Optimization of the Effect of Accelerated Weathering Conditions on Wood Surfaces *via* the Taguchi Method

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This study investigated the effect of accelerated weathering conditions on total color changes on Scots pine (*Pinus sylvestris* L.) and poplar (*Populus x euroamericana*) wood surfaces using the Taguchi method. The experiments, based on the L_{18} orthogonal array, were conducted separately for both tree species. The radial and tangential surfaces of wood specimens were subjected to an accelerated weathering process using 340 nm ultraviolet (UV) lamps and temperature conditions of 50 °C. The factors for the minimum color change were determined *via* the signal-to-noise (S/N) ratios of the four parameters thought to be effective on color change. These parameters were cutting direction (two levels), UV-irradiance, conditioning, and water (three levels each). The most important factor affecting the color change was then determined by analysis of variance (ANOVA) testing. The results showed that the maximum UV-irradiance (W/m^2) had the largest effect on the total color change, while the cutting direction (radial and tangential) had the smallest effect. The factors that affected the total color change of the poplar and Scots pine wood specimens were the same. However, the analysis revealed that different application times had varying effects on the color change.

Keywords: Accelerated weathering; Color change; Optimization; Taguchi method; Wood

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INTRODUCTION

Wood is one of the most abundant materials in nature, and it possesses superior properties compared with other building materials. Wood is a renewable material with low density, low heat conductivity, high mechanical strength, easy processability, and good aesthetic appearance. When wood is exposed to weathering without any protective treatment, it degrades under ultraviolet (UV) light. This degradation can cause leaching, hydrolysis and water swelling, discoloration, and decay by microorganisms. Ultimately, chemical changes in wood, changes in color, microscopic changes, physical changes, and changes caused by biological factors are developed as a time-specific effect.

There can be significant changes in the surface of the wood as a result of UV-radiation, humidity (rain, snow, moisture, and dew), mechanical effects (wind and dirt), temperature, and atmospheric factors (O_2, SO_2, and pollutant gases). The most important among these factors are light, moisture, and oxygen. The UV-radiation of the sun change the chemical components of the lignin on the wood surface and initiate photo degradation. The moisture in the wood increases free radical formation by expanding the gaps in the substructure of the wood, thus allowing deeper penetration of the light. Temperature is another factor in the outdoor weathering that affects wood properties. However, the temperature does not have as significant an effect on wood specimens as water and UV light do (Feist and Hon 1984; Feist 1990; Temiz 2005; Kropat *et al*. 2020).

Wood functions at its maximum strength in the tangential direction (parallel to the annual rings), slightly less in the radial direction (perpendicular to the annual rings) and very little in the longitudinal direction against weathering. Over time, physical changes in the surface of the wood due to moisture content, such as shrinkage and expansion, can cause defects such as cracking and detachment. On tangential surfaces exposed to weathering, lengthwise cracks occur in earlywood, whereas on radial surfaces in latewood, cracks form in the annual ring boundary. These cracks allow water and UV-radiation to penetrate the depths of the wood. Therefore, more degradation occurs from the wood surface (Temiz 2005; Özgenç 2014; Can and Sivrikaya 2019; Kropat *et al*. 2020). Because testing of weathering requires a long period of time, accelerated weathering tests are carried out in laboratory environments (Temiz *et al.* 2005, 2007; Way *et al.* 2018; Tian *et al.* 2019). Using this method, the results are obtained in less time.

When exposed to outdoor conditions, wood surfaces rapidly change color. The wood surface at first turns yellow and then turns brown as time passes. It is sometimes possible to detect these color changes with the naked eye, but this is not significant. A significant expression of this change is possible by measuring the L^*, a^*, and b^* values using a spectrophotometer. The CIE LAB colourimetric system, which is described by three parameters: L^* (lightness that defines the black-white axis), a^* (represents the red-green axis), and b^* (represents the yellow-blue axis), has been commonly used to evaluate HT induced wood discolouration (Temiz 2005; Temiz *et al.* 2007; Can 2018; Aydemir *et al*. 2019). The most important value for detecting the color difference between test and control samples is the ΔE^*. It alone expresses the "total color difference" between two specimens. The greater the ΔE^*, the greater the difference between the colors compared (Can 2018).

