Effects of Various Bleaching Chemicals on Some Surface Properties of Ebony Species (African, Black, and Macassar)

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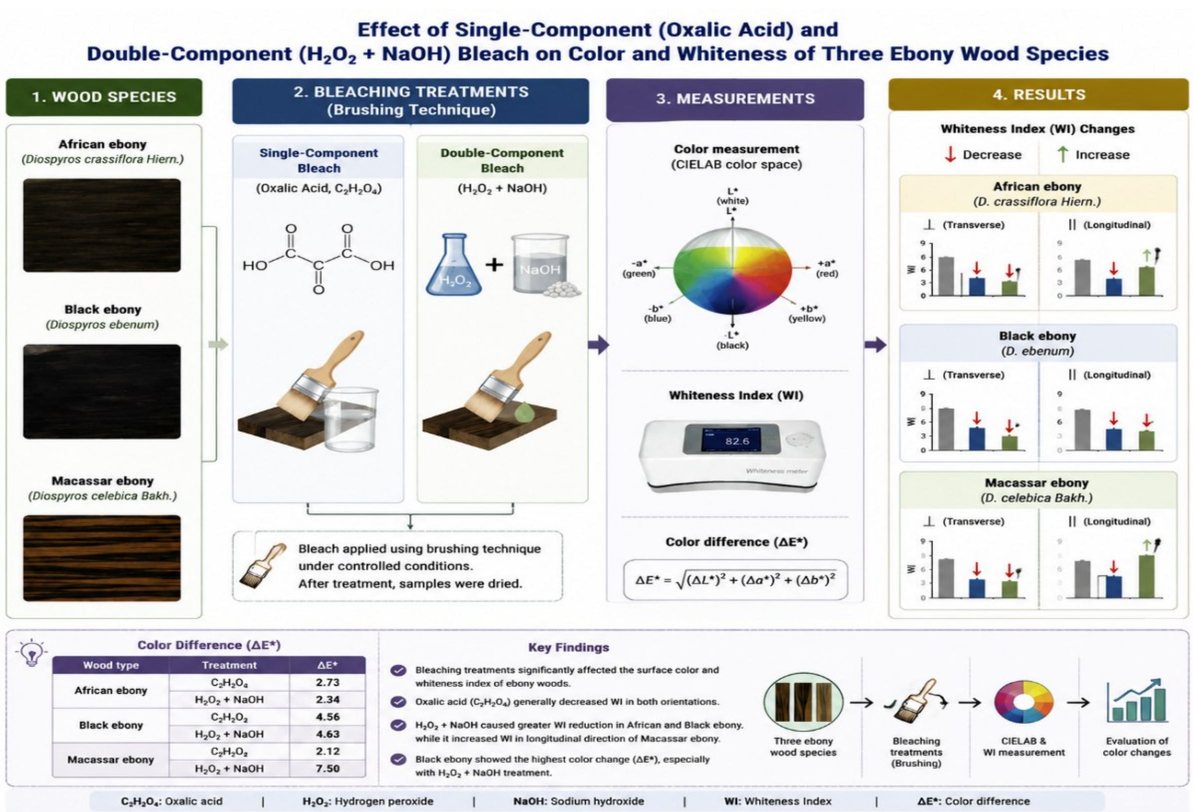
GRAPHICAL ABSTRACT



Wood type	Treatment	ΔE*
African ebony	$C_2H_2O_4$	2.73
	H_2O_2 + NaOH	2.34
Black ebony	$C_2H_2O_2$	4.56
	H_2O_2 + NaOH	4.63
Macassar ebony	$C_2H_2O_2$	2.12
	H_2O_2 + NaOH	7.50

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The concept of color is not always suitable for some trees according to customers' preferences. The color of the wooden material changes with processes such as heat treatment, impregnation, bleaching, *etc.* When the color of the wooden material changes, the surface also undergoes changes in its inherent properties. African ebony (*Diospyros crassiflora* Hiern.), black ebony (*Diospyros ebenum*), and Macassar ebony (*Diospyros celebica* Bakh.) wood species were treated using a single-component bleaching chemical [oxalic acid ($C_2H_2O_4$)] and double component bleaching chemical [hydrogen peroxide (H_2O_2) + sodium hydroxide (NaOH)] using a brushing technique. Subsequently, the characteristics of the changes that occurred were determined, including color parameters and whiteness index (*WI**) values. The wood species exhibited different behaviors (increases and decreases specific to each test) in response to both bleaching agents. There was an observed increase in the *a**, *b** and *C** values, while the *h*° values decreased for all wood species. Furthermore, *WI** values in directions perpendicular and parallel to the fibers were reduced in all wood species by oxalic acid treatment.

