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SERVICES FOR SCIENCE AND EDUCATION

Outdoor Exposure Effects on Different Formulated Clear Coats of Wood as Sustainable Urban Design Material

Candan Kus Sahin
Suleyman Demirel University, Architecture Faculty,
Department of Landscape Architecture Isparta, Turkiye

Rahim Merdan
Isparta University of Aplied Sciences, Keçiborlu Vocational School,
Department of Interior Design, Isparta, Turkiye

ABSTRACT

When wood is exposed to the outdoors, degradation can occur either in the coatings or the wood surface, or in both materials. However, interaction between exposure radiation and the wood surface produces complex photooxidation reactions that degrade the clear film and appear as discoloration. There are very complicated variations found for the changes in all three-color coordinates in terms of outdoor exposure impact on modifications of seven different coatings and exposure directions. However, the similar surface coatings on tangent and radial surfaces respond differently when exposed to outdoor. The varnish+teak oil and plant oil+teak oil (ΔEEr: 3.47 vs. ΔEFr: 8.65) coated samples show higher radial surface discolorations than counterpart tangent surfaces, while tangent surfaces show higher discoloration than radial surfaces for the other five transparent coated samples. The most stable surface against outdoor exposure was found with a radial surface of varnish+enamel treatment of ΔECr: 1.71 (metric), followed by radial and tangent surface of varnish+teak oil treatments (ΔEEr: 2.78 and ΔEEt: 3.47). It is notable that all discolorations were perceptible to the human eye (ΔE:>1.0 unit) when look carefully. There is no trend observed for chroma and hues of samples. Solely varnish coated (hBt) and plant oil+varnish coated (hGt) samples show considerably shifts of color for tangent surfaces and solely varnish coated (hBr) and plant oil+ varnish coated (hFr) samples for radial surfaces (Δh ± >5 degree), while all other samples do not show noticeable differences between radial and tangent surfaces of coated samples, either weathered or not, and those changes were not perceptible by the human eye.

Keywords: Transparent coating, CIEL*a*b*, discoloration, weathering.

INTRODUCTION

Because wood is a natural material that has its own characteristic color and appearance, it has become a popular sustainable urban design element that is expected to have a long service life [1-3]. However, this specific aesthetic value can quickly be lost if left unprotected from outdoor exposure. Therefore, to prolong the service life of wood products, enhanced resistance against natural and artificial fading is necessary. In this regard, numerous bulk and surface protective methods have been developed to slow down degradation processes [4-6]. Some of those methods (e.g., thermal, surface, physical, chemical, impregnation, etc.,) have shown good potential for increasing abiotic and biological resistance and enhancing the natural performance of wood [5-7].

Research in the field of open space design represents a source of technological evolution for urban furniture objects. However, one of the considerations is to obtain resistive materials against light (UV/Vis), be flexible in design places, and have an aesthetic appearance with acceptable costs [2, 3]. Thus, wood is one of the best materials for urban furniture manufacturing. It is noticeable that well-designed elements should be flexible and bring an interesting practice [1-3]. Due to the variety of age groups accessing open spaces and interacting with urban furniture, they could be accessible to the aged, the disabled and also children [2].

One of the simplest and most cost-effective approaches is applying protective transparent finishes or opaque coatings to wood surfaces. In this way, clear finishes display the natural surface color and texture of the wood [8-10]. However, specially formulated surface coatings could enhance performance by reducing the water uptake and increasing dimensional stability, resistance to weathering, and insert color stability [6, 11, 12]. The formulations of surface coating agents are primarily considered to be well penetrated and polymerized, resulting in cell wall bulking, but a major proportion of the agents also remain located in the cell lumens [4, 10]. Moreover, environmental concerns associated with the use of conventional preservatives have drawn attention to the wood modification approach, which has also altered some material properties [5, 6, 13, 14]. Recent studies have reported the combined coating of wood with various types of synthetic and natural agents to enhance the aesthetic quality of the wood substrate [15, 16]. Šimunková et al. (2018) proposed that UV aging affected high-gloss polyurethane lacquer and traditional shellac varnish-coated wood samples differently. For evaluating these variations, they measured the coated wood's surface resistance to cold liquids, adherence to the wood surface, surface hardness, and gloss properties [17]. It had also been reported that shellac and polyurethane finishes were similarly effective in protecting gloss following UV exposure in an accelerated lab test, but there was a marked decrease in the water resistance of shellac finishes [17]. Silva et al., (2007) evaluated the photodecomposition process of five tropical wood species and the protection effect of two wood finishing products under artificial weathering [11]. It was suggested that changes in the natural color of wood indicative of the photodegradation process, and the protection degree of a transparent poliuretanic varnish and a semitransparent stain be monitored by spectrocolorimetry. It was explained that the protective properties of varnish and stain are different for certain wood species [11].