This study used the Taguchi method to examine the accelerated weathering test factors of UV, water, and conditioning (at 50 °C) to determine which factors had the largest effect on the total color change of wood. In addition, the effects of the cutting direction of the wood surface and the wood species on the total color change were also investigated.

EXPERIMENTAL

Materials

Scots pine (*Pinus sylvestris* L.) (oven-dry density of 0.49 g/cm^3) and poplar (*Populus x euroamericana*) (oven-dry density of 0.28 g/cm^3) timber were purchased from the Kartal Ahşap Company in Bartin, Turkey. The wood was cut into specimens with dimensions of 5 cm × 7.5 cm × 15 cm. The specimens were cut to give tangential and radial surfaces. The specimens were free of knots and they showed no visible evidence of infection by mold or fungi. Prior to weathering, the wood specimens were put in the conditioning room at 65% relative humidity (RH) and 22 °C until a constant weight was achieved (ISO 554, 2016).

Methods

Accelerated weathering test (QUV)

The accelerated weathering test was carried out according to the ASTM standard G154-16 (2016). However, different parameters were applied to determine the effect of different weathering factors on the total color change. Table 1 outlines the parameters that were applied in the accelerated weathering test. The applied UV process used a 340 nm lamp and the average temperature in the chamber was set to 50 °C. Four replicate specimens of each variation were exposed to the accelerated weathering. The UV treatment was applied for a total of 24 h. After every 2 h of UV treatment, water (for 15, 30, and 45 min) and conditioning (for 2, 4, and 6 h) treatments were applied. For example, after 2 h 0.5 W/m^2 UV application, water spray was applied for 45 min. After the water spray treatment was applied, the sample was conditioned for 6 h at 50 °C in the accelerated weathering cycle. After repeating accelerated weathering test 12 times, the accelerated weathering of the group was completed.

Total color change measurement

The color measurement was performed with a Konica Minolta spectrophotometer (Osaka, Japan) by measuring the L^*, a^*, and b^* values on the specimens. For each sample, four color measurements were made in randomly selected zones, according to the ISO standard 7724-2 (1984). The changes in the color coordinates (ΔL^*, Δa^*, and Δb^*) were determined by the difference between the final and initial values. The total color change (ΔE^*) was calculated according to Eq. 1,

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

Taguchi method

The Taguchi method is used extensively for industrial and engineering problems due to its wide range of applications (Chamoli 2015; Günay *et al.* 2011). Taguchi method of creating a statistical design by using an orthogonal array also offers an opportunity to reduce the number of experiments (Bose *et al.* 2013; Sarikaya and Güllü 2015; Balki *et al.* 2016). Thus, the design parameters can be optimized, and the overall experimental costs can be significantly reduced (Joshaghani *et al.* 2015). Taguchi has recommended three stage processes to achieve the desired product quality by design: system design, parameter design, and tolerance design. The system design stage helps to identify the suitable working levels of the design parameters. The parameter design stage determines the factor levels that produce the best process performance. The tolerance design stage fine-tunes the results of the parameter design by tightening the tolerance of the factors with significant influence on the product (Apparao and Birru 2017).

The Taguchi technique computes a signal-to-noise (S/N) ratio based on experimental data (Kivak 2014). The S/N ratio is defined as the desired signal ratio for the undesired random noise value and shows the quality characteristics of the experimental data (Kurt *et al.* 2009; Günay *et al.* 2011; Günay and Yücel 2013). A larger S/N ratio represents a better quality characteristic and the corresponding process parameters are incentive to the variation of environmental conditions and other noise factors (Chiang and Hsieh 2009). Depending on the particular characteristics of the design problem, different S/N ratios may be applicable, including "lower-is-better" (LB), "nominal-is-best" (NB), or "higher-is-better" (HB) (Chen *et al.* 2007). The goal of this study was to minimize the color change for Scots pine and poplar. Therefore, aiming to reach the minimum value the LB quality characteristic was used for all levels of process parameters, as shown in Eq. 2,

$$\boldsymbol{S}/\boldsymbol{N} = -\mathbf{10log}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \quad (2)$$

where, n is the number of observations of the experiment and y_i is the observed data at the i^{th} experiment (Taguchi *et al.* 2005; Mandal *et al.* 2011; Kivak 2014).

