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THE EFFECTS OF THERMAL AGING ON COLOR AND GLOSSINESS IN UV CURED COATINGS APPLIED TO SESSILE OAK

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ABSTRACT

Color and glossiness are two important aesthetic properties of wood flooring and wood furniture that significantly affect consumers choice. With time the coating deteriorates altering the surface properties. Understanding these changes is important for furniture industry, impacting design choices, material selection, and long-term maintenance.

The effects of thermal aging (30 °C for 30 days, 60 °C for 60 days, and 90 °C for 90 days) on color parameters (C^*, L^*, b^*. a^*, h^o) and glossiness on both perpendicular ($\perp$) and parallel ($\parallel$) directions at 20°, 60°, and 85° angles in UV-cured coatings applied on sessile oak were studied. Results show that statistically significant differences were observed in the glossiness values, as well as in C^*, b^*, a^*, L^* and h^o. As the temperature and duration of the thermal aging process increased, there was a noticeable increase in the values of color parameters b^*, a^*, and C^*, while the values of h^o and L^* decreased. The characteristics of the surfaces exposed to thermal aging have undergone a complete transformation.

Keywords: Coating, color, glossiness, sessile oak, wood surface quality, thermal aging, wood flooring

INTRODUCTION

In laminate flooring, the top surface is typically coated with 5-7 layers of acrylic or polyurethane varnishes and cured using an ultraviolet (UV) system. Deteriorations that occur over time on the top surface of varnished flooring can be repaired by sanding off the damaged varnish layer and reapplying a new varnish coat (Döngel 2005). UV-cured coatings continue to find application in several furniture and kitchen cabinet scenarios. For wooden furniture, 100 % solid UV lacquer has been recognized as the most environmentally friendly choice for surface coating (Gustafsson and Borjesson 2007). Generally, UV-curable formulations usually consist of oligomers or prepolymers that contain reactive regions centered around a functional acrylate group to adhere to regulations regarding volatile organic compounds (VOCs).

A variety of acrylated prepolymers with different backbone structures, including epoxy acrylates, polyester acrylates, urethane acrylates, acrylic oils, polyether acrylates, are readily available (Narayan 2002). UV curing provides several benefits, including rapid drying, the ability to coat heat-sensitive substrates, fast curing times, minimal space requirements, and a low capital investment for curing equipment (Wang *et al.* 2008, Moon *et al.* 2005). The term "radiation curing" is used to describe processes in which physical changes occur when electromagnetic radiation interacts with matter. These physical changes can manifest in various ways. For instance, a liquid can be converted into a solid, alterations in solubility can take place, or there can be modifications in hardness, toughness, or brittleness (Davidson 2001).

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A comprehensive description of coatings that can be cured with UV involves coatings that solidify and harden when subjected to intense UV radiation. A more precise and chemical interpretation would refer to coatings that undergo curing via chain-growth polymerization initiated by free radicals in unsaturated monomers and oligomers (Fibiger 1998). UV-curable formulations, which are most frequently employed, consist mainly of unsaturated acrylates because of their heightened reactivity and a broad selection of monomers. Polyurethane acrylates are extensively utilized as oligomers in UV coatings due to their ability to offer exceptional physical and mechanical characteristics, strong adhesion, high flexibility, and remarkable impact resistance (Takami *et al.* 2011).

Artificial weathering simulates natural weathering, spending far less time than would be necessary in natural weathering. Although in artificial weathering wood is not subjected to biotic effects, the major changes still occur, and biotic effects are generally not important in wood flooring applications. One of the most important properties that significantly affect wood degradation due to weathering is temperature and therefore studies on thermal aging are important (Liu *et al.* 2017, Tolvaj *et al.* 2013). There are several studies on the variations of color and glossiness with artificial weathering and thermal aging, but the studies have shown that the changes depend on the species and on the applied varnishes.

For example, Salca *et al.* (2021) studied the glossiness of black alder wood (*Alnus glutinosa* L.) samples coated with two varnish types and concluded that UV varnish exhibited higher gloss than the ones coated with a water-borne varnish and that the gloss values of the samples decreased with the exposure time to artificial aging. Artificial weathering of lemon wood (*Citrus limon* (L.) Burm.) (Ayata 2019), apricot (*Prunus armeniaca* L.) (Ayata *et al.* 2021a), acacia (*Robinia pseudoacacia* L.) (Ayata *et al.* 2021b), taurus cedar (*Cedrus libani* A. Rich) (Ayata *et al.* 2021c), black poplar (*Populus nigra* L.) (Ayata *et al.* 2022a), russian olive (*Elaeagnus angustifolia* L.) (Ayata *et al.* 2022b) and pine radiata (*Pinus radiata* D. Don) (Sahin *et al.* 2023) showed that generally lightness (*L**) color parameter and parallel and perpendicular gloss decrease for 20 º and 60 º angles.