There have been numerous reports regarding urban furniture properties prepared from wood. However, the majority of these investigations are related to wood's drawbacks during outdoor exposure and protective treatments against those detrimental factors in order to improve the serviceability of wooden products. In this regard, this study aims to evaluate specially selected seven different formulated surface transparent (clear) coating agents on two different surfaces of the same Calabrian pine (Pinus brutia) wood, one of the most common wood species for urban furniture manufacturing in Turkiye. Therefore, the aging of those transparent coatings has been investigated by general color measurement assessments.

MATERIAL AND METHODS

For the conduction of this work, the Calabrian pine (*Pinus brutia*) wood was used. The small samples in the dimensions of 50 mm x 50 mm x 10 mm were prepared from a planed flat (tangent surfae)- and quarter-sawn (radial surface) boards that were purchased from a local timber company. The prepared samples were climatized at 20 °C and 65% relative humidity (RH) until equilibrium moisture content was reached. There were five commercially available, ready-to-use agents supplied from local markets to prepare desired coating formulations in laboratory conditions. These are: teak oil, oil-modified alkyd-based varnish, synthetic alkyd-based impregnation agent, wax-based synthetic wood enamel, and natural plant oil (sesame oil). From those agents, as given above, the following seven coating formulations were prepared and applied to wood specimens to evaluate their stability against outdoor exposure. These are: **A:** Solely teak oil coatings; **B:** Solely varnish coatings; **C:** Varnish and then surface enamel coatings; **D:** Impregnated and then varnish coatings; **E:** Varnish and then teak oil coatings; **F:** Plant oil and then teak oil coatings; and **G:** Plant oil and then varnish coatings. The dipping procedure in one minute were applied to all transparent coating applications. At the end of the dipping, the samples were placed horizontally on a laboratory table to dry for at least 72 hours. The both uncoated (controls) and seven different transparent coated of tangent and radial surfaces of the wood samples were placed horizontally on the south side of a height (Sobu height) to facilitate free distortion and exposed outdoors for the period May 2024 to September 2024 in Isparta, Turkiye. Concerning discoloration determination, three measurements from each group were taken to analyze the performance of wood coatings. The natural weathering aging of the coatings and tangent and radial surfaces of the same wood species were equally prepared, and their surface discolorations were compared after periods of weathering. In total, 48 wood samples were outdoor exposed.

The determination of the color coordinates was carried out by using an X-rite SP68 spectrophotometer with a circular measuring area with a diameter of 10 mm. Color evaluation was done using the CIE L*a*b* C*, h° color system, the color parameters L* (lightness), a* (redness), and b* (yellowness) as well as the total color changes (ΔE*) were determined after weathering. The total color changes (ΔE*) were calculated using the following equation:

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

Where ΔL, Δa* and Δb* are the changes of the colour coordinates L*, a* and b*.*

However, L*C*h° values are obtained by converting L*a*b* values. The L*C*h° color space of lightness (L*), color saturation (C*) and hue angle (h°) were measured.

RESULTS AND DISCUSSIONS

Wooden elements are usually preferred for architectural purposes due to their naturalness and aesthetic properties. However, natural or modified wood can be degraded, especially those left outdoors for a long time, such as that shown in Figure 1 (a-i). The photos in Figure 1 clearly show the degradation, discoloration or considerable changes from their original appearances of some wooden urban elements. When those elements were analyzed visually, the outer layers appeared to be destroyed, and a visually unpleasant form was established. As a result of those changes, the wooden elements began to exhibit extensive graying on their surfaces after outdoor weathering, while some signs of fungal decay were also observed in these elements (Fig.1a and d). Color modeling of open-space designs with wooden objects has been performed by various researchers. However, it has been consistently reported that if surface finishing is not well established on outdoor exposed urban furniture, esthetic durability is mainly affected by heat, moisture and light, which could degrade the underlying surface and cause the finish to peel, which causes discoloration and chalking, followed by a loss in film integrity [4,10,18]. The examples of some urban elements shown in Figure 1 clearly support this information.