Definition of factors and levels

To identify the most important factors affecting the color change in Scots pine and poplar woods, factors affecting the color applied in this study are shown in Table 1.

Table 1. Color Change Parameters and Levels

Codes	Parameters	Levels		
		1	2	3
A	Direction	Radial	Tangential	-
B	UV-irradiance (W/m^2)	0.5	0.75	1.0
C	Conditioning (h)	2.0	4.0	6.0
D	Water (min)	15.0	30.0	45.0

Orthogonal array selection

With the Taguchi method, it is possible to achieve results with a much smaller number of experimental studies using an orthogonal array table. The main feature of the orthogonal indices is that all the factors are included in the experiment with an equal number of trials. The orthogonal indices shown in the form of L_a (b^c) are derived from the Latin square design, with "*L*" representing the Latin square design. The "*a*" refers to the number of experiments, the "*b*" refers to the number of levels in each column, and the "*c*" refers to the number of factors (Ross 1988; Mezarcioz and Ogulata 2010). In this study, the optimum measurement parameters affecting color change were two levels of direction and three levels each of wavelength, conditioning, and water. The L_{18} $(2^1 \times 3^3)$ array was chosen as the most suitable orthogonal sequence for these factors and levels. In order to reach the optimum solution under normal conditions, 54 experiments would have been required for each of the two tree species, while the ideal solution was reached with 18 experiments per species using the Taguchi experimental design. Table 2 shows the L_{18} mixed orthogonal array used for the experiments.

Table 2. Orthogonal Array of Taguchi L_{18} $(2^1 \times 3^3)$

Experiment No.	Scots pine					Poplar			
	Factor A	Factor B	Factor C	Factor D		Factor A	Factor B	Factor C	Factor D
1	1	1	1	1		1	1	1	1
2	1	1	2	2		1	1	2	2
3	1	1	3	3		1	1	3	3
4	1	2	1	1		1	2	1	1
5	1	2	2	2		1	2	2	2
6	1	2	3	3		1	2	3	3
7	1	3	1	2		1	3	1	2
8	1	3	2	3		1	3	2	3
9	1	3	3	1		1	3	3	1
10	2	1	1	3		2	1	1	3
11	2	1	2	1		2	1	2	1
12	2	1	3	2		2	1	3	2
13	2	2	1	2		2	2	1	2
14	2	2	2	3		2	2	2	3
15	2	2	3	1		2	2	3	1
16	2	3	1	3		2	3	1	3
17	2	3	2	1		2	3	2	1
18	2	3	3	2		2	3	3	2

Analysis of Variance (ANOVA)

Analysis of variance (ANOVA) is a statistical method used to determine the individual interactions of all the control factors in a test design (Kivak 2014). The ANOVA test the variables by mean squaring and estimate the experimental errors at specific levels (Naik and Reddy 2018). The ANOVA test was performed to determine the most important parameter that affected the color change. MINITAB 18 software package was used for all statistical analysis.

RESULTS AND DISCUSSION

Color Changes

Table 3 shows the color changes (L^*, a^*, b^*) of wood before and after weathering. After the weathering process, the specimen surfaces were darker. The declining L^* value is proof of this. The L^* value is the parameter most affected by weathering conditions, especially UV and rainwater. Other color parameters are less affected by rainwater (Temiz *et al.* 2005).

