares	df	Mean Square	F	Sig.
Number of Layer	⊥20° glossiness	0.699	3	0.233	14.979	0.000*
	⊥60° glossiness	122.493	3	40.831	643.288	0.000*
	⊥85° glossiness	259.445	3	86.482	363.284	0.000*
	∥ 20° glossiness	3.395	3	1.132	93.440	0.000*
	∥ 60° glossiness	190.835	3	63.612	1072.607	0.000*
	∥ 85° glossiness	850.975	3	283.658	922.216	0.000*
Error	⊥20° glossiness	0.560	36	0.016		
	⊥60° glossiness	2.285	36	0.063		
	⊥85° glossiness	8.570	36	0.238		
	∥ 20° glossiness	0.436	36	0.012		
	∥ 60° glossiness	2.135	36	0.059		
	∥ 85° glossiness	11.073	36	0.308		
Total	⊥20° glossiness	44.940	40			
	⊥60° glossiness	1309.610	40			
	⊥85° glossiness	1339.240	40			
	∥ 20° glossiness	35.160	40			
	∥ 60° glossiness	1719.430	40			
	∥ 85° glossiness	4096.650	40			
Corrected Total	⊥20° glossiness	1.259	39			
	⊥60° glossiness	124.778	39			
	⊥85° glossiness	268.015	39			
	∥ 20° glossiness	3.831	39			
	∥ 60° glossiness	192.970	39			
	∥ 85° glossiness	862.048	39			
*: Significant						

Table 6 illustrates the measurement findings for glossiness values.

Table 6: Measurement results for glossiness values

Test	Wax Application	N	Mean	Change (%)	*HG*	*SS*	Minimum	Maximum	COV
⊥20°	Control	10	0.86	-	C**	0.22	0.60	1.10	25.83
	1-layer	10	1.00	↑16.28	B	0.00	1.00	1.00	0.00
	2-layers	10	1.10	↑27.91	B	0.08	1.00	1.20	7.42
	3-layers	10	1.22	↑41.86	A*	0.08	1.10	1.30	6.47
⊥60°	Control	10	2.50	-	C**	0.00	2.50	2.50	0.00
	1-layer	10	5.99	↑139.60	B	0.22	5.70	6.20	3.64
	2-layers	10	6.18	↑147.20	B	0.34	5.70	6.50	5.54
	3-layers	10	7.10	↑184.00	A*	0.30	6.60	7.40	4.20
⊥85°	Control	10	0.82	-	C**	0.19	0.70	1.10	23.56
	1-layer	10	6.39	↑679.27	B	0.09	6.30	6.50	1.37
	2-layers	10	6.21	↑657.32	B	0.92	4.90	7.00	14.83
	3-layers	10	7.28	↑787.80	A*	0.24	6.90	7.60	3.35
∥20°	Control	10	0.50	-	C**	0.00	0.50	0.50	0.00
	1-layer	10	0.88	↑76.00	B	0.13	0.70	1.00	14.96
	2-layers	10	0.84	↑68.00	B	0.05	0.80	0.90	6.15
	3-layers	10	1.32	↑164.00	A*	0.17	1.10	1.50	12.78
∥60°	Control	10	2.53	-	C**	0.05	2.50	2.60	1.91
	1-layer	10	6.91	↑173.12	B	0.16	6.70	7.10	2.31
	2-layers	10	6.93	↑173.91	B	0.18	6.70	7.10	2.64
	3-layers	10	8.34	↑229.64	A*	0.42	7.80	8.80	5.03
∥85°	Control	10	1.36	-	D**	0.05	1.30	1.40	3.80
	1-layer	10	9.90	↑627.94	C	0.43	9.40	10.40	4.34
	2-layers	10	11.05	↑712.50	B	0.19	10.80	11.30	1.72
	3-layers	10	13.66	↑904.41	A*	1.00	11.90	14.60	7.35

N: Number of Measurements, *SS*: Standard Deviation, *HG*: Homogeneity Group,
COV: Coefficient of Variation, *: Lowest Value, **: Highest Value

Table 7 presents the results for the total color differences (Δ*E**).

Table 7: Results for the total color differences

Wax Application	Δ*L**	Δ*a**	Δ*b**	Δ*C**	Δ*H**	Δ*E**	Color change criteria (DIN 5033, 1979)
1-layer	-2.31	0.38	1.90	1.94	-	3.02	Very distinct (3.0 to 6.0)
2-layers	-2.48	0.74	2.60	2.68	0.34	3.67	
3-layers	-3.01	0.98	3.61	3.72	0.40	4.80	

Table 8 displays the recorded data for whiteness index (*WI**) values.