Thermal aging studies with iroko (*Milicia excelsa* Welw. C.C. Berg) (Ayata and Bal 2023b), sapele (*Entandrophragma cylindricum* Harms) (Ayata and Bal 2023a), beech (*Fagus orientalis* Lipsky), northern red oak (*Quercus rubra* L.), walnut (*Juglans regia* L.), American black walnut (*Juglans nigra* L.) and maple (*Acer pseudoplatanus* L.) (Ayata *et al.* 2018), show that the changes on color and glossiness are similar to those observed in artificial weathering with a general decrease in *L** and glossiness and *a** and *b** depending on the initial wood color. A decrease in gloss with thermal aging has been also reported for several varnishes applied on scots pine (*Pinus sylvestris* L.), eastern beech (*Fagus orientalis* L.), and sessile oak (*Quercus petraea* L.) (Demirci *et al.* 2013).

Changes with thermal treatment have been proven to differ for heartwood and sapwood tissues. For example, Sjökvist *et al.* (2019) obtain no differences in moisture content on heartwood and sapwood of coated samples of Norway spruce wood, contrary to the reported before for uncoated wood where uncoated heartwood absorbed less amount of water compared to sapwood in the tangential and longitudinal directions (Blom *et al.* 2013, Sjökvist *et al.* 2018). According to these authors this is due to the coating that reduces the differences in water sorption probably due to wetting properties and different sorption mechanisms (Sjökvist *et al.* 2019) or due to the coating potentially inhibit the influence of wood extractives on water absorption (Sjökvist *et al.* 2020).

There are also differences between hardwoods and softwoods. Concerning color, hardwoods typically undergo discoloration at lower temperatures compared to softwoods. However, it is normally observed that heat can directly influence color by triggering hydrolysis and oxidation of wood components (Sandoval-Torres *et al.* 2010).

Temperature plays a significant role in the color changes of wood surfaces due to its impact on chemical reactions and physical processes within the wood, it can also accelerate oxidation reactions in wood, causing changes in color over time (Gao *et al.* 2004). Oxidation reactions lead to the formation of compounds that darken the wood surface. These changes can happen at low to moderate temperatures at around 65 ºC (Sandoval-Torres *et al.* 2010, White and Dietenberger 2001).

In this study, surface changes resulting from thermal aging of UV cured coating applied on sessile oak wood surfaces were investigated. Understanding the influence of temperature on wood surface color changes is crucial for various applications such as woodworking, furniture making, conservation of wooden artifacts, and understanding the behavior of wood in different environmental conditions. By controlling temperature conditions, one can potentially manipulate and manage the color stability and appearance of wood surfaces.

Materials and methods

Sessile oak (*Quercus petraea*) wood was obtained from a commercial supplier, ensuring it met the highest quality standards, and it had dimensions of 100 x 500 x 17 mm (Rigorous criteria were applied to select the test samples, ensuring they were chosen randomly, without cracks, possessed consistent fibers, had no knots or imperfections, and exhibited uniform color and density. Subsequently, the samples were prepared following the TS ISO 13061-1 (2021) and TS ISO 642 554 (1997).

UV coating application

Samples measuring 50 cm × 10 cm × 1,7 cm (lengthwise × widthwise × thickness) were extracted from each untreated wood specimen. Subsequently, these samples underwent coating with a UV system typically employed for laminated parquet, following the procedures described before (Ayata *et al.* 2018. In the UV varnish application, wood material surfaces were initially subjected to calibration sanding processes (80, 120 and 220 grit). Following this, the application was completed with the following processes: UV parquet paste (25 g/m^2) + UV lamp curing (80 °C) + UV Sealer Clear S (25 g/m^2) + UV lamp curing (80 °C) + UV Sealer Clear S (25 g/m^2) + UV lamp curing (400 °C) + sanding (280 and 320 grit) + UV antiscratch semi matt (7,5 g/m^2) + UV lamp curing (80 °C) + UV antiscratch semi matt (7,5 g/m^2) + UV lamp curing (400 °C). This application was conducted at the KPS factory located in Duzce, Turkey. Post-application, the samples were sectioned into smaller units measuring 10 cm × 10 cm × 1,7 cm. All samples were then stored in a controlled environment with 65 % ± 3 relative humidity and at a temperature of 20 °C ± 2 °C until they reached a constant weight, adhering to the specifications outlined in the TS ISO 642 554 (1997) standard.

Thermal aging applications

The thermal aging applications for the samples treated with UV system parquet varnish were conducted at different temperatures and durations (30 °C for 30 days, 60 °C for 60 days, and 90 °C for 90 days) three weeks after the application. The untreated experimental samples are referred to as the control. The Microtest MST series incubator device (Saray street 676. Cd. No: 22 (Aksan Yapı Kooperatifi) Ankara, Turkey) was used for the thermal aging applications.

Determination of glossiness characteristics

Glossiness characteristics were assessed in accordance with the ISO 2813 (1994) standard. Glossiness tests were carried out utilizing the ETB-0833 model gloss meter device (Shenzhen Graigar technology CO., LTD., Xinfu Building, Center Road, Shajing Street, Baoan District, Shenzhen CN) at three distinct angles (20°, 60°, and 85°) in both perpendicular and parallel orientations to the wood fibers.