Table 3. Colour Changes Before and After Weathering of Wood

Wood surface	Before weathering			After weathering		
	L^*	a^*	b^*	L^*	a^*	b^*
Scots Pine Radial	79.64 (0.95)	6.52 (0.57)	24.75 (1.08)	71.67 (1.63)	11.97 (0.96)	35.95 (1.33)
Scots Pine Tangential	81.99 (2.52)	5.65 (1.85)	28.59 (3.63)	74.24 (3.12)	10.58 (1.54)	39.85 (1.97)
Poplar Radial	85.77 (1.15)	3.34 (0.56)	16.39 (0.62)	79.20 (1.17)	7.38 (0.76)	31.57 (1.36)
Poplar Tangential	85.84 (1.36)	3.20 (0.55)	15.66 (0.55)	79.15 (1.42)	6.95 (0.78)	31.77 (1.59)

In parentheses: SD

Since the surface of the wood exposed to weathering becomes more fibrous (rough) and darker, the L^* value from the surface of the control specimens decreased. Moreover, polymerization of lignin on the exposed surface caused the surface to become darker. This situation is also supported by the literature studies (Temiz *et al*. 2005; Baysal *et al*. 2014; Turkoglu *et al*. 2015). Among the chromatic coordinates, the (a^*) value representing the red-green coordinates and the (b^*) value representing the blue and yellow coordinates increased with the weathering process.

Analysis of the S/N ratio and the Optimization of the Experimental Results

Table 4 shows the experimental results of the S/N ratio calculated for each experiment based on Eq. 2 (LB) according to the Taguchi experimental design L_{18} orthogonal index related to the color changes in Scots pine and poplar woods.

After the S/N values were calculated according to the experimental results, the effect of each factor on all levels was investigated. For this, the average of the S/N ratios given in Table 3 was calculated separately for each level of each factor. Table 4 shows the S/N response table for color change in Scots pine and poplar wood. The S/N values that are highest (here minimum absolute values) in the table in question indicate the best level of that parameter, *i.e.*, the test result with the least amount of color change (Table 4).

Table 4. Experimental Results and the S/N Ratio Values

Experiment No	Control Factors for Scots Pine (SP) and Poplar (P)				Δ*E* (SP)	S/N Ratio for SP	Δ*E* (P)	S/N Ratio for P
	A	B	C	D				
1	Radial	0.50	2	15	15.24	-23.6615	20.65	-26.2997
2	Radial	0.50	4	30	14.77	-23.3862	15.58	-23.8531
3	Radial	0.50	6	45	15.17	-23.6214	16.25	-24.2161
4	Radial	0.75	2	15	13.69	-22.7283	17.70	-24.9611
5	Radial	0.75	4	30	12.83	-22.1626	14.86	-23.4391
6	Radial	0.75	6	45	14.02	-22.9364	13.58	-22.6560
7	Radial	1.00	2	30	14.53	-23.2434	17.30	-24.7633
8	Radial	1.00	4	45	15.70	-23.9161	19.08	-25.6123
9	Radial	1.00	6	15	17.73	-24.9762	18.84	-25.5003
10	Tangential	0.50	2	45	18.40	-25.2974	17.96	-25.0862
11	Tangential	0.50	4	15	19.96	-26.0043	21.26	-26.5526
12	Tangential	0.50	6	30	16.62	-24.4141	15.10	-23.5794
13	Tangential	0.75	2	30	10.68	-20.5751	17.66	-24.9403
14	Tangential	0.75	4	45	12.98	-22.2654	15.06	-23.5538
15	Tangential	0.75	6	15	15.62	-23.8716	16.96	-24.5878
16	Tangential	1.00	2	45	13.46	-22.5837	20.04	-26.0383
17	Tangential	1.00	4	15	12.68	-22.0601	17.03	-24.6247
18	Tangential	1.00	6	30	12.60	-22.0059	19.71	-25.8925

Table 5. S/N Response Table for Scots Pine and Poplar (LB)

Level	Scots pine					Poplar			
	A	B	C	D		A	B	C	D
1	-23.40	-24.40	**-23.01**	-23.88		**-24.59**	-24.93	-25.35	-25.42
2	**-23.23**	**-22.42**	-23.30	**-22.63**		-24.98	**-24.02**	-24.61	**-24.41**
3	-	-23.13	-23.64	-23.44			-25.41	**-24.41**	-24.53
Delta	0.17	1.97	0.62	1.25		0.39	1.38	0.94	1.01
Rank	4	1	3	2		4	1	3	2

Figure 1 shows the graphical appearance of the optimum color change parameters and levels for Scots pine (Fig. 1a) and poplar (Fig. 1b) wood. The optimum parameters required to minimize the color change can easily be seen in the figure. According to Fig.