Table 8: Analysis of variance results for whiteness index (*WI**) values

Source	Test	Sum of Squares	df	Mean Square	F	Sig.
Number of Layer	*WI** (⊥)	359.827	3	119.942	404.907	0.000*
	*WI** (∥)	510.864	3	170.288	743.977	0.000*
Error	*WI** (⊥)	10.664	36	0.296		
	*WI** (∥)	8.240	36	0.229		
Total	*WI** (⊥)	29714.380	40			
	*WI** (∥)	22646.720	40			
Corrected Total	*WI** (⊥)	370.491	39			
	*WI** (∥)	519.104	39			

*: Significant

Table 9 showcases the measurement outcomes for whiteness index (*WI**) values.

Table 9: Measurement results for whiteness index (*WI**) values

Test	Wax Application	N	Mean	Change (%)	*HG*	*SS*	Minimum	Maximum	COV
*WI** ⊥	Control	10	31.38	-	A*	0.35	30.90	31.80	1.11
	1-layer	10	28.32	↓9.75	B	0.39	27.70	28.80	1.36
	2-layers	10	24.92	↓20.59	C	0.94	24.40	26.70	3.77
	3-layers	10	23.72	↓24.41	D**	0.18	23.40	23.90	0.76
*WI** ‖	Control	10	29.38	-	A*	0.31	28.90	29.70	1.05
	1-layer	10	23.34	↓20.56	B	0.62	22.60	24.10	2.66
	2-layers	10	21.22	↓27.77	C	0.15	21.00	21.40	0.73
	3-layers	10	20.14	↓31.45	D**	0.64	19.00	20.70	3.19
N: Number of Measurements, *SS*: Standard Deviation, *HG*: Homogeneity Group, COV: Coefficient of Variation, *: Lowest Value, **: Highest Value									

4. Discussion

In the provided test result tables, it was determined that the factor representing the number of categories significantly influenced the variance analyses (Table 3, 5, and 8).

Decreases in *WI** were observed for both perpendicular and parallel directions to the fibers with applications of different coating ratios, while decreases were observed in h^o and *L** parameters. Increases were detected in *a**, *C**, and *b** values. The highest results for *L** and h^o values were found in the samples belonging to the control experimental group (73.29 and 81.90, respectively). Alternatively, the decline rates in the h^o values are recorded as 0.33% for 1-layer, 1.09% for 2-layer, and 1.31% for 3-layer. The highest reduction rate for *L** was determined to be 4.11% on surfaces treated with 3-layer of wax, while the lowest reduction rate was observed to be 3.14% on samples treated with 1-layer of wax. The lowest results for the *a**, *b**, and *C** parameters were found in the control samples (2.99, 21.02, and 21.23, respectively). Additionally, the highest values for these parameters were also observed on surfaces treated with 3-layer of wax (*a**: 3.98, *b**: 24.63, and *C**: 24.95, respectively). In the 3-layer wax application, the parameters *a**, *b**, and *C** experienced the highest increase rates, with percentages of 33.11%, 17.17%, and 17.52%, respectively, in that order (Table 4).

Wax applications on walnut and maple woods (Liu et al., 2022), along with beech, linden, poplar, and pine woods (Akçay, 2020), were noted to have resulted in a reduction in *L** and an increase in *a** and *b** values.

According to these results, increases in glossiness values were observed in all degrees and directions following the application of wax. Additionally, the lowest measurement results for all degrees and directions were obtained from the samples belonging to the control experimental group, while the highest results were found in the samples with 3-layer of wax application. Particularly, it was determined that the increase values in both directions at 85 degrees were above 600% (Table 6).

Following all applications, negative values were observed in Δ*L** (darker than the reference), while positive results were determined in Δ*a**, Δ*b**, and Δ*C** (redder, yellower, and clearer/brighter than the reference, respectively). The Δ*E** values were found to be 3.02 for the 1-layer wax application, 3.67 for the 2-layer wax application, and 4.80 for the 3-layer wax application. Additionally, the increase in the coefficients of Δ*E**, Δ*a**, Δ*b**, and Δ*C** corresponds to the increase. When compared with color change criteria (DIN 5033, 1979), it is evident that the result "very distinct (3.0 to 6.0)" was obtained after all applications (Table 7).

The *WI** values in the vertical direction relative to the fibers were found to be higher compared to those in the parallel direction to the fibers. The highest results for *WI** values were found in the control samples (⊥: 31.38 and ‖: 29.38), while the lowest results were observed in the group of experimental samples with 3-layer of wax application (⊥: 23.72 and ‖: 20.14). The values for *WI** were found as 9.75% in the ⊥ direction for 1-layer, 20.59% for 2-layer, and 24.41% for 3-layer, whereas in the ‖ direction, they were determined as 20.56% for 1-layer, 27.77% for 2-layer, and 31.45% for 3-layer (Table 9).