Figure 1: Outdoor exposure and weathered some urban furniture elements (a, g and i: peeled off semitransparent sitting units, b and h: heavily surface distorted sitting units, c: aged trash bin, d and e: heavily surface aged camellias, f: Faded picnic table)

It has been assumed that anatomical variation in the wood can enhance the penetration of the coating and its adhesion on the plane of surfaces. In this case, concerning directional discoloration evaluation of wood quantitatively, the mean values of the measured CIE color coordinate values (L*a*b*) for tangent (t) and radial (r) surfaces of six-month weathered wood specimens are shown in Table 1. All the transparently coated samples show some level of color coordinate differences compared to the controls.

It was found to be the highest and lowest lightness (L*), redness-greeness (a*) and yellowness-blueness (b*) differences values of $\Delta Lt_{(max-min)}$: 19.56 (metric) (Bt: 75.37 vs. Gt: 55.81), $\Delta at_{(max-min)}$: 7.70 (metric) (Bt: 2.44 vs. Dt: 10.14), $\Delta bt_{(max-min)}$: 10.08 (metric) (Bt: 29.68 vs. Dt: 39.72), for tangent surfaces, respectively. It apparent that the solely varnish-coated sample (Bt) showed the lowest a* and b* color coordinates, but not the L* values. For radial surfaces, the highest and lowest lightness, redness and yellowness differences are: $\Delta Lr_{(max-min)}$: 7.78 (metric) (0r: 67.69 vs. Fr: 59.91), $\Delta ar_{(max-min)}$: 4.84 (metric) (0r: 7.66 vs. Fr: 12.60), $\Delta br_{(max-min)}$: 8.79 (metric) (0r: 31.99 vs. Dr: 40.78), for radial surfaces, respectively. It appeared that the control sample (0r) showed the lowest a* and b* color coordinates but the highest lightness values.

Table 1: Color coordinate properties of control samples.

Controls	L*0	a*0	b*0
Tangent surfaces			
0t	67.99	6.03	30.97
At	68.14	6.22	33.25
Bt	75.37	2.44	29.68
Ct	67.80	5.59	30.24
Dt	58.17	10.14	35.99
Et	69.01	6.35	34.26
Ft	64.48	9.67	39.21
Gt	55.81	14.58	39.72
Radial surfaces			
0r	67.69	7.76	31.99
Ar	66.69	8.68	35.80
Br	60.85	12.12	35.30
Cr	63.47	8.60	35.93
Dr	62.15	11.28	40.78
Er	66.92	8.36	38.24
Fr	59.91	12.60	39.93
Gr	60.13	12.31	40.28

After a six-month weathering for seven different transparently formulated coated samples, the color coordinate values were measured and given in Table 2. For tangent surfaces, the highest color coordinates values of $\Delta Ltw_{(max)}$: 66.49 (metric), $\Delta atw_{(max)}$: 8.18 (metric), and $\Delta btw_{(max)}$: 35.36 (metric) were found with varnish+teak oil coating (E), plant oil+varnish coatings (F), and varnish+teak oil coating (E), respectively. For radial surfaces, the highest color coordinates values of $\Delta Lrw_{(max)}$: 66.01 (metric), $\Delta arw_{(max)}$: 8.72 (metric), and $\Delta btw_{(max)}$: 38.27 (metric) were found with solely varnish (B) and varnish+teak oil coating (E) for both a* and b* coordinates, respectively.