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Keywords: Whiteness index; Color; Bleaching; Black ebony; African ebony; Macassar ebony

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INTRODUCTION

No two tree species are alike, and even within the same tree species, the characteristics vary. In fact, when wood samples taken from different parts of the same tree are examined, different properties are observed. These distinct characteristics are apparent not only in their outward appearance but also in aspects such as density, pattern, color, and odor when the material is examined. These differences in trees are said to stem from factors such as the region where they grow, the environmental conditions they are exposed to, and their genetic structure. The properties of wood materials obtained from the same tree differ depending on their source (Gürtekin and Oğuz 2006).

One useful characteristic for determining the genus of trees is their color. The color of some trees may fade due to the effect of sunlight, while others may darken to a certain extent over time, but each tree still possesses its unique color. The darkening of color over time occurs in trees with a high tannin content in their structure (Şanıvar and Zorlu 1980).

Bleaching involves the application of chemicals to cellulosic fibers to enhance their brightness. This brightness enhancement can be achieved through either the removal of lignin or the reduction of lignin coloration. Despite undergoing chemical pulping digestion, lignin continues to be a significant component of the wood pulp used to manufacture different grades of paper (Anonymous 1989). Various chemicals are used for bleaching in different industries. Some examples of these chemicals include; acetic acid (CH_3COOH), sodium hypochlorite (NaClO), carbamide peroxide ($CH_6N_2O_3$), sodium dithionite ($Na_2S_2O_4$), hydrogen peroxide (H_2O_2), sodium hydrosulfite (NaSH), sodium percarbonate ($Na_2CO_3 \cdot 1.5H_2O_2$), chlorine dioxide (ClO_2), chlorine (Cl), sodium hydroxide (NaOH), peracetic acid (CH_3COOOH), oxalic acid ($H_2C_2O_4$), and calcium hydroxide ($Ca(OH)_2$). Hypochlorite is also utilized in certain recycling facilities to bleach the pulp and remove its color (Suess 2010). The objective of chemical wood bleaching is to disrupt the conjugated double bonds within the color-causing compounds. This entails halting the sharing of electrons between atoms, rather than breaking all double bonds. By doing so, the absorption of visible light is interrupted, leading to the elimination of color. Chemical wood bleaching can be accomplished through either oxidation or reduction (Kristiansson 2012).

The term "color" refers to the sensory impression transmitted by the eye, which is an optical phenomenon (Loos 1989). In the literature, there seems to be insufficient research on the bleaching of wood material surfaces. These studies have focused on investigating changes in color parameters, where both increases and decreases in all color parameters have been reported. For instance, it has been reported that sipo (Ulay and Ayata 2023a), sapele (Ulay and Ayata 2023b), satinwood ceylon (Ayata and Çamlıbel 2023), doussié, hornbeam, merbau, iatandza, mahogany (Çakıcıer and Ulay 2023), olon (Peker and Ayata 2023), Scots pine (Ulay and Ayata 2023c), and Anatolian chestnut (Ulay and Ayata 2023d) woods, when treated with NaClO, showed changes in color parameters. For woods treated with NaOH, such as Scots pine and oriental beech (Özçifçi and Özbay 2010), ayous, lime, and poplar (Lu *et al*. 2023) changes in color parameters were observed.

These studies indicate that the application of different chemical bleaching agents [oxalic acid ($C_2H_2O_4$) and the combination of hydrogen peroxide (H_2O_2) + sodium hydroxide (NaOH)] lead to alterations in color parameters for various wood species.

In this study, three types of wood, namely African ebony (*Diospyros crassiflora* Hiern.), black ebony (*Diospyros ebenum*), and Macassar ebony (*Diospyros celebica* Bakh.) were subjected to the application of two different bleaching chemicals on their surfaces, and the resulting color and whiteness index values were investigated. Although wood bleaching processes have been extensively studied, comparative information on the bleaching response of different ebony species under identical chemical and experimental conditions is limited. In particular, systematic evaluation of African ebony, black ebony, and Macassar ebony in terms of color change on the CIELAB scale is underreported. Therefore, this study contributes to a better understanding of species-specific bleaching behavior by providing a direct comparison of these three commercially important ebony species under identical bleaching processes.

EXPERIMENTAL

The wood species African ebony (*Diospyros crassiflora* Hiern.), black ebony (*Diospyros ebenum*), and Macassar ebony (*Diospyros celebica* Bakh.) were selected for this study. The experimental material was obtained from a commercial timber supplier in Türkiye in first-class quality boards with dimensions of 100 mm × 100 mm × 10 mm.

Before bleaching, the wood surfaces were sanded with 80, 100, 120, 150, 180, and 220 grit sandpaper respectively using a vibrating sander to obtain a smooth and even surface.

For each wood species, a total of 30 specimens were prepared and divided into three groups: control group (n = 10), single-component bleach (single-com-bleach) treatment group (n = 10), and double-com-bleach treatment group (n = 10). The specimens were randomly selected, with straight and uniform fiber orientation, and were free from visible defects such as knots, cracks, and discoloration.