Determination of color properties

The color changes of the samples were quantified using a CS-10 device (CHN Spec. Hangzhou City, China) manufactured by CHN Spec, China. This measurement was based on the CIELAB color system, and it followed the ASTM D 2244-3 (2007) standard. The assessments were carried out under CIE 10° standard observer conditions and CIE D65 light source, with an 8/d (8°/diffuse illumination) lighting system. ΔE^* values representing color differences for visual assessment are presented in Table 1 according to the comparison criteria established by Barański *et al.* 2017.

Table 1: Color change criteria by Barański *et al.* (2017).

Color change criteria	ΔE^* value
Invisible color change	$\Delta E^* < 0{,}2$
Slight change of color	$2 > \Delta E^* > 0{,}2$
Color change visible in high filter	$3 > \Delta E^* > 2$
Color change visible with average quality of filter	$6 > \Delta E^* > 3$
High color change	$12 > \Delta E^* > 6$
Different color	$\Delta E^* > 12$

The results for total color differences were determined using the following Equation 1, Equation 2, Equation 3, Equation 4, Equation 5, Equation 6, Equation 7 and Equation 8:

$$C^* = \left[\left(a^*\right)^2 + \left(b^*\right)^2 \right]^{0,5} \quad (1)$$

$$h^o = arctan\left(\frac{b^*}{a^*}\right) \quad (2)$$

$$\Delta C^* = \left(C^* thermal\ aged\ test\ sample - C^* unaged\ test\ sample\right) \quad (3)$$

$$\Delta a^* = \left(a^* thermal\ aged\ test\ sample - a^* unaged\ test\ sample\right) \quad (4)$$

$$\Delta L^* = \left(L^* thermal\ aged\ test\ sample - L^* unaged\ test\ sample\right) \quad (5)$$

$$\Delta b^* = \left(b^* thermal\ aged\ test\ sample - b^* unaged\ test\ sample\right) \quad (6)$$

$$\Delta H^* = \left[\left(\Delta E^*\right)^2 - \left(\Delta L^*\right)^2 - \left(\Delta C^*\right)^2 \right]^{0,5} \quad (7)$$

$$\Delta E^* = \left[\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 \right]^{0,5} \quad (8)$$

The definitions of Δb^*, Δa^*, ΔC^*, ΔH^*, and ΔL^* are provided below (Lange 1999):

ΔC^* : Chroma or saturation difference, positive sample is clearer and brighter than the reference and negative sample is duller than the reference

ΔL^* : Negative sample is darker than the reference and positive sample is lighter than the reference

Δb^* : Negative sample is bluer than the reference and positive sample is more yellow than the reference

Δa^* : Negative sample is greener than the reference and positive sample is redder than the reference,

ΔH^* : Hue or shade difference.

Statistical analysis

After analyzing the data collected in the study through a statistical software, various metrics were computed, including maximum and minimum values, standard deviations, means, multivariate analysis of variances, percentage (%) change rates, and groups based on homogeneity.

RESULTS AND DISCUSSION

The results of the multivariate analysis of variance are presented in Table 2. These results indicate that there were statistically significant differences observed in the lightness (L^*) value, chroma (C^*) value, yellow (b^*) and red (a^*) color tone values, hue (h^o) angle value, as well as the glossiness values in both perpendicular (⊥) and parallel (∥) directions at 20°, 60°, and 85° angles.+

Table 2: Results of multivariate analysis of variance.

Source	Dependent Variable	Sum of Squares	df	Mean Square	F	Sig.
Thermal Aging Time	Lightness (L^*)	619,740	3	206,580	2652,173	0,000*
	Red (a^*) color tone	28,024	3	9,341	724,482	0,000*
	Yellow (b^*) color tone	37,522	3	12,507	232,460	0,000*
	Chroma (C^*) value	52,887	3	17,629	296,154	0,000*
	Hue (h^o) angle	62,276	3	20,759	565,722	0,000*
	Glossiness at ⊥20°	1,727	3	0,576	110,807	0,000*
	Glossiness at ⊥60°	18,937	3	6,312	95,199	0,000*
	Glossiness at ⊥85°	36,578	3	12,193	194,391	0,000*
	Glossiness at ∥20°	1,174	3	0,391	108,369	0,000*
	Glossiness at ∥60°	27,035	3	9,012	52,803	0,000*
	Glossiness at ∥85°	301,358	3	100,453	149,694	0,000*
Error	Lightness (L^*)	2,804	36	0,078		
	Red (a^*) color tone	0,464	36	0,013		
	Yellow (b^*) color tone	1,937	36	0,054		
	Chroma (C^*) value	2,143	36	0,060		
	Hue (h^o) angle	1,321	36	0,037		
	Glossiness at ⊥20°	0,187	36	0,005		
	Glossiness at ⊥60°	2,387	36	0,066		
	Glossiness at ⊥85°	2,258	36	0,063		
	Glossiness at ∥20°	0,130	36	0,004		
	Glossiness at ∥60°	6,144	36	0,171		
	Glossiness at ∥85°	24,158	36	0,671		
Total	Lightness (L^*)	152423,425	40			
	Red (a^*) color tone	2513,841	40			
	Yellow (b^*) color tone	24592,971	40			
	Chroma (C^*) value	27105,951	40			
	Hue (h^o) angle	209699,246	40			
	Glossiness at ⊥20°	188,970	40			
	Glossiness at ⊥60°	6060,630	40			
	Glossiness at ⊥85°	628,660	40			
	Glossiness at ∥20°	200,220	40			
	Glossiness at ∥60°	11048,940	40			
	Glossiness at ∥85°	9098,960	40			
Corrected Total	Lightness (L^*)	622,544	39			
	Red (a^*) color tone	28,488	39			
	Yellow (b^*) color tone	39,459	39			
	Chroma (C^*) value	55,030	39			
	Hue (h^o) angle	63,597	39			
	Glossiness at ⊥20°	1,914	39			
	Glossiness at ⊥60°	21,324	39			
	Glossiness at ⊥85°	38,836	39			
	Glossiness at ∥20°	1,304	39			
	Glossiness at ∥60°	33,179	39			
	Glossiness at ∥85°	325,516	39			