In the existing literature, alterations in color, glossiness, and whiteness index values resulting from the wax application on olive (Peker et al., 2024a), plum (Peker et al., 2024b), balau red (Peker et al., 2024c), and ebony Macassar (Kaplan et al., 2024) wood species were documented. In wax studies conducted on olive (Peker et al., 2024a) and plum (Peker et al., 2024b) woods with different application rates, it has been reported that *L** and h^o values decrease, and additionally, *a**, *b**, and *C** values increase. The results obtained in color measurements in this study are consistent with the literature.

5. Conclusion

The waxes utilized in the study were noted to alter the chosen surface characteristics of magnolia wood. Wax applications resulted in enhancements across all glossiness levels and orientations. The ΔE^* values were determined to be 3.02 for the 1-layer application, 3.67 for the 2-layer application, and 4.80 for the 3-layer application. A decline was noted in WI^* values in both directions ($\perp$ and $\parallel$).

Disclosure Statement

No potential conflict of interest was reported by the authors.

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SURFACE TENSION, CONTACT ANGLE AND WETTABILITY OF WOOD

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Abstract

Surface tension is an internal force due to an unbalance in molecular forces that occurs when two different materials, such as a wood surface and adhesive, are brought into contact with each other, forming an interface or boundary. The force is due to the tendency for all materials to reduce their surface area in response to the unbalance in molecular forces that occurs at their points of contact. Wetting properties between solids and liquids are of major importance for most industrial products and processes, such as adhesives, paint and lacquers, photograph films, printing inks, finishing, and textiles. Contact angle analysis is a widely used method to study the wetting characteristics of solid materials. There are several methods to determine the contact angles of a liquid on a wood surface. However, the most widely applied method is the sessile drop method.

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SURFACE TENSION, CONTACT ANGLE AND WETTABILITY OF WOOD

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1. Surface Tension, Wettability and Contact Angle

When a drop of liquid is dropped on a flat solid material surface, it may spread completely on the surface or, more likely, remain as a drop, forming a certain angle (θ - contact angle) with the solid surface. The contact angle (θ) is a function of the liquid and the solid surface. When the forces of attraction between the liquid and the solid surface (adhesion) are equal to or greater than those between the liquid and the solid surface (cohesion), the contact angle is 0. When the adhesion forces between the liquid and the solid surface are smaller than the cohesion forces in the liquid, the contact angle approaches infinity (∞) (Shaw, 1970).

When two different materials (such as a drop of liquid on a solid surface) come into contact with each other to form an interface or boundary, an internal force called "surface tension" is generated due to the imbalance in the molecular forces that arise. This force is caused by the fact that all materials try to reduce their surface area in response to the imbalance in the molecular forces that occur at the contact points (Aydin, 2004a). Figure 1 shows the forces of attraction that cause surface tension.

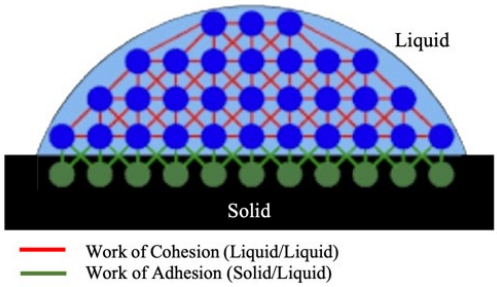


Figure 1: Attraction forces between molecules on the surface and inside a liquid drop (Web-1)

Surface tension is the cohesive force at the liquid's surface that tends to minimize surface area. It is a crucial factor in determining how a liquid interacts with a solid surface. In wood materials, surface tension affects the spreading and penetration of liquids, and the surface tension of both the wood and the interacting liquid significantly affects processes like finishing and adhesion (Smith, 2018).

Several factors can influence wood's surface tension, including moisture content, surface roughness, and chemical composition. A Higher moisture content generally reduces surface tension. Increased roughness can lead to higher surface tension due to capillary effects. Variations in lignin, cellulose, and extractives also affect the surface tension of wood (Wu, 1982).

Materials can be broadly classified based on their affinity with water into hydrophobic (water-repelling) and hydrophilic (water-attracting). Hydrophobicity and hydrophilicity are critical concepts in chemistry, biology, and materials science. They describe the affinity of substances for water, which influences a variety of phenomena, from molecular interactions to materials' macroscopic properties. The interaction of materials with water is expressed by the terms hydrophobic (water repellent) or hydrophilic (water loving). Hydrophilic materials have the ability to absorb water rapidly (Figure 2-a). Surface chemistry allows such materials to wet by forming a film of water or coating agent on their surface. Hydrophilic materials have large surface tension values and have the ability to form hydrogen bonds with water (Aydin, 2004a).