Table 2: Color coordinate properties of weathered samples

Weathered	L*w	a*w	b*w
Tangent surfaces			
0t	62.93	4.42	23.93
At	62.92	7.23	34.31
Bt	64.58	5.56	30.25
Ct	59.37	7.29	31.63
Dt	52.72	7.31	24.78
Et	66.49	6.75	35.36
Ft	60.22	8.18	33.37
Gt	57.93	6.14	25.53
Radial surfaces			
0r	**59.81**	7.08	28.95
Ar	61.91	8.7	35.68
Br	**66.01**	6.57	33.11
Cr	62.06	7.9	36.61
Dr	60.39	7.96	31.9

Er	63.47	8.72	38.27
Fr	65.8	7.42	36.28
Gr	60.05	6.49	28.7

The difference in color coordinate values ΔL(w-0) (Fig.2A), Δa(w-0) (Fig. 2B) and Δb(w-0) (Fig. 2C) between control and counterpart weathered samples in each direction are shown in Figure 2, comparatively.

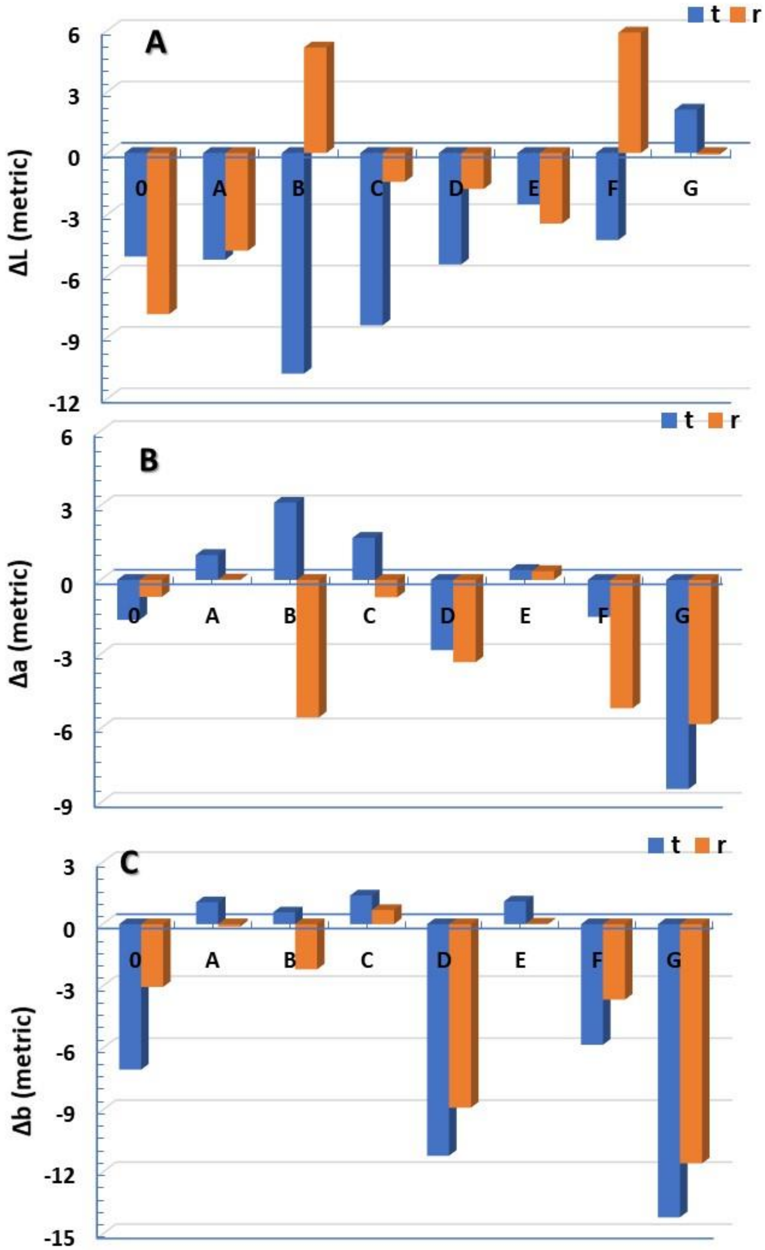

Figure 2: Color coordinate changes of samples after weathering (A: Lightness, B: redness-greeness, C: yellowness-blueness).