*: Significant

The results for color parameters and glossiness values are provided in Table 3. According to these results, with an increase in temperature and duration of the thermal aging application, the values of color parameters *a**, *b**, and *C** increased, while *L** and h^{o} values decreased. The highest decrease rate for the *L** value was obtained at 90 °C for 90 days, with a percentage decrease of 16,46 %, while the lowest decrease rate was observed at 30 °C for 30 days, with a 5,80 % decrease.) (Table 3). Ayata *et al.* (2018) reported that in materials subjected to thermal aging (30 days at 30 °C, 60 days at 60 °C, and 90 days at 90 °C), the *L** values decreased in all species, including red oak, beech, maple, American walnut, and walnut, which had been coated with UV varnish. Similarly, Cavus (2021) obtained a decrease in *L** after artificial weathering of UV Varnish applied onto Mulberry Wood.

The control samples exhibited the lowest *a** value (6,67), whereas the highest *a** value was recorded in the experimental samples that underwent 90 days of thermal aging at 90 °C (9,02). This *a** increase corresponded to 35,35 %. The highest increase in the *b** value was noted during the 90 days of thermal aging at 90 °C, with a percentage increase of 10,47 % (26,39), while the most modest increase, at 1,26 %, was observed during the 30 days of thermal aging at 30 °C. The experimental samples subjected to 90 °C for 90 days of thermal aging exhibited the highest *C** value (27,89), whereas the control samples had the lowest *C** value (24,80) The most significant increase in the *C** value was observed after 90 days of thermal aging at 90 °C, with a percentage increase of 12,45 %. The lowest h^{o} value was determined in the experimental samples subjected to 90 days of thermal aging at 90 °C (71,13), 4,71 % of the initial samples while the highest h^{o} value was obtained in the control samples (74,41). Similar results were reported before for Sapele with thermal aging and UV system varnishing, where the samples subjected to 90 days of thermal aging at 90 °C showed the lowest values for *L**, *a**, *b**, and *C**, while the control group exhibited the highest values (Ayata and Bal 2023a) or Ayata and Bal (2023b) that reported that in UV system varnished iroko wood subjected to thermal aging, an increase in temperature and duration led to a decrease in *L**, *b**, and *C** parameters.

Temperatures used in the treatment were mild, therefore no significant changes in chemical composition are expected. In accordance with Kamperidou (2021) temperatures below 160 ºC do not cause any changes to lignin. There might however be some changes on hemicelluloses and extractives. Oxidation reactions have been mentioned to occur at low to moderate temperatures at around 65 ºC (Sandoval-Torres *et al.* 2010, White and Dietenberger 2001) and to lead to the formation of compounds that darken the wood surface. Nevertheless, results show that changes are observed even at 30 ºC with a 5,8 % change in lightness. The major increase is observed, however, at 90 ºC with a 16,46 % change in relation to initial *L**. Similar changes have been found for the remaining color parameters, *a*, b** and *C**. The major difference from initial wood was found for *a** with a 35,35 % increase which indicates a clear redness of the surface with also some yellowing with the increase in *b** values.

Table 3: Measurement results for color parameters and glossiness values.