Hydrophobic materials, compared to hydrophilic materials, react inversely to the interaction with water. Such materials absorb little or no water and tend to form bubbles on their surfaces (Figure 2-b). Hydrophobic materials have small surface tension values and lack active groups in the chemical structure of their surfaces to form hydrogen bonds with water (Aydin, 2004a).

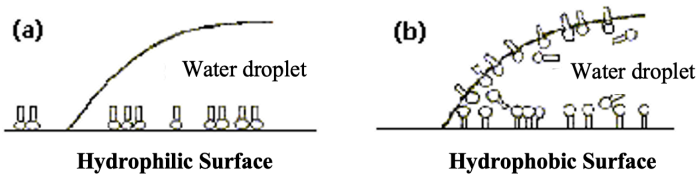


Figure 2: Movement of water molecules on hydrophilic and hydrophobic surfaces (Shaw, 1970)

Wettability is a critical characteristic of wood that affects its performance in various applications, including adhesion, coating, and impregnation processes. Good wettability ensures that adhesives and coatings can spread uniformly and adhere strongly to the wood surface. Effective adhesive bonding requires high wettability to ensure adequate spread and penetration of the adhesive (Marra, 1992). Improved wettability results in stronger and more durable bonds. It is a measure of how easily a liquid can spread across a wood surface, which in turn is influenced by the wood's surface energy, roughness, and chemical composition. Understanding the wettability of wood is essential for optimizing its use in construction, furniture making, and other industries where wood-water interactions are significant (Kamke and Lee, 2007).

Wettability is also important for wood impregnation processes, where liquids such as preservatives, fire retardants, or dyes are introduced into the wood's cellular structure. High wettability facilitates deeper and more uniform penetration of these substances, enhancing the wood's performance in various applications. For example, pressure-treated wood, which involves impregnating wood with preservatives, relies on good wettability to ensure effective protection against decay and pests (Lebow, 2010).

The wettability of wood also affects its susceptibility to biological degradation and weathering. Hydrophobic treatments that reduce wettability can enhance the durability and lifespan of wood products by preventing moisture ingress and subsequent microbial attack (Jones et al., 2016). Recent studies have focused on developing eco-friendly and sustainable treatments that balance wettability and environmental impact (Kim et al., 2022).

The wettability of wood is influenced by its surface characteristics, including chemical composition, surface roughness, and the presence of contaminants (Gray, 1962). Various treatments can enhance the wettability of wood, such as plasma treatment, chemical modification, and sanding (Gardner et al., 1996). Plasma treatment modifies the wood surface at a molecular level, improving wettability by introducing polar functional groups (Griffin, 1962). Chemical treatments can alter the surface energy of wood, making it more hydrophilic or hydrophobic, depending on the intended application (Rowell, 1984).

Different wood species exhibit varying degrees of wettability due to their unique anatomical and chemical characteristics. For instance, Gindl et al. (2013) demonstrated that hardwood species generally have lower contact angles compared to softwoods, attributed to differences in surface energy and porosity. Similarly, Bächle et al. (2019) found that the presence of extractives in certain wood species can significantly reduce wettability, emphasizing the need for species-specific treatment approaches.

Surface roughness is also a critical determinant of wood's wettability. Studies have shown that smoother wood surfaces tend to have higher contact angles, indicating lower wettability (Kúdela and Paprčka, 2016). The interplay between surface roughness and contact angle is complex; rougher surfaces can either increase or decrease wettability depending on the scale and pattern of the roughness (Laskowska and Kozakiewicz, 2021). Techniques such as sanding and mechanical planing are often employed to modify the surface roughness and, consequently, the wettability of wood.

Chemical composition, including the presence of lignin, cellulose, and hemicelluloses, plays a significant role in wood wettability. Treatments that alter the chemical composition, such as thermal modification and chemical grafting, have been extensively studied. Thermal modification, for example, generally decreases wood wettability by increasing hydrophobicity and reducing surface energy (Hakkou et al., 2019). Chemical treatments, such as acetylation and silanization, have also been shown to enhance the hydrophobic properties of wood surfaces (Li et al., 2017).

Contact angle measurements are the most common method used to determine the wettability of a material and to describe the adhesion between a solid and a liquid (Collet, 1972; Kazayawoko et al., 1997; Aydin and Çolakoglu, 2002; Aydin, 2004a; Aydin, 2004b). The contact angle, also called the wetting angle, is the angle between the plane tangent to the liquid surface and the plane tangent to the surface of the solid (Woodward, 2000; Aydin and Çolakoglu, 2002; Jones et al., 2020). It quantifies the wettability of a surface: a low contact angle indicates high wettability, while a high contact angle suggests low wettability (Kalnins and Feist, 1993; Shi and Gardner, 2001).