It appeared to a complex variation were found for the changes in all these coordinates in terms of outdoor exposure impact on modifications of coatings and exposure directions. In tangent surfaces, only plant oil+varnish coated sample (Gtw) show increasing lightness (ΔLGt(w-0): 2.12 (metric) than counterpart control, while all others show lowering lightness values (Fig. 2A). Interestingly, the plant oil+varnish coated sample (Gtw) show the highest a* (Fig. 2B) and b*(Fig. 2C) coordinate differences (lower values than counterpart controls) ΔaGt(w-0): -8.44 (metric), and ΔbGt (w-0): -14.19 (metric), respectively.

It appeared that similar treatments on two different wood surfaces (t and r) behave differently when exposed to outdoor. In radial surfaces, the solely varnish (Brw) and plant oil+ teak oil (Frw) treated samples show increasing lightness values of ΔLBr(w-0): 5.16 (metric) and ΔLFr(w-0): 5.86 (metric), while all others show lowering lightness properties (Fig. 2A). The highest lightness reduction was found with the control sample (ΔL0r(w-0): -7.88 (metric). The solely varnish coated (ΔaBr(w-0): -5.55), impregnated+varnish coated (ΔaDr(w-0): -3.32), plant oil+teak oil coated (ΔaFr(w-0): -5.18) and plant oil+ varnish coated (ΔaGr(w-0): -5.82) samples show considerably lowering a* coordinate values than others, which shows only negligible changes (<0.7 degree) (Fig. 2B). However, the highest b* coordinate reductions were found with plant oil+varnish coated samples (ΔbGr(w-0):-11.58), followed by impregnated+varnish coated sample (ΔbDr(w-0): -8.88), and plant oil+teak oil coated sample (ΔbGr(w-0): -3.65), in that order (Fig. 2C).

Quantifying each color coordinate values are very complex and not intended to be further evaluated, whereas the total color difference (ΔE) have been suggested to be used for determining the discoloration properties of substrates [2,19-21]. It has assumed that ΔE can be used to provide an estimation of how weathering affects the seven different surface clear coating agents applied on two different directions to the same wood substrate. Regarding this suggestion, discoloration of wood samples was evaluated using total color change calculations in each direction separately and presented in Figure 3, comparatively.

It can be seen that varnish+teak oil ΔEEr: 3.47 (metric) and plant oil+teak oil (ΔEFr: 8.65 (metric) samples show higher radial surface discolorations than counterpart tangent surfaces, while tangent surfaces show higher discoloration than radial surfaces at the rest of the samples. However, the most stable sample in terms of discoloration, against weathering was found with a radial surface of varnish+enamel treatment of ΔECr: 1.71 (metric), followed by radial and tangent surface of varnish+teak oil treatments (ΔEEr: 2.78 and ΔEEt: 3.47, but the highest color change values of ΔEGt: 16.64 (metric) and ΔEGr: 12.96 (metric) were observed with radial and tangent surfaces which coated with plant oil+varnish (G), respectively.

It seems that these all-color changes (discolorations) were perceptible to the human eye (ΔE:>1.0 unit) when look carefully. A number of researchers have already reported surface agent stability/performance variables between different surfaces of the same wood (e.g., tangent and radial). Those differences are found to be mainly due to greater physical degradation of the cell wall layers in one direction than in other directions [8,22-24]. It had been hypothesized that the cross-field pits in radial faces led to micro-checking, which lowers the adhesion of coating agents to Radiata pine sapwood in radial faces after weathering [25]. Those could partially support our findings regarding the discoloration of Calabrian pine in this study. It could be concluded that the color stability against weathering on all samples are not the same for not only treated surfaces but also selected coating formulations. However, it is notablle that the varnish+teak oil (E) appeared to show the highest resistance for both surfaces against outdoor exposure.