The specimens were supplied in a pre-conditioned state under standard laboratory conditions; therefore, no direct moisture content measurement was performed. All samples were kept under standard laboratory conditions prior to testing in accordance with TS ISO 642 554 (1997).

Two different bleaching agents were used in this study: a single-component aqueous solution of oxalic acid ($C_2H_2O_4$) (odorless, liquid, and colorless, with a pH value of 2.0±0.5), and a dual-component system consisting of Part A: hydrogen peroxide (H_2O_2) and Part B: sodium hydroxide (NaOH), mixed in a ratio of 100 mL to 50 mL (2:1). The reagents were purchased from a private trading company. The bleaching solutions were applied as a single layer to the wood surfaces using a sponge brush until full surface coverage was achieved. After application, the treated specimens were dried under standard laboratory conditions for 2 weeks prior to further testing.

The color changes of the samples were measured according to the ASTM D 2244-3 (2007) standard using the CIELAB color system with a CS-10 (CHN Spec, China) device [CIE 10° standard observer; CIE D65 light source, illuminating system: 8/d (8°/diffuse illumination)] (h^o: hue, L^*: lightness, a^*: red color tone, b^*: yellow color tone, C^*: chroma). In this study, the determination of whiteness index (WI^*) values [perpendicular (⊥) and parallel (‖) to the fibers] was carried out using the Whiteness Meter BDY-1 device according to the ASTM E313-15e1 (2015) standard.

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

$$C^* = [(a^*)^2 + (b^*)^2]^{0.5} \tag{1}$$

$$h^o = \arctan (b^*/a^*) \tag{2}$$

$$\Delta a^* = (a^*_{\text{bleached test sample}}) - (a^*_{\text{unbleached test sample}}) \tag{3}$$

$$\Delta L^* = (L^*_{\text{bleached test sample}}) - (L^*_{\text{unbleached test sample}}) \tag{4}$$

$$\Delta b^* = (b^*_{\text{bleached test sample}}) - b^*_{\text{unbleached test sample}}) \tag{5}$$

$$\Delta C^* = (C^*_{\text{bleached test sample}}) - (C^*_{\text{unbleached test sample}}) \tag{6}$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5} \tag{7}$$

$$\Delta H^* = [(\Delta E^*)^2 - (\Delta L^*)^2 - (\Delta C^*)^2]^{0.5} \tag{8}$$

The definitions of ΔH^*, ΔC^*, Δa^*, ΔL^*, and Δb^* are as follows (Lange 1999): Δb^*: A positive value of Δb^* indicates that the sample is more yellow than the reference, while a negative value indicates that the sample is more blue than the reference. ΔL^*: A positive value indicates that the sample is lighter than the reference, while a negative value indicates that the sample is darker than the reference. The parameter ΔH^* represents the hue difference or shade variation. Δa^*: A positive value indicates that the sample is redder than the reference, while a negative value indicates that the sample is greener than the reference. ΔC^* represents the difference in chroma (color saturation), with positive values indicating increased vividness and brightness, and negative values indicating a duller and less clear appearance compared to the reference.

The comparison of ΔE^* color difference through visual evaluation is provided in Table 1 (Cividini *et al*. 2007).

Table 1. Comparison Criteria Related to ΔE^* Evaluation (Cividini *et al*. 2007)

Range of ΔE^*	Rate of Color Difference
$\Delta E^* < 0.2$	No visible difference
$2 > \Delta E^* > 0.2$	Small difference
$3 > \Delta E^* > 2$	Color difference visible with high quality screen
$6 > \Delta E^* > 3$	Color difference visible with medium quality screen
$12 > \Delta E^* > 6$	High color difference
$\Delta E^* > 12$	Different colors

A statistical program (IBM SPSS Statistics 27) was used to calculate variance analyses, minimum and maximum values, means, percentage change rates, standard deviations, and homogeneity groups.

RESULTS AND DISCUSSION

The color parameters of all the specified woods before and after the bleaching process are presented in Table 2. The L^* values exhibited decreases in African ebony and black ebony wood species with both chemicals, while an increase was observed in Macassar ebony wood. The extent of the reduction in black ebony wood was found to be nearly double with the H_2O_2/NaOH bleaching system application compared to the oxalic acid chemical application. The highest L^* value was obtained from the specimens treated with H_2O_2/NaOH bleaching system in this wood species, while the lowest value was found in the control (unbleached) samples (Table 2).

The a^* values showed an increase in all wood types with both chemicals. The lowest a^* values for all wood species were obtained from the control samples. Whereas a^* values were negative only in African ebony under the control condition, bleaching treatments increased a^* values toward zero in African ebony and increased positive a^* values in black ebony and Macassar ebony compared to the control, indicating a shift toward redness in all wood species. For the control groups, highest a^* values were recorded as follows: -2.33, 0.57, and 0.66 for African ebony, Macassar ebony, and black ebony wood, respectively (Table 2).