Several factors impact the contact angle on wood, such as surface energy, roughness, chemical composition, moisture content, and the presence of surface treatments. A higher surface energy typically

reduces the contact angle. Increased roughness can lead to higher contact angles due to air entrapment (Berg, 1993). The chemical composition of the wood, including the presence of extractives and treatment chemicals, significantly affects wettability. For instance, a higher lignin content generally reduces wettability (Gray, 1962). The moisture content of wood influences its surface energy and, consequently, the contact angle. Higher moisture content usually results in lower contact angles due to the swelling of wood fibers (Wu, 1982). Chemical modifications can either increase or decrease the contact angle, depending on the treatment (Sharma and Chattopadhyay, 2021). Surface treatments such as sanding, plasma treatment, or chemical modification, can alter the surface energy of wood, thereby affecting contact angles. For example, plasma treatment increases surface energy and reduces contact angles, enhancing wettability (Hosseinaei et al., 2015).

When a small drop of liquid is dropped on a flat solid surface, there are three possible wetting patterns. These are complete wetting, partial wetting, and non-wetting as can be seen from Figure 3 (Aydin, 2004a).

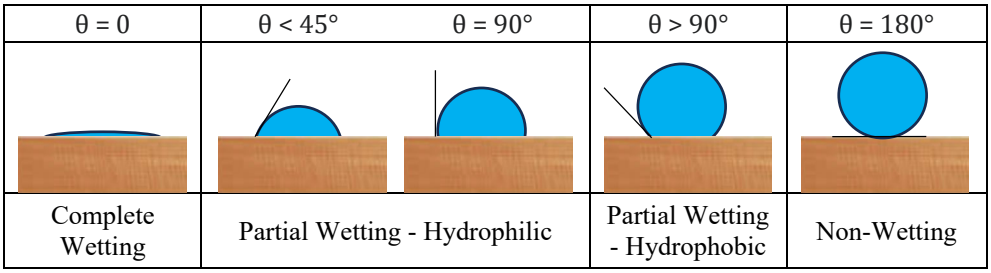


Figure 3: Wetting behaviors on wood (Aydin, 2004a).

For perfect wetting, a contact angle θ=0° is required. In this case, the liquid spreads as a thin film on the solid surface. The case θ=180° is practically not observed. This is not feasible because it would require the adhesion between the liquid and the solid to be zero, or the surface tension between the liquid and the air to be infinite. There is always some force of attraction between the solid and the liquid. If θ<90°, it can be said that the liquid wets the solid surface; if θ>90°, it does not (Bodig, 1962). Both partial wetting with θ<90° and complete wetting (θ=0°) provide acceptable interface-free energy for adhesion (Aydin, 2004a). Table 1 also indicates the degree of wetting and interaction strength depending on the contact angle.

Table 1: Degree of wettability and interaction strength depending on the contact angle

Contact Angle	Degree of wettability	Forces of Attraction	
		Solid–liquid	Liquid–liquid
θ = 0	Complete wetting	Strong	Weak
0 < θ < 90°	High wettability	Strong	Strong
90° ≤ θ < 180°	Low wettability	Weak	Strong
θ = 180°	Non-wetting	Weak	Strong

It is thought that there are three forces affecting the liquid drop that forms an angle on the surface when dropped on the surface of a solid, and that these forces are in equilibrium. These forces are surface tension between solid and liquid (γ_{SL}), surface tension between solid and gas (γ_{SG}) and surface tension between liquid and gas (γ_{LG}) (Wålinder, 2000; Clint, 2001).

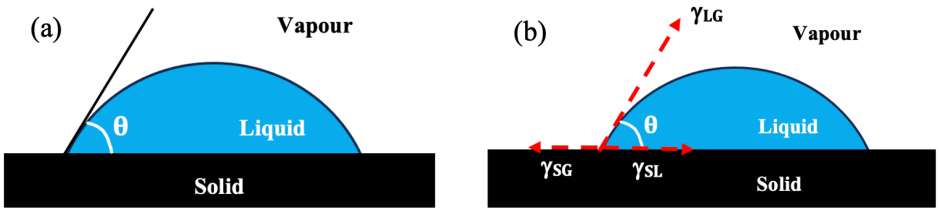


Figure 4: Formation of the contact angle (θ) (a) and the balance of forces acting on the liquid drop on the solid surface (b) (Aydin, 2004a)

The relationship between the surface tensions of a solid and a liquid, the interfacial tensions between the solid and the liquid, and the contact angle (θ) formed by a drop of liquid dropped on a flat surface was formulated by Thomas Young in 1805. This equation, also called Young's Equation, is given below (Kalnins and Feist, 1993):

$$\gamma_{LG} \cos \theta = \gamma_{SG} - \gamma_{SL}$$

Dupré developed an equation for the thermodynamic energy of the interaction between these interface forces, commonly known as the work of adhesion (Mantanis and Young, 1997). According to this equation:

$$W_A = \gamma_S + \gamma_L - \gamma_{SL}$$

Combining the two equations above yields the following equation for adhesion work (Clint, 2001):

$$W_A = \gamma_L (1 + \cos \theta)$$

Thus, the thermodynamic energy of the interaction at an interface can be calculated using the surface tension and contact angle values of the liquid.