Test	Thermal Aging Time	N	Mean	Change (%)	*HG*	*SD*	Minimum	Maximum	COV
*L**	Control	10	66,63	-	A*	0,37	66,06	67,27	0,55
	30 °C for 30 days	10	62,77	↓5,80	B	0,35	62,19	63,41	0,56
	60 °C for 60 days	10	61,35	↓7,93	C	0,19	61,02	61,60	0,31
	90 °C for 90 days	10	55,67	↓16,46	D**	0,12	55,55	55,90	0,22
*a**	Control	10	6,67	-	D**	0,10	6,59	6,95	1,54
	30 °C for 30 days	10	8,02	↑20,39	B	0,16	7,69	8,31	2,04
	60 °C for 60 days	10	7,82	↑17,33	C	0,10	7,69	7,94	1,23
	90 °C for 90 days	10	9,02	↑35,35	A*	0,07	8,93	9,14	0,78
*b**	Control	10	23,89	-	D**	0,15	23,71	24,20	0,64
	30 °C for 30 days	10	24,19	↑1,26	C	0,33	23,56	24,53	1,37
	60 °C for 60 days	10	24,64	↑3,15	B	0,10	24,53	24,76	0,39
	90 °C for 90 days	10	26,39	↑10,47	A*	0,27	25,97	26,78	1,03
*C**	Control	10	24,80	-	D**	0,17	24,62	25,18	0,67
	30 °C for 30 days	10	25,49	↑2,76	C	0,34	24,78	25,86	1,35
	60 °C for 60 days	10	25,85	↑4,23	B	0,12	25,73	26,00	0,46
	90 °C for 90 days	10	27,89	↑12,45	A*	0,28	27,46	28,30	0,99
h^o	Control	10	74,41	-	A*	0,18	73,98	74,63	0,24
	30 °C for 30 days	10	71,65	↓3,71	C	0,29	71,21	72,01	0,41
	60 °C for 60 days	10	72,39	↓2,71	B	0,15	72,22	72,63	0,20
	90 °C for 90 days	10	71,13	↓4,41	D**	0,08	71,01	71,28	0,12
⊥20°	Control	10	2,30	-	B	0,00	2,30	2,30	0,00
	30 °C for 30 days	10	2,37	↑3,04	A*	0,07	2,30	2,50	2,85
	60 °C for 60 days	10	2,15	↓6,52	C	0,08	2,00	2,20	3,95
	90 °C for 90 days	10	1,83	↓20,43	D**	0,09	1,70	2,00	5,18
⊥60°	Control	10	12,83	-	A*	0,25	12,30	13,10	1,98
	30 °C for 30 days	10	12,68	↓1,17	AB	0,14	12,50	13,00	1,10
	60 °C for 60 days	10	12,53	↓2,34	B	0,31	12,00	12,90	2,50
	90 °C for 90 days	10	11,11	↓13,41	C**	0,29	10,80	11,60	2,60
⊥85°	Control	10	5,04	-	A*	0,24	4,80	5,40	4,70
	30 °C for 30 days	10	4,17	↓17,26	B	0,30	3,90	4,60	7,24
	60 °C for 60 days	10	3,76	↓25,40	C	0,29	3,40	4,10	7,65
	90 °C for 90 days	10	2,39	↓52,58	D**	0,14	2,20	2,60	6,06
∥20°	Control	10	2,33	-	B	0,07	2,20	2,40	2,90
	30 °C for 30 days	10	2,40	↑3,00	A*	0,00	2,40	2,40	0,00
	60 °C for 60 days	10	2,24	↓3,86	C	0,08	2,10	2,30	3,76
	90 °C for 90 days	10	1,95	↓16,31	D**	0,05	1,90	2,00	2,70
∥60°	Control	10	17,20	-	A*	0,24	17,00	17,70	1,37
	30 °C for 30 days	10	16,94	↓1,51	A	0,14	16,70	17,20	0,84
	60 °C for 60 days	10	17,06	↓0,81	A	0,69	15,80	17,70	4,07
	90 °C for 90 days	10	15,18	↓11,74	B**	0,35	14,70	15,60	2,32
∥85°	Control	10	17,86	-	A*	1,02	15,30	18,60	5,74
	30 °C for 30 days	10	14,73	↓17,53	C	0,47	14,00	15,60	3,19
	60 °C for 60 days	10	16,19	↓9,35	B	1,10	13,80	17,70	6,82
	90 °C for 90 days	10	10,46	↓41,43	D**	0,44	9,70	11,10	4,23

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

In measurements conducted at a 20-degree angle, it is observed that glossiness values in the perpendicular direction to the fibers increased with the measurements conducted, with a 3,04 % increase attributed to the application of 30 °C for 30 days. Additionally, thermal aging associated with the applications of 60 °C for 60 days and 90 °C for 90 days resulted in decreases of 6,52 % and 20,45 %, respectively. We also observe the same trend in measurements conducted at a 20-degree angle in the parallel direction to the fibers, with increases for 30 °C for 30 days (3,00 %), 60 °C for 60 days (3,86 %), and 90 °C for 90 days (16,31 %).

Furthermore, the results for measurements in the parallel direction to the fibers were found to be higher than those in the perpendicular direction. Salca *et al.* (2016) mentioned that there was no significant difference between gloss measured parallel or perpendicular directions on the gloss values at 20° geometry for coated black alder (*Alnus glutinosa* L.) wood, nevertheless the reported values were also slightly higher for parallel measurements. In the glossiness measurements conducted at 60 and 85 degrees in both perpendicular and parallel directions to the fibers, decreases were observed after the thermal aging process. Furthermore, the highest glossiness values at 60º and 85º were found in the control samples where thermal aging was not applied.