The b^* values increased in all wood species with the application of both chemicals. The lowest b^* values for all wood species were observed in the control group. For the control groups, the highest b^* values were found to be 6.12, 5.72, and 4.26 for black ebony, Macassar ebony, and African ebony wood, respectively. Positive results were obtained for all wood species. In Macassar ebony wood, the b^* values showed a moderate increase with oxalic acid chemical and a larger increase with hydrogen peroxide/sodium hydroxide mixture. The chemical treatment with oxalic acid showed a higher b^* value for black ebony wood compared to the H_2O_2/NaOH bleaching system treatment (Table 2).

Table 2. Color Parameters Results for Wooden Materials Before and After Bleaching

Wood Type	Test	Treatment	Mean	Change (%)	*HG*	*SD*	Mini-mum	Maxi-mum	COV
African ebony (*Diospyros crassiflora* Hiern.)	*L**	Control	28.48	-	A*	0.47	27.70	29.17	1.64
		$C_2H_2O_4$	25.93	↓8.95	C**	0.70	24.99	26.73	2.70
		H_2O_2 + NaOH	27.11	↓4.81	B	1.02	25.35	28.89	3.76
	*a**	Control	-2.33	-	C**	0.17	-2.59	-2.13	-7.23
		$C_2H_2O_4$	-1.45	↑37.77	B	0.05	-1.52	-1.35	-3.71
		H_2O_2 + NaOH	-0.78	↑66.52	A*	0.18	-1.03	-0.35	-23.36
	*b**	Control	4.26	-	B**	0.36	3.93	5.03	8.53
		$C_2H_2O_4$	4.72	↑10.80	B	0.31	4.39	5.19	6.66
		H_2O_2 + NaOH	5.36	↑25.82	A*	0.86	3.99	7.02	15.97
	*C**	Control	4.87	-	B**	0.35	4.48	5.54	7.11
		$C_2H_2O_4$	4.94	↑1.44	AB	0.30	4.63	5.40	6.03
		H_2O_2 + NaOH	5.43	↑11.50	A*	0.86	4.01	7.06	15.88
	h°	Control	118.76	-	A*	2.29	114.90	121.10	1.93
		$C_2H_2O_4$	107.19	↓9.74	B	1.33	105.69	109.13	1.24
		H_2O_2 + NaOH	98.31	↓17.22	C**	1.60	95.04	100.54	1.63
Black ebony (*Diospyros ebenum*)	*L**	Control	30.20	-	A*	0.55	29.49	31.10	1.82
		$C_2H_2O_4$	27.82	↓7.88	B	0.34	27.19	28.13	1.23
		H_2O_2 + NaOH	25.70	↓14.90	C**	0.38	25.24	26.54	1.47
	*a**	Control	0.66	-	C**	0.26	0.34	1.02	39.49
		$C_2H_2O_4$	3.34	↑406.06	A*	0.49	2.55	4.09	14.77
		H_2O_2 + NaOH	1.67	↑153.03	B	0.35	1.23	2.30	21.05
	*b**	Control	6.12	-	C**	0.34	5.46	6.52	5.49
		$C_2H_2O_4$	8.93	↑45.92	A*	0.50	8.25	9.46	5.55
		H_2O_2 + NaOH	6.63	↑8.33	B	0.64	5.36	7.24	9.61
	*C**	Control	6.16	-	C**	0.35	5.47	6.58	5.66
		$C_2H_2O_4$	9.55	↑55.03	A*	0.60	8.63	10.31	6.28
		H_2O_2 + NaOH	6.84	↑11.04	B	0.68	5.52	7.51	9.96
	h°	Control	83.84	-	A*	2.29	80.48	86.67	2.73
		$C_2H_2O_4$	69.56	↓17.03	C**	2.19	66.61	72.78	3.15
		H_2O_2 + NaOH	75.95	↓9.41	B	2.09	71.98	78.82	2.76
Macassar ebony (*Diospyros celebica* Bakh.)	*L**	Control	31.54	-	B**	1.02	29.55	32.99	3.23
		$C_2H_2O_4$	31.67	↑0.41	B	0.43	31.15	32.65	1.37
		H_2O_2 + NaOH	36.77	↑16.58	A*	1.02	34.88	38.70	2.77
	*a**	Control	0.57	-	C**	0.22	0.23	0.83	38.70
		$C_2H_2O_4$	2.10	↑268.42	B	0.20	1.76	2.49	9.73
		H_2O_2 + NaOH	3.30	↑478.95	A*	0.30	2.81	3.75	9.10
	*b**	Control	5.72	-	C**	0.41	5.10	6.56	7.09
		$C_2H_2O_4$	7.17	↑25.35	B	0.38	6.75	8.01	5.31
		H_2O_2 + NaOH	10.35	↑80.94	A*	0.60	9.25	11.33	5.82
	*C**	Control	5.75	-	C**	0.41	5.11	6.57	7.12
		$C_2H_2O_4$	7.47	↑29.91	B	0.41	7.04	8.39	5.45
		H_2O_2 + NaOH	10.87	↑89.04	A*	0.66	9.66	11.89	6.04
	h°	Control	84.32	-	A*	2.15	81.65	87.66	2.55
		$C_2H_2O_4$	73.87	↓12.39	B	0.99	72.69	75.46	1.34
		H_2O_2 + NaOH	72.32	↓14.23	C**	0.81	71.38	73.74	1.12