2. Contact Angle Measurement Methods to Determine the Wettability of Wood Surfaces

Wetting properties between solids and liquids are critical for many industrial products, including adhesives, surface treatments such as paints and varnishes, printing inks, photographic films, video and audio tapes, and so on. Understanding wood's wettability is critical for optimizing its use in a variety of industrial applications. Controlling and enhancing wettability significantly improves wood adhesion, coating, and impregnation processes, resulting in more durable and reliable wood products.

The wettability of a material is usually determined by contact angle measurements. The accurate measurement of contact angles on wood surfaces is crucial for assessing wettability. There are many techniques available for measuring the contact angles of a liquid on a wood surface. The most commonly used methods are optical and gravimetric techniques. Direct measurement of contact angles from the profile of a liquid drop on the wood surface (Sessile Drop Method) is the most widely used method (Herczeg, 1965; Jordan and Wellons, 1977; Nguyen and Johns, 1979). With the optical technique known as drop shape analysis (Sessile Drop Method), contact angles are measured visually. This method involves placing a liquid droplet on the wood surface and capturing its profile with a high-resolution camera. The contact angle is determined by analyzing the shape of the droplet using software. In the sessile drop method, the contact angle (θ) is defined as the angle between the tangent to the liquid droplet surface and the solid surface at the three-phase contact line. A droplet of liquid is dispensed onto the wood surface, and the equilibrium contact angle is recorded once the droplet stabilizes (Gardner, 1996). The process typically involves the following steps:

1. Surface Preparation: The wood surface is cleaned and conditioned to remove contaminants.
2. Droplet Placement: A microliter syringe or a similar device is used to place a droplet of distilled water or another test liquid on the surface.
3. Image Capture: A high-speed camera captures the side view of the droplet.
4. Angle Measurement: Image analysis software calculates the contact angle from the droplet profile.

The sessile drop method is favored for its simplicity and directness. Although this technique has the advantages of requiring small quantities of test liquid and a small sample of wood, the contact angle of a liquid on a wood surface is difficult to obtain. The reason for this difficulty is the problem of accurately plotting the tangent on the drop profile at the point of contact with the wood surface (Casilla et. al., 1981). Wood surfaces are rough and heterogeneous. A drop of liquid (such as glue) on such a surface like wood does not have perfect axial symmetry. If a single contact angle is measured with such a technique, this measurement may not be representative of all drops on the wood surface, as the contact angles will vary from point to point. Furthermore, an accurate contact angle reading using this technique depends on the experience and skill of the operator taking the measurement (Kazayawoko et. al., 1997). This method can often give different results depending on the operator performing the measurement (Aydin and Çolakoglu, 2002). In addition, contact angle measurements with this method are quite time consuming. Because the angle changes in a short time due to the interaction between the liquid and the solid, direct determination

of the contact angle on solid surfaces is very difficult (Kalnins et. al., 1988). Since porous materials are highly absorbent, it is difficult to obtain contact angles with an optical technique (Aydin and Çolakoglu, 2002).

Recent advancements in goniometry and image analysis have improved the precision of contact angle measurements. Shi et al. (2018) highlighted the importance of using sessile drop methods combined with high-resolution imaging to capture the dynamic changes in contact angle over time. Furthermore, the use of environmental scanning electron microscopy (ESEM) has enabled researchers to study the wettability of wood under various humidity conditions, providing deeper insights into the moisture-related behavior of wood surfaces (Zhao et al., 2020).

In order to overcome the difficulties encountered in the direct measurement of contact angles by sessile drop analysis and to obtain more precise measurements, devices equipped with video cameras and computers have been developed. In today's applications, automated devices equipped with video cameras and computer support, schematically shown in Figure 5, are mostly used to observe the behavior of a liquid drop on a solid surface after contact with the surface, to directly measure the contact angles with precision, and to calculate the surface tension.