1a, the minimum total color change in the Scots pine wood was obtained tangentially, at a UV-irradiance of 0.75 W/m^2, after 30 min of water spray and 2 h of conditioning. In the poplar specimens, it was obtained in the radial direction after a process of 0.75 W / m^2 UV-irradiance, 30 min of water spray and 6 h of conditioning.

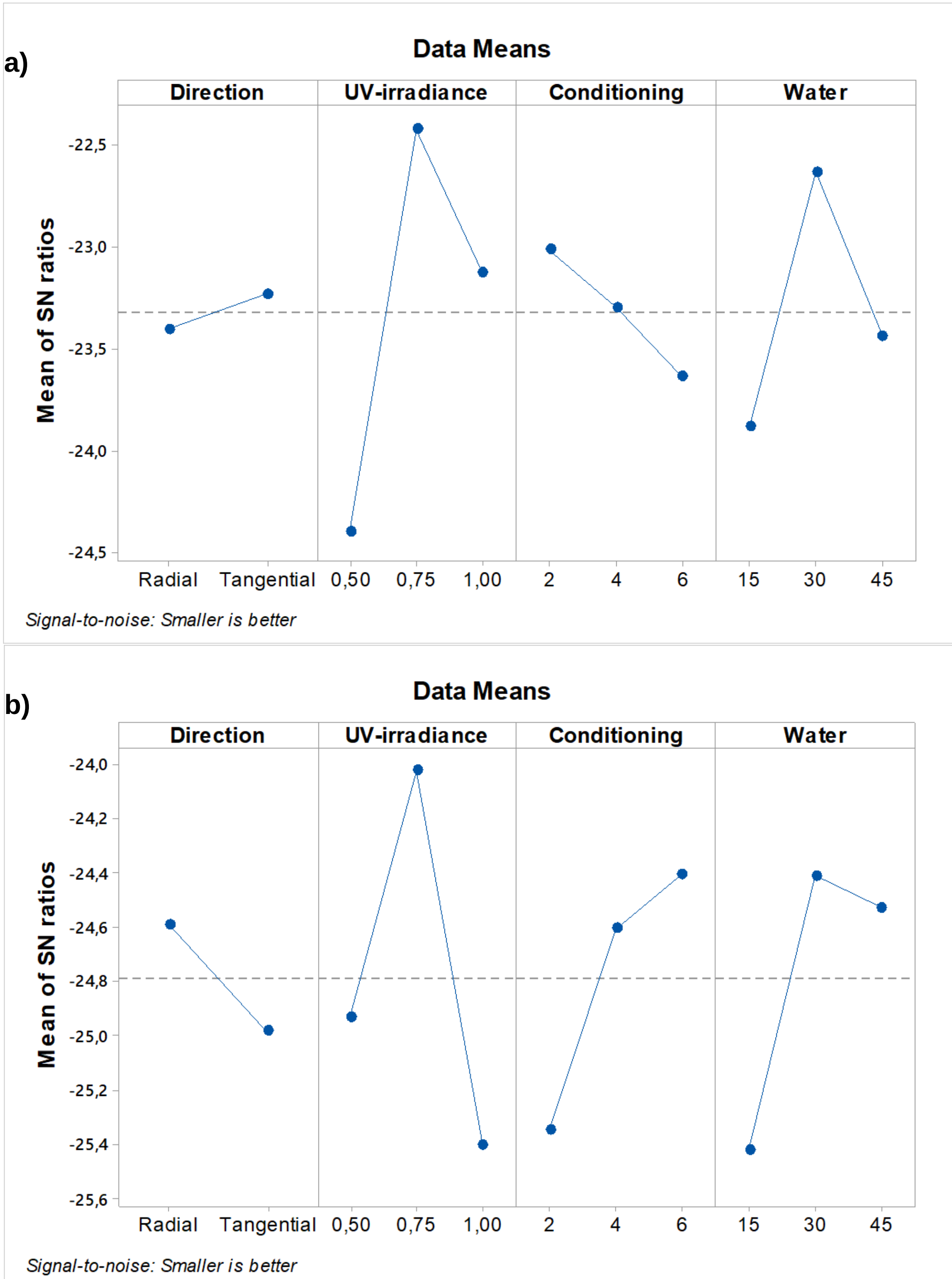

Fig. 1. The main effect plots for S/N ratios for a) Scots pine and b) poplar

The degradation that occurs on the wood surface due to external environmental conditions weakens the chemical bonds in the cell wall and causes microscopic and / or macroscopic stresses and cracks between and within cells. Wood with high density is more durable in outdoor conditions than wood with low density. In general, deciduous tree wood having high specific gravity degrades more slowly than coniferous wood. By the differences shown by the wood itself it exhibits different behaviors against outdoor environmental conditions. The walls of earlywood are eroded faster than those of latewood (Feist and Hon 1984; Williams *et al*. 2001).

Study has demonstrated that there are significant degradation differences on the radial and tangential surfaces of wood exposed to outdoor conditions. It has been observed that cracks are more numerous and deeper on tangential surfaces than on radial surfaces. Cracks on tangential wood surfaces occur especially between earlywood and latewood, whereas on radial surfaces, cracks form at the annual ring boundaries. The most prominent difference in erosion on tangential and radial surfaces was observed at the microscopic level in the cell membrane passages. Cell wall degradation occurs on both surfaces; but the separation in the middle lamella occurs on tangential surfaces, especially in latewood (Feist 1990).