COV: Coefficient of Variation, Number of measurements: 10, *HG*: Homogeneity Group
SD: Std. Deviation, *: Maximum value, **: Minimum value
Control: This experimental group did not undergo any bleaching process.
$C_2H_2O_4$: Oxalic acid, H_2O_2: Hydrogen peroxide, NaOH: Sodium hydroxide

The *C** values increased in all wood species with the application of both chemicals. The lowest *C** values for all wood species were obtained from the control group. For the control groups, the highest *C** values were determined to be 4.87, 5.75, and 6.16 for African ebony, Macassar ebony, and black ebony wood, respectively. The H_2O_2/NaOH bleaching system chemical resulted in approximately 10 times more increase in *C** parameter for African ebony wood compared to the oxalic acid chemical (Table 2).

The *h*° values decreased in all wood species with the application of both chemicals. The highest *h*° values for all wood species were obtained from the control group samples. The oxalic acid chemical application resulted in a higher reduction in *h*° values for black ebony wood compared to the H_2O_2/NaOH bleaching system application (Table 2).

Total color differences are presented in Table 3. The Δ*L** values were negative (darker than the reference) for African ebony and black ebony wood species, while they were positive (lighter than the reference) for Macassar ebony wood (Table 3).

The bleaching process showed its strongest impact on Macassar ebony when using the H_2O_2/NaOH system which produced the most substantial color variation (Δ*E** = 7.50). The value indicates that the color difference between the two samples reached a level that most people can see. The increases in Δ*a** (more red), Δ*b** (more yellow), and Δ*C** (clearer and more vivid) values indicate notable changes in chromatic coordinates, reflecting alterations in surface color properties. The oxalic acid treatment produced a smaller change in color (Δ*E** = 2.12), which indicates that it reacts less forcefully with the components of wood. It is proposed that the three species show different bleaching behaviors because their chemical makeup contains different amounts of extractives and phenolic compounds and tannins. The extractive content of African ebony and black ebony reaches higher levels, which creates problems for bleaching operations and results in uneven color changes. The chemical structure of Macassar ebony differs from others which enables better oxidation of its chromophoric groups when treated with alkaline hydrogen peroxide. The research findings show that bleaching treatment success depends on species type with H_2O_2/NaOH system achieving best color change for Macassar ebony (Table 3).

Table 3. Total Color Difference Results Determined in Different Wood Species after Bleaching Applications

Wood type	Treatment	Δ*L**	Δ*a**	Δ*b**	Δ*C**	Δ*H**	Δ*E**	Color change criterion (Cividini *et al*. 2007)
African ebony	$C_2H_2O_4$	-2.54	0.88	0.45	0.07	0.99	2.73	Color difference visible with high quality screen (3>Δ*E**>2)
	H_2O_2 + NaOH	-1.37	1.55	1.10	0.56	1.82	2.34	
Black ebony	$C_2H_2O_4$	-2.38	2.68	2.82	3.39	1.90	4.56	Color difference visible with medium quality screen (6>Δ*E**>3)
	H_2O_2 + NaOH	-4.49	1.01	0.52	0.69	0.90	4.63	
Macassar ebony	$C_2H_2O_4$	0.13	1.53	1.46	1.72	1.23	2.12	Color difference visible with high quality screen (3>Δ*E**>2)
	H_2O_2 + NaOH	5.23	2.74	4.64	5.12	1.65	7.50	High color difference (12>Δ*E**>6)

$C_2H_2O_4$: Oxalic acid, H_2O_2: Hydrogen peroxide, NaOH: Sodium hydroxide

When comparing the results obtained in this study with the color criteria, it was found that both bleaching chemicals from African ebony wood met the "*Color difference visible with high-quality screen* (3>Δ*E**>2)*"* criterion, while both bleaching chemicals from black ebony wood met the "*color difference visible with medium-quality screen* (6>Δ*E**>3)*"* criterion. In the case of Macassar ebony wood, oxalic acid chemical application resulted in meeting the "*color difference visible with high-quality screen* (3>Δ*E**>2)" criterion, while the H_2O_2/NaOH bleaching system application met the "*high color difference* (12>Δ*E**>6)" criterion (Table 3). The Δ*E** values obtained from oxalic acid and H_2O_2/NaOH bleaching on olon wood were found to be 2.07 for the single-component treatment and 10.30 for the two-component treatment (Peker and Ayata, 2023).