It has been stated that the glossiness values measured both parallel ($\parallel$) to the fibers at 20° and 60° and perpendicular ($\perp$) to the fibers at 20°, 60°, and 85° decreased after thermal aging on UV varnished sapele material (Ayata and Bal 2023a). On UV-varnished iroko wood, it has been determined that the glossiness values at 60°, measured both perpendicular and parallel to the fibers, showed the highest reduction, with decreases of 9,92 % and 8,54 %, respectively, after the application of 90 days at 90 °C. The lowest reductions, on the other hand, were observed after the application of 30 days at 30 °C, with reductions of 1,12 % and 3,26 %, respectively. Additionally, the measurement results obtained parallel to the fibers were higher than those obtained perpendicular to the fibers (Ayata and Bal 2023b).

The results of the total color difference calculated using color formulas after the thermal aging applications are presented in Table 4. After all thermal aging applications, ΔL^* (darker than the reference) values were determined as negative, while Δb^* (more yellow than the reference), Δa^* (redder than the reference), and ΔC^* (clearer and brighter than the reference) values were obtained as positive. Δa^*, ΔC^*, and ΔE^* values were observed to increase with an increase in temperature and duration of the thermal aging application. The ΔE^* values were obtained as 4,11 for 30 °C for 30 days, 5,46 for 60 °C for 60 days, and 11,49 for 90 °C for 90 days (Table 4). When compared to the color criteria proposed by Barański *et al.* (2017), it can be observed that for 30 °C for 30 days and 60 °C for 60 days, the category is "Color change visible with an average quality of filter (6>ΔE*>3)", while for 90 °C for 90 days, it falls into the category of "High color change (12>ΔE*>6)".

In study Ayata and Bal (2023a), they subjected materials obtained after applying UV system parquet varnishes to sapele wood surfaces to thermal aging under various temperatures and durations (30 °C for 30 days, 60 °C for 60 days, and 90 °C for 90 days) in an incubator setting. The results showed that the ΔE^* values were determined to be 1,69; 4,98 and 8,78 for the respective variations of 30 °C for 30 days, 60 °C for 60 days, and 90 °C for 90 days. The ΔE^* values exhibited an increase as the duration of thermal aging increased. In another study, it was reported that the ΔE^* values for UV-varnished iroko wood after thermal aging applications were 0,57 for the 30 days at 30 °C application, 4,10 for the 60 days at 60 °C application, and 4,81 for the 90 days at 90 °C application (Ayata and Bal 2023b). In the study by Ayata *et al.* (2018), it was reported that the ΔE^* increased in all thermal aging processes, with a greater increase observed in more severe aging conditions.

From these obtained results, it can be seen that the properties of surfaces with thermal aging have undergone a complete transformation.

Table 4: Results for total color differences.

Thermal Aging Time	ΔL^*	Δb^*	Δa^*	ΔC^*	ΔH^*	ΔE^*	Color change criteria by (Barański *et al.* 2017)
30 °C for 30 days	-3,87	1,36	0,30	0,69	1,21	4,11	Color change visible with an average Quality of filter (6>ΔE^*>3)
60 °C for 60 days	-5,28	1,16	0,75	1,05	0,89	5,46	
90 °C for 90 days	-10,97	2,36	2,50	3,09	1,51	11,49	High color change (12>ΔE^*>6)

CONCLUSIONS

Comprehending how temperature affects alterations in wood surface color is essential for several applications. By regulating temperature conditions, it becomes possible to potentially influence and oversee the stability and visual appeal of wood surfaces. This study yielded the following findings:

As the temperature and duration of the thermal aging process increased, the values of color parameters b^*, a^*, and C^* exhibited an upward trend, whereas the values of h^o and L^* showed a decrease.

The ΔE^* values were determined in descending order as follows: 90 °C for 90 days (11,49) > 60 °C for 60 days (5,46) > 30 °C for 30 days (4,11).

During thermal aging application, measurements for all tests have shown variations with an increase in temperature and duration. Variance analyses have supported this, showing that measurements for all tests exhibited significant differences with the increase in temperature and duration of thermal aging.

Author contributions

U.A.: Contributed to the conception, experimental work and interpretation of the analyzed data, writing and reviewing of the manuscript, read and approved the final manuscript. S.S.: Contributed to the conception, experimental work and interpretation of the analyzed data, writing and reviewing of the manuscript, read and approved the final manuscript. B.E.: Contributed to writing and reviewing of the manuscript, read and approved the final manuscript.

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REFERENCES

ASTM. 2007. Standard practice for calculation or color tolerances and color, differences from instrumentally measured color coordinates, ASTM D 2244-3. ASTM. West Conshohocken, PA. USA.

Ayata, Ü. 2019. Effects of artificial weathering on the surface properties of ultraviolet varnish applied to lemonwood (*Citrus limon* (L.) Burm.). *BioResources* 14:8313-8323. https://doi.org/10.15376/biores.14.4.8313-8323.