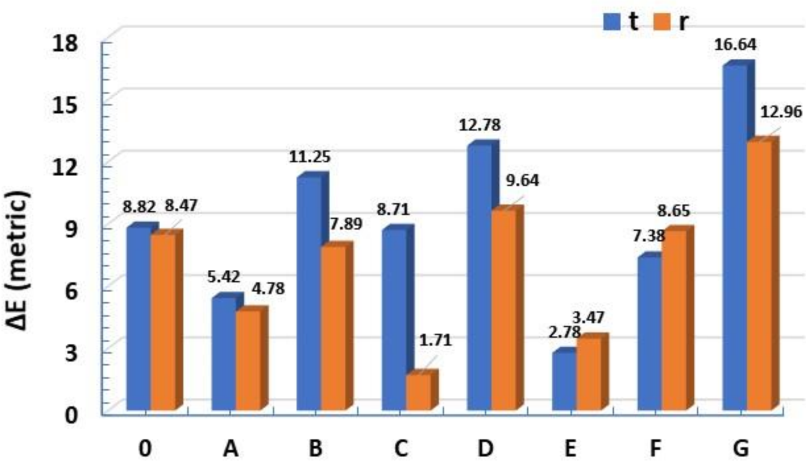

Figure 3: Toal color change properties of coated wood samples after weathering

In general, strength of a color depends on both hue (basic color) and saturation (purity of hue). Table 3 show the chromacity properties of seven different transparent coated controls and outdoor exposure samples. The chroma values were found to be in range of CBt: 29.78 (metric) to CGt: 42.31 (metric) for controls of tangent surfaces and in range of C0r: 32.92 (metric) to to CDt: 42.31 (metric) for controls of radial surfaces. However, after six months outdoor exposure, there is both increasing and mainly reducing chromacity values were observed for both surfaces (negligible <2.0 degrees). The highest chroma value reductions for both surfaces were found to be with plant oil+ varnish coated samples (ΔCGt (w-0): -16.05 vs. ΔCGr (w-0): -12.70) followed by impregnated+varnish coated samples (ΔCDt (w-0): -11.55 vs. ΔCDr (w-0): -9.43). It has hypothesized that as the lightness of wood is bigger than chromaticity indices, whiteness and lightness might be correlated in most cases [26]. In our study, it is difficult to correlate chromacity changes with color coordinate values. But it is important to note that plant oil+ varnish coated (G), plant oil+ teak oil coated (F), impregnated+ varnish coated (D) samples show considerably chromacity reductions for both surfaces while the tangent surfaces appeared to higher chroma value reductions than radial surfaces at similar treatment conditions.

Table 3: Chromacity (C*) properties of samples

C*	Tangent surfaces			Radial surfaces		
	0t	wt	Δt (w-0)	0r	wr	Δr (w-0)
0	31.55	24.33	-7.22	32.92	29.8	-3.12
A	33.83	35.06	1.23	36.84	36.73	-0.11
B	29.78	30.76	0.98	37.32	33.76	-3.56
C	30.75	32.46	1.71	36.94	37.45	0.51
D	37.39	25.84	-11.55	42.31	32.88	-9.43
E	34.84	36	1.16	39.14	39.25	0.11
F	40.38	34.36	-6.02	41.87	37.03	-4.84
G	42.31	26.26	-16.05	42.12	29.42	-12.7

The changes in hue angle (h^0) for both surfaces which coated with seven different coatings and then natural weathered are given in Table 4. Like chromacity given values in above, very complicated results which is no clear trend were also observed for hues of samples. It was found to be in range of 69.84 (hGt) to 85.29 (hBt) for control of tangent surfaces and in range of 71.05 (hBr) to 76.53 (hCr) for control of radial surface of samples. However, solely varnish coated (hBt) and plant oil+varnish coated (hGt) samples show a considerably shifts of color (< 5 degree) for tangent surfaces (ΔhBt (w-0): -5.72 and ΔhGt (w-0): -6.63), and solely varnish coated (hBr) and plant oil+ varnish coated (hFr) samples show noticeable differences (>5 degree) for radial surfaces (ΔhBr (w-0): 7.72 and ΔhFr (w-0): 5.95) while all other samples are not show noticeable differences between radial and tangent surfaces of coated samples, either weathered or not which those changes were not perceptible by the human eye. It could be kept in mind that the temperate wood's hue values fall around 60 to 80^0 in color chart and a positive value between treated and control (w-0) value indicate more yellow color while negative value (w-0) indicate more red color in color wheel. The results presented above show that solely varnish (Bt) and plant oil+varnish coated (Gt) tangent surfaces tend to more reddish color while solely varnish coated (Br) and plant oil+ varnish coated (Fr) samples show more yellow color after six months weathering.