The results of the variance analysis calculated for different wood species regarding color parameters are given in Table 4. According to these results, all parameters except the *C** parameter in Africa ebony wood, and all color parameters in the measurements taken for the other two wood types, were determined to be statistically significant (Table 4).

Table 4. Analysis of Variance Results for Color Parameters

Wood Type	Source	Dependent Variable	Sum of Squares	Degrees of Freedom	Mean Square	F Value	*: Significant
African ebony (*Diospyros crassiflora* Hiern.)	Type of Bleaching Chemical	*L**	32.424	2	16.212	27.835	0.000*
		*a**	12.071	2	6.036	279.556	0.000*
		*b**	6.113	2	3.056	9.502	0.001*
		*C**	1.851	2	0.925	2.920	0.071
		h°	2103.161	2	1051.580	329.769	0.000*
	Error	*L**	15.726	27	0.582		
		*a**	0.583	27	0.022		
		*b**	8.685	27	0.322		
		*C**	8.558	27	0.317		
		h°	86.099	27	3.189		
	Total	*L**	22194.960	30			
		*a**	82.179	30			
		*b**	700.728	30			
		*C**	783.484	30			
		h°	352668.923	30			
	Corrected Total	*L**	48.149	29			
		*a**	12.654	29			
		*b**	14.798	29			
		*C**	10.409	29			
		h°	2189.259	29			
Black ebony (*Diospyros ebenum*)	Type of Bleaching Chemical	*L**	101.095	2	50.547	268.818	0.000*
		*a**	36.602	2	18.301	126.260	0.000*
		*b**	45.020	2	22.510	88.230	0.000*
		*C**	64.207	2	32.104	101.853	0.000*
		h°	1022.959	2	511.479	106.189	0.000*
	Error	*L**	5.077	27	0.188		
		*a**	3.914	27	0.145		
		*b**	6.889	27	0.255		
		*C**	8.510	27	0.315		
		h°	130.051	27	4.817		
	Total	*L**	23467.400	30			
		*a**	147.641	30			
		*b**	1619.084	30			
		*C**	1766.824	30			
		h°	176491.085	30			
	Corrected Total	*L**	106.172	29			
		*a**	40.516	29			

Wood Type	Source	Dependent Variable	Sum of Squares	Degrees of Freedom	Mean Square	F Value	*: Significant
		b^*	51.909	29			
		C^*	72.718	29			
		h^o	1153.010	29			
Macassar ebony (*Diospyros celebica* Bakh.)	Type of Bleaching Chemical	L^*	177.833	2	88.917	117.781	0.000*
		a^*	37.610	2	18.805	313.103	0.000*
		b^*	112.364	2	56.182	250.473	0.000*
		C^*	135.913	2	67.956	266.798	0.000*
		h^o	851.839	2	425.919	204.396	0.000*
	Error	L^*	20.383	27	0.755		
		a^*	1.622	27	0.060		
		b^*	6.056	27	0.224		
		C^*	6.877	27	0.255		
		h^o	56.262	27	2.084		
	Total	L^*	33518.218	30			
		a^*	158.035	30			
		b^*	1919.520	30			
		C^*	2077.699	30			
		h^o	178015.081	30			
	Corrected Total	L^*	198.216	29			
		a^*	39.232	29			
		b^*	118.420	29			
		C^*	142.790	29			
		h^o	908.101	29			
*: Significant if is less than or equal to 0.05							

Table 5. Whiteness Index (WI^*) for Wooden Materials Before and After Bleaching

Wood Type	Test	Treatment	Mean	Change (%)	*HG*	*SD*	Mini-mum	Maxi-mum	COV
African ebony (*Diospyros crassiflora* Hiern.)	WI^* (⊥)	Control	4.79	-	A*	0.34	4.20	5.10	7.13
		$C_2H_2O_4$	3.58	↓25.26	B	0.08	3.50	3.70	2.20
		H_2O_2 + NaOH	3.42	↓28.60	B**	0.08	3.30	3.50	2.31
	WI^* (∥)	Control	1.69	-	A	0.22	1.50	2.00	12.92
		$C_2H_2O_4$	1.50	↓11.24	B**	0.07	1.40	1.60	4.44
		H_2O_2 + NaOH	1.76	↑4.14	A*	0.12	1.60	1.90	6.67
Black ebony (*Diospyros ebenum*)	WI^* (⊥)	Control	5.21	-	A*	0.20	5.00	5.50	3.78
		$C_2H_2O_4$	3.05	↓41.46	B	0.11	2.90	3.20	3.54
		H_2O_2 + NaOH	2.84	↓45.49	C**	0.25	2.60	3.30	8.97
	WI^* (∥)	Control	1.89	-	A*	0.21	1.60	2.20	11.28
		$C_2H_2O_4$	1.16	↓38.62	C**	0.24	0.90	1.40	20.40
		H_2O_2 + NaOH	1.34	↓29.10	B	0.05	1.30	1.40	3.85
Macassar ebony (*Diospyros celebica* Bakh.)	WI^* (⊥)	Control	6.62	-	A*	0.12	6.50	6.80	1.86
		$C_2H_2O_4$	5.36	↓19.03	C**	0.05	5.30	5.40	0.96
		H_2O_2 + NaOH	6.28	↓5.14	B	0.15	6.00	6.40	2.47
	WI^* (∥)	Control	1.62	-	B	0.12	1.50	1.80	7.59
		$C_2H_2O_4$	1.52	↓6.17	B**	0.08	1.40	1.60	5.19
		H_2O_2 + NaOH	4.12	↑154.32	A*	0.60	3.50	4.90	14.51