Ayata, Ü.; Bal, B.C. 2023a. The effects of thermal aging on the color and glossiness properties of UV-cured varnish coatings applied to sapele (*Entandrophragma cylindricum*) wood. EU 2nd International Conference on Health, Engineering and Applied Sciences, August 4-6, 2023, Belgrade, Serbia, 106-114. https://www.avrupakongresi.org/_files/ugd/797a84_99809de94f7e46cdb8d07fe67258f37e.pdf

Ayata, Ü.; Bal, B.C. 2023b. Investigation of some surface properties of iroko (*Milicia excelsa* Welw. C.C. Berg) wood with UV system parquet varnish exposed to thermal aging application. EU 1st International Conference on Health, Engineering and Applied Sciences, May 5-7, 2023, Bucharest, Romania, 578-586. https://www.avrupakongresi.org/_files/ugd/797a84_16ee778530a74f50998c7b98209a297e.pdfTürkiye

Ayata, Ü.; Çakıcıer, N.; Gürleyen, L. 2021a. Determination of the artificial aging performance of the apricot wood applied with UV system parquet varnish used indoors. *Furniture and Wooden Material Research Journal* 4(1):40-50. https://doi.org/10.33725/mamad.922311

Ayata, Ü.; Çakıcıer, N.; Gürleyen, L. 2021b. Effects of artificial aging of UVB-313 lamps on some surface properties of UV system varnished black locust wood. *Bitlis Eren University Journal of Science and Technology* 10(4):1492-1505. https://doi.org/10.17798/bitlisfen.980669

Ayata, Ü.; Çakıcıer, N.; Gürleyen, L. 2021c. Determination of some surface properties of UV curable varnish-applied cedar wood after artificial aging application. *Furniture and Wooden Material Research Journal* 4(2):145-154. https://doi.org/10.33725/mamad.1005120

Ayata, Ü.; Çakıcıer, N.; Gürleyen, L. 2022a. The effect of artificial aging on color, glossiness, pendulum hardness and adhesion to the surface of black poplar wood treated with UV curable varnish. *Gümüşhane University Journal of Science and Technology* 12(3):951-963. https://doi.org/10.17714/gumusfenbil.986610

Ayata, Ü.; Efe, FT.; Türk, M.; Çakıcıer, N.; Gürleyen, L. 2022b. Comparison of the effects of accelerated aging with different lamps (UV-A and -B) on color and pendulum hardness properties of Russian olive wood treated with UV system varnish. *Eurasian Journal of Forest Science* 10(1):11-19. https://doi.org/10.31195/ejejfs.1039629

Ayata, U.; Sahin, S.; Esteves, B.; Gurleyen, L. 2018. Effect of thermal aging on colour and glossiness of UV system varnish-applied laminated parquet layers. *Bioresources* 13(1):861-868. https://doi.org/10.15376/biores.13.1.861-868

Barański, J.; Klement, I.; Vilkovská, T.; Konopka, A. 2017. High temperature drying process of beech wood (*Fagus sylvatica* L.) with different zones of sapwood and red false heartwood. *BioResources* 12(1):1861-1870. https://doi.org/10.15376/biores.12.1.1861-1870

Blom, Å.; Johansson, J.; Sivrikaya, H. 2013. Some factors influencing susceptibility to discoloring fungi and water uptake of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and Oriental spruce (*Picea orientalis*). *Wood Material Science and Engineering* 8(2): 139-144. https://doi.org/10.1080/17480272.2012.745095

Cavus, V. 2021. Weathering Performance of Mulberry Wood with UV Varnish Applied and Its Mechanical Properties. *BioResources* 16(4):6791-6798. https://doi.org/10.15376/biores.16.4.6791-6798

Davidson, R.S. 2001. *Radiation Curing*. Rapra Technology Ltd., Shawbury, England 12.

Demirci, Z.; Sönmez, A.; Budakci, M. 2013. Effect of thermal ageing on the gloss and the adhesion strength of the wood varnish layers. *BioResources*, 8(2):1852-1867. https://doi.org/10.15376/biores.8.2.1852-1867

Döngel, N. 2005. Technical properties of wood and wood-based floor covering materials (parquet). Ph.D. Thesis, Gazi University Institute of Natural and Applied Sciences, Ankara, Turkey.

Fibiger, W. 1998. *Coating Technology. III*. Industrial Coatings. 3rd Edition. Ed. Fibiger, W.; Boyce, A.C. ITE Consultants: Canada.