Table 5: Hue (h^0) properties of samples

h^0	Tangent surfaces			Radial surfaces		
	0t	wt	Δt (w-0)	0r	wr	Δr (w-0)
0	78.97	79.52	0.55	76.36	76.25	-0.11
A	79.39	78.09	-1.3	76.36	76.29	-0.07
B	85.29	79.57	-5.72	71.05	78.77	7.72
C	79.52	77.01	-2.51	76.53	77.81	1.28
D	74.26	73.56	-0.7	74.53	75.98	1.45
E	79.49	79.18	-0.31	77.66	77.15	-0.51
F	76.14	76.22	0.08	72.48	78.43	5.95
G	69.84	76.47	6.63	73.0	77.25	4.25

Finally, we evaluated how seven different coating agents impact on yellowness changes (ASTM E-313) for two different directions of the same wood, under weathering conditions. Table 6 shows the yellowness properties (presented as yellowness index, YI) of controls and weathered samples. The different formulated transparent surface agents appeared to change initial yellow color (YI0t: 51.33 vs YI0r: 52.79). However, the highest yellow color change was found with plant oil+varnish coated samples for tangent surface (YIG0t: 68.63) and plant oil+teak oil coated sample (YIF0r: 66.40) for radial surface. There is no any clear trend was observed between two surfaces and applied agents, regarding yellowness changes. It has already well established that natural weathering generally impacts on color properties of wood substrates. The initial color change of wood exposed to outdoor is a yellowing that proceeds to an eventual graying [12,21]. In our study, there is a distinct yellow color changes either increase or decrease were found after six months of weathering. The highest yellowness decrease was found with plant oil+varnish coated sample (ΔYIGt (w-0): -19.83), followed by impregnated+varnish coated sample (ΔYIDt (w-0): -12.39) and control sample ΔYI0t (w-0): -7.39). In contrast, varnish+enamel coated sample ΔYICt (w-0): 6.13, solely varnish coated sample ΔYIBt (w-0): 5.61, and solely teak oil coated sample ΔYIAt (w-0): 3.99 show increasing yellow properties after weathering. For radial surfaces, similar to tangent surfaces, the plant oil+ varnish coated sample show the highest yellow color reduction ΔYIGr (w-0): -14.38 while the solely teak oil- ΔYIAr (w-0): 2.40, varnish+enamel- ΔYICr (w-0): 1.58 and varnish+teak oil coated samples ΔYIEt (w-0): 1.87 show increasing yellowness after weathering.

It has well documented by researchers that most of the time, weathered wood would have a more pronounced yellow color than unexposed wood as a result of the modification of surfaces [3,9,27]. Besides the distinct discoloration, wood species exposed outdoors changed in color from yellow to brown to gray after six months of exposure, while significant discoloration took place between 3 and 4 months of exposure [27]. Garcia et al. (2014) suggested that colorimetry is very useful for wood color investigations, by using colorimetric variables [21]. As seen in Table 6, it is very difficult to evaluate yellow color change relationships between coating formulations and weathering impacts on them.

Table 6. Yellowness (YI) properties of samples

	Tangent			**Radial**		
	0	**w**	**ΔYIt (w-0)**	**0**	**w**	**ΔYIr (w-0)**
0	51.33	43.94	-7.39	52.79	52.74	-0.05
A	54.13	58.12	3.99	57.95	60.35	2.4
B	46.46	52.07	5.61	60.45	55.02	-5.43
C	50.49	56.62	6.13	59.78	61.36	1.58
D	62.85	50.46	-12.39	66.03	56.42	-9.61
E	54.94	57.52	2.58	60.64	62.51	1.87
F	63.03	58.41	-4.62	66.4	58.96	-7.44
G	68.63	48.8	-19.83	52.28	66.66	-14.38

CONCLUSIONS

In general, coatings have used as a generic name for all types of paints, varnishes, lacquers etc., are applied on wood-based materials. These can provide with the desired aesthetical properties like color, but are also protection of wood against environmental influences (e.g., light radiation, biological deterioration, moisture so on.) Although there is a visible similarity between the color of the different surfaces of the same wood, the appearance of wooden surfaces was strongly altered when exposed to outdoor conditions. It is found that the rate of discolouration is different for tangent and radial surfaces. The results distinctly demonstrate that the different wood surfaces impact transparent coatings during weathering. But all these changes were not correlated to each other.

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