COV: Coefficient of Variation, Number of measurements: 10, *HG*: Homogeneity Group
SD: Std. Deviation, *: Maximum value, **: Minimum value
Control: This experimental group did not undergo any bleaching process.
$C_2H_2O_4$: Oxalic acid, H_2O_2: Hydrogen peroxide, NaOH: Sodium hydroxide

All the whiteness index values for the identified woods before and after the bleaching process are presented in Table 5. The two different wood bleaching chemicals used in the study significantly altered the whiteness index values of different wood species due to their distinct chemical properties. These results are supported by variance analysis (ANOVA). In all wood species, both wood bleaching chemicals exhibited a decrease in *WI** values in the perpendicular (⊥) direction to the fibers. The *WI** ⊥ values for the African ebony, black ebony, and Macassar ebony wood species were obtained from the highest control group samples and determined as 4.79, 5.21, and 6.62, respectively. With both bleaching chemicals, reductions were observed in all wood species in directions perpendicular to the fibers (Table 5).

The results of the variance analysis calculated for whiteness index (*WI** ⊥ and ‖) values in different wood species are given in Table 6. According to these results, it is seen that significant data were obtained in both directions (⊥ and ‖) in *WI** measurements for all wood types (Table 6).

Table 6. Analysis of Variance Results for Whiteness Index (*WI** ⊥ and ‖) Values

Wood Type	Source	Dependent Variable	Sum of Squares	Degrees of Freedom	Mean Square	F Value	*: Significant
African ebony	Bleaching Chemical	*WI** (⊥)	11.222	2	5.611	130.488	0.000*
		*WI** (‖)	0.362	2	0.181	8.241	0.002*
	Error	*WI** (⊥)	1.161	27	0.043		
		*WI** (‖)	0.593	27	0.022		
	Total	*WI** (⊥)	475.730	30			
		*WI** (‖)	82.630	30			
	Corrected Total	*WI** (⊥)	12.383	29			
		*WI** (‖)	0.955	29			
Black ebony	Bleaching Chemical	*WI** (⊥)	34.422	2	17.211	447.685	0.000*
		*WI** (‖)	2.893	2	1.446	41.677	0.000*
	Error	*WI** (⊥)	1.038	27	0.038		
		*WI** (‖)	0.937	27	0.035		
	Total	*WI** (⊥)	446.160	30			
		*WI** (‖)	68.070	30			
	Corrected Total	*WI** (⊥)	35.460	29			
		*WI** (‖)	3.830	29			
Macassar ebony	Bleaching Chemical	*WI** (⊥)	8.499	2	4.249	305.138	0.000*
		*WI** (‖)	43.400	2	21.700	171.919	0.000*
	Error	*WI** (⊥)	0.376	27	0.014		
		*WI** (‖)	3.408	27	0.126		
	Total	*WI** (⊥)	1120.300	30			
		*WI** (‖)	222.500	30			
	Corrected Total	*WI** (⊥)	8.875	29			
		*WI** (‖)	46.808	29			

*: Significant if is less than or equal to 0.05

It was reported that bleaching treatments with oxalic acid and H_2O_2/NaOH on Ceylon satinwood wood resulted in *WI** values increasing in the direction parallel to the fibers and the h^o parameter increasing, while *a** and *C** decreased (Ayata and Çamlıbel, 2023). In another study, it was found that h^o and *L** values increased with oxalic acid and H_2O_2/NaOH bleaching treatments applied to olon wood. In addition, while *a**, *b** and *C** values decreased with H_2O_2/NaOH bleaching, these parameters increased with oxalic acid bleach. *WI** values showed an increase in both directions with both bleaching chemicals

(Peker and Ayata 2023). A graphical representation of the results for color parameters and whiteness index (*WI**) values is presented in Fig. 1.