Gao, J.; Zhang, B.; Chang, J. 2004. Induced discoloration of buerger maple during drying process. *Forestry Studies in China* 6(2): 50-55. https://doi.org/10.1007/s11632-004-0020-6

Gustafsson, L.; Borjesson, P. 2007. Life cycle assessment in green chemistry: A comparison of various industrial wood surface coatings. *The International Journal of Life Cycle Assessment* 12:151-159. https://doi.org/10.1065/lca2006.11.280

Kamperidou, V. 2021. Chemical and Structural Characterization of Poplar and Black Pine Wood Exposed to Short Thermal Modification. *Drvna Industrija* 72(2): 155-167. https://doi.org/10.5552/drvind.2021.2026

ISO. 1994. Paints and varnishes - determination of specular gloss of non-metallic paint films at 20 degrees, 60 degrees and 85 degrees, ISO 2813. ISO: Geneva, Switzerland.

Lange, D.R. 1999. Fundamentals of Colourimetry - Application Report No. 10e. D.R Lange: New York, NY, USA.

Liu, X.Y.; Timar, M.C.; Varodi, A.M.; Sawyer, G. 2017. An investigation of accelerated temperature-induced ageing of four wood species: colour and FTIR. *Wood Science and Technology* 51:357-378. https://doi.org/10.1007/s00226-016-0867-4

Moon, J.H.; Shul, Y.G.; Han, H.S.; Hong, S.Y.; Choi, Y.S.; Kim, H.T. 2005. A study on UV-curable adhesives for optical pick-up: I. Photo-initiator effects. *International Journal of Adhesion and Adhesives* 25(4):301-312. https://doi.org/10.1016/j.ijadhadh.2004.09.003

TS. 1997. Standard atmospheres for conditioning and/or testing; specifications. TS ISO 642 554. Turkish Standards Institution: Ankara, Turkey.

TS. 2021. Physical and mechanical properties of wood - Test methods for small clear wood specimens - Part 1: Determination of moisture content for physical and mechanical tests. TS ISO 13061-1. Turkish Standards Institution: Ankara, Turkey.

Narayan, R. 2002. Doctoral Thesis, Submitted to ISM Dhanbad, India.

Sahin, S.; Esteves, B.; Can, A.; Sivrikaya, H.; Domingos, I.; Ferreira, J.; Ayata, Ü. 2023. Effects of Artificial Weathering on the Surface Properties of Coated Radiata Pine. *Maderas. Ciencia y Tecnología* 25: e29. https://doi.org/10.4067/S0718-221X2023000100429

Salca, E.A.; Krystofiak, T.; Lis, B.; Mazela, B.; Proszyk, S. 2016. Some coating properties of black alder wood as a function of varnish type and application method. *BioResources* 11(3): 7580-7594. https://doi.org/10.15376/biores.11.3.7580-7594

Salca, E.A.; Krystofiak, T.; Lis, B.; Hiziroglu, S. 2021. Glossiness Evaluation of Coated Wood Surfaces as Function of Varnish Type and Exposure to Different Conditions. *Coatings* 11: e558. https://doi.org/10.3390/coatings11050558

Sandoval-Torres, S.; Jomaa, W.; Marc, F.; Puiggali, J.R. 2010. Causes of color changes in wood during drying. *Forestry Studies in China* 12(4): 167-175. https://doi.org/10.1007/s11632-010-0404-8

Sjökvist, T.; Blom, Å.; Ahmed, S. A.; Sjökvist, T.; Blom, Å.; Ahmed, S. A. 2020. Liquid water absorption in coated Norway spruce: Impact of heartwood, sapwood, density and weather exposure. *Maderas. Ciencia y Tecnologia* 22(3): 335-346. https://doi.org/10.4067/S0718-221X2020005000308

Sjökvist, T.; Blom, Å.; Wålinder, M.E.P. 2019. The influence of heartwood, sapwood and density on moisture fluctuations and crack formations of coated Norway spruce in outdoor exposure. *Journal of Wood Science* 65(1): e45. https://doi.org/10.1186/s10086-019-1825-1

Sjökvist, T.; Wålinder, M.E.P.; Blom, Å. 2018. Liquid sorption characterisation of Norway spruce heartwood and sapwood using a multicycle Wilhelmy plate method. *International Wood Products Journal* 9(2): 58-65. https://doi.org/10.1080/20426445.2018.1467602

Takami, K.; Matsuno, R.; Ishihara, K. 2011. Synthesis of polyurethanes by polyaddition using diol compounds with methacrylate-derived functional groups. *Polymer* 52(24):5445-5451. https://doi.org/10.1016/j.polymer.2011.09.037

Tolvaj, L.; Molnar, Z.; Nemeth, R. 2013. Photodegradation of wood at elevated temperature: Infrared spectroscopic study. *Journal of Photochemistry and Photobiology B: Biology* 121:32-36. https://doi.org/10.1016/j.jphotobiol.2013.02.007

Wang, F.; Hu, J.Q.; Tu, W.P. 2008. Study on microstructure of UV-curable polyurethane acrylate films. *Progress in Organic Coatings* 62(3):245-250. https://doi.org/10.1016/j.porgcoat.2007.12.005

White, R.H.; Dietenberger, M.A. 2001. Wood products: Thermal degradation and fire. Encyclopedia of Materials: Science and Technology. 9712-9716. https://doi.org/10.1016/B0-08-043152-6/01763-0