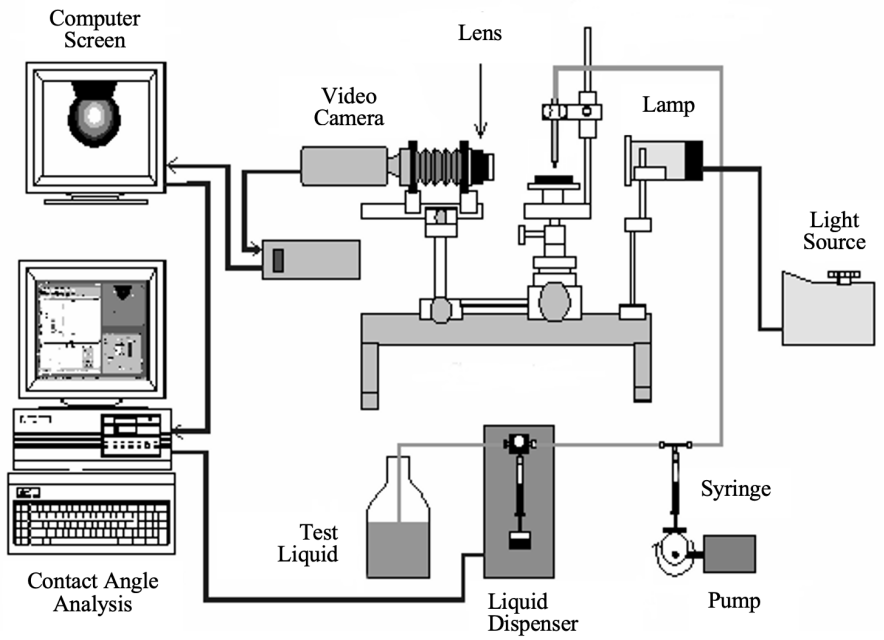


Figure 5: A computer-aided automatic contact angle measurement and analysis (Aydin, 2004a)

The Wilhelmy Plate method offers an alternative approach, particularly suitable for dynamic wettability studies. This method is widely used due to its simplicity, accuracy, and ability to provide insights into the wetting behaviors of various materials. The Wilhelmy Plate Method operates on the principle that a thin, vertical plate made of a known material is partially immersed in a liquid. The liquid wets the plate and climbs up its surface, creating a meniscus whose shape and height are influenced by the contact angle (Adamson and Gast, 1997). It measures the force exerted on a vertically immersed plate as it interacts with a liquid, providing contact angle data based on the force balance. The force exerted by the liquid on the plate is measured as a function of depth, allowing the calculation of contact angles. This technique is particularly useful for assessing the contact angle of wood fibers and small samples (van Oss et. al., 1988).

As can be seen from the schematic diagram of the Wilhelmy Plate Method (Figure 6), when a vertically suspended plate touches a liquid surface or interface, then a force F, which correlates with the surface tension or interfacial tension σ and with the contact angle θ according to the following equation, acts on this plate (Web-2):

$$\gamma = \frac{F}{L \times \cos\theta}$$

The wetted length L of the plate is equal to its perimeter. To measure the force F, the plate is attached to the force sensor of a tensiometer.

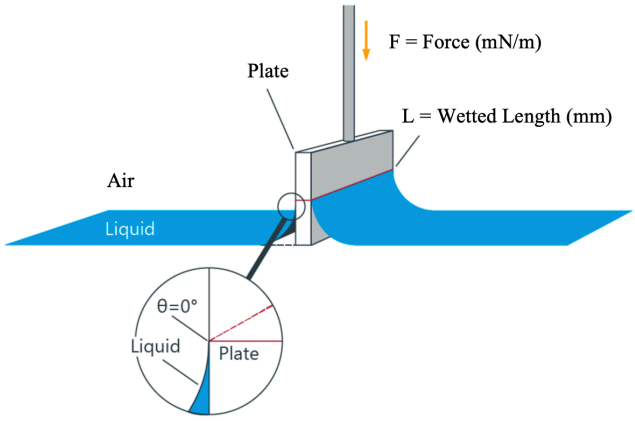


Figure 6: Schematic diagram of the Wilhelmy Plate Method (Web-2)

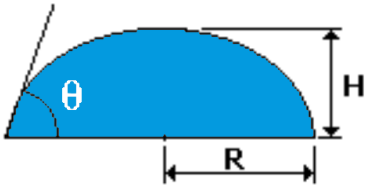
Dynamic contact angle measurements involve determining the contact angle during the advancing and receding motions of the liquid on the solid surface. This is critical for understanding hysteresis, which is the difference between advancing and receding contact angles and is indicative of surface heterogeneity and roughness (Kwok and Neumann, 1999). With the Wilhelmy method, a dynamic contact angle is normally measured by slowly immersing and then withdrawing the solid. The advancing angle is determined during the wetting process and the receding angle during the de-wetting process (Web-2). The advancing contact angle is measured as the plate is immersed in the liquid. The meniscus climbs up the plate, and the contact angle increases until it stabilizes at a maximum value. This angle reflects the liquid's tendency to wet the surface. The receding contact angle is measured as the plate is withdrawn from the liquid. The meniscus descends, and the contact angle decreases until it stabilizes at a minimum value. This angle indicates the liquid's tendency to de-wet the surface (Kwok and Neumann, 1999).