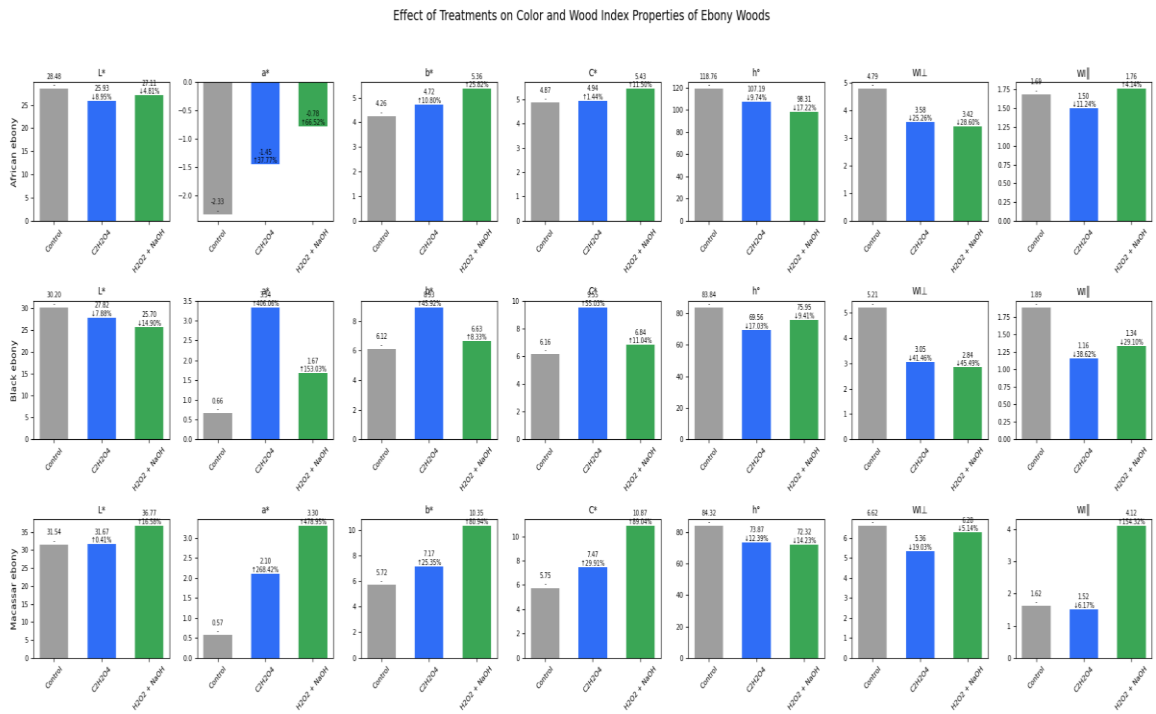

Fig. 1. Graphical representation of the results regarding color parameters and whiteness index (*WI**) values

For black ebony, the black heartwood may exhibit a dark blue tint, and the pores are often completely filled with black pigments, making them almost invisible on the surface. The fiber orientation is irregular. The wood is generally chemically inactive, except in the case of a polyester varnish which is inhibited by the pigments and has a propensity for discoloration due to wood extracts (Schmerbeck and Naudiyal 2017). The reasons for changes in overall color variations, color parameters, and whiteness index values may include the following: the NaOH pretreatment dissolves extractives on the surface of the wood, and then, the color-emitting groups, color-assisting groups, and coloring-related components in the wood are destroyed by oxidation, reduction, and degradation through the bleaching agent. Therefore, the wood is decolorized (Lu *et al*. 2023). Throughout the bleaching process, the wood constituents, primarily lignin, undergo degradation, significant alteration, chlorination, and ultimately dissolve into the effluent. Consequently, the effluent produced from bleaching appears dark brown in hue, which can be attributed to the presence of chromophoric polymeric lignin derivatives (Springer 1993). The surface modification will remove color chromophores that are associated with functional groups bound to lignin. It is widely recognized that bleaching with H_2O_2 in thermomechanical pulp production decreases the presence of wood extracts in the pulp and enhances the pulp's brightness. Throughout this process, quinones, which are constituents of lignin groups responsible for color, undergo oxidation and convert into colorless forms, while coniferyl aldehyde groups and conjugated double bond structures within lignin are broken down (Lindholm *et al*. 2009).

CONCLUSIONS

1. After the application of both chemical treatments (oxalic acid and a combination of hydrogen peroxide and NaOH) to the wood surfaces, the *b**, *a** and *C** values increased, while the *h*° values decreased in all wood species.
2. In all wood species, application of oxalic acid chemical resulted in a decrease in whiteness index (*WI**) values in both perpendicular and parallel directions to the fibers.
3. This study investigated the effects of oxalic acid and alkaline hydrogen peroxide (H_2O_2/NaOH) bleaching systems on African ebony, black ebony, and Macassar ebony woods. The results showed that bleaching efficiency varied depending on both the wood species and the chemical system used. Overall, Macassar ebony exhibited the most pronounced color change, particularly under the H_2O_2/NaOH treatment, while African and black ebony showed comparatively moderate changes.
4. The differences among species are mainly attributed to variations in their chemical composition, including extractives, phenolic compounds, and tannins, which influence their reaction to bleaching agents.
5. It is recommended that future studies evaluate the long-term stability of bleached wood under natural or artificial weathering conditions.

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