The Wilhelmy Plate method is straightforward and requires minimal sample preparation. It provides precise measurements of contact angles and is applicable to a wide range of liquids and solid materials. On the other hand, it is highly sensitive to surface roughness and heterogeneity, which can affect accuracy. Temperature and humidity can also influence the measurements and need to be controlled.

Casilla et al. (1981) developed an alternative approach to determining the wettability of wood surfaces. This approach is a modified version of the Wilhelmy technique. This modified version determines a wettability index (the area under the force-dip curve) by immersing a conical wood sample in a solution (Kazayawoko et al., 1997). In contrast to drop shape analysis methods, the Wilhelmy technique does not directly obtain a quantitative contact angle value. Although this technique is an alternative tool to characterize the wettability and surface properties of wood, its inability to provide a quantitative contact angle value is a major obstacle since most thermodynamic wetting and adhesion theories require contact angle information (Kazayawoko, 1996; Kazayawoko et al., 1997). However, in specific applications such as gluing and varnishing, dynamic contact angle has been reported to be more informative (Boehme and Hora, 1996).

Rotenberg et al. (1983) developed an alternative method called ADSA (Axisymmetric Drop Shape Analysis) to calculate the contact angle based on measurements of the drop shape.

It is also possible to approximate the contact angles on a material surface using the dimensions of the liquid drop on the surface using the following equation (Liptáková and Kúdela, 1994):



$$\theta = 2 \times \arctan(H/R)$$

Where θ is the contact angle, H is the height of the drop and R is the radius of the drop base.

Using the Dynamic Contact Angle (DCA) method, it is possible to measure the contact angle at equilibrium. The time required for a liquid drop to reach equilibrium on the surface where it is dropped depends on the liquid used. For example, for a water drop, the equilibrium state is reached in a few seconds, while for oil drops, the time to reach equilibrium is about 3 minutes. The contact angle before reaching equilibrium is called the advancing contact angle. After reaching the equilibrium state, the contact angle

starts to retreat towards the initial state, and the contact angle in this state is called the retreating contact angle (Liptáková and Kúdela, 1994). The lack of thermodynamic equilibrium in non-ideal systems leads to the formation of a contact angle due to the formation in the field of motion of the fluid. This phenomenon is called contact angle hysteresis (Wulf et al., 1997).

There are some factors that cause the formation of contact angle hysteresis. Surface roughness and the heterogeneous structure of the surface are the most important of these factors (Kazayawoko, 1996; Extrand, 1998; Dominigue; 2000). As the liquid drop spreads, it can be contaminated by some contaminants on the surface, and this changes the surface tension of the liquid. The contamination of the liquid drop is also considered among the factors that cause the formation of contact angle hysteresis (Extrand, 1998). Another factor shown to cause hysteresis is the reorganization of molecules and functional groups on the surface of the solid after contact with the liquid (Wålinder; 2000). The occurrence of the hysteresis phenomenon poses a difficulty in the practical measurement of contact angles (Kazayawoko, 1996).

3. Conclusions

The surface tension, contact angle, and wettability of wood are critical parameters influencing its performance in various applications. By understanding and manipulating these properties, we can enhance wood processing techniques, improve product quality, and expand the range of wood's practical uses. Future research should focus on developing more efficient surface treatments and better understanding the interactions between wood surfaces and different liquids.

Understanding wood's wettability is critical for optimizing its use in a variety of industrial applications. Factors such as surface energy, surface roughness, and chemical treatments significantly influence wettability. Accurate measurement of wettability through techniques like contact angle goniometry and the Wilhelmy plate method provides valuable insights into wood-liquid interactions. Controlling and enhancing wettability significantly improves the performance of wood in adhesion, coating, and impregnation processes, resulting in more durable and reliable wood products.

Contact angle measurement is a valuable tool for investigating the wettability and surface properties of wood. By understanding the factors influencing contact angles and employing appropriate measurement techniques, researchers and industry professionals can optimize wood treatment processes, enhancing the performance and longevity of wood products.

Contact angle measurement methods, including the sessile drop, Wilhelmy plate, and dynamic measurements, are fundamental in assessing the wettability of wood surfaces. Each method has its own unique advantages and limitations, making them suitable for different aspects of wettability studies. Understanding these methods enables researchers to select appropriate techniques for specific applications, ultimately improving wood surface treatments and applications.

Disclosure Statement

No potential conflict of interest was reported by the author.

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