ANOVA Results

The ANOVA results demonstrate that the UV-irradiance was the most significant factor that affected the color change in both Scots pine and poplar wood (Table 6). The UV-irradiance had a 39.45% effect on the color change in the Scots pine wood and a 28.51% effect on the poplar wood. However, the error frequencies were quite high for both tree species. The rows which are marked as “Error” refer to the error caused by uncontrollable factors (noise). In the literature, it is stated that this value should be below 50% for the results to be reliable (Pourjafar *et al.* 2013). The error value was below 50% for both specimens.

Table 6. ANOVA Results for Scots Pine and Poplar Wood

Parameters	Codes	DF	Sum of Squares (SS)	Mean of Squares (MS)	F-Value	Contribution Rate	Rank
	Scots pine						
Direction	A	1	0.0252	0.0252	0.01	0.03	4
UV-irradiance (W/m^2)	**B**	**2**	**35.7220**	**17.8610**	**4.70**	**39.45**	**1**
Conditioning (h)	C	2	2.7600	1.3800	0.36	3.05	3
Water (min)	D	2	14.0381	7.0190	1.85	15.50	2
Error (%)	-	10	38.0126	3.8013	-	41.98	-
Total	-	17	90.5579	-	-	100	-
	Poplar						
Direction	A	1	2.669	2.669	0.92	3.34	4
UV-irradiance (W/m^2)	**B**	**2**	**22.775**	**11.388**	**3.93**	**28.51**	**1**
Conditioning (h)	C	2	10.894	5.447	1.88	13.64	3
Water (min)	D	2	14.590	7.295	2.52	18.26	2
Error (%)	-	10	28.966	2.897	-	36.26	-
Total	-	17	79.894	-	-	100	-

Regression models were established to estimate the color change parameters of Scots pine and poplar wood. These models are provided in Eq. 3 and Eq. 4.

$$\Delta E_{scotspine} = 14.816 + 0.037D_{radial} - 0.037D_{tangential} + 1.879UV_{0.50} - 1.513UV_{0.75} - 0.367UV_{1.00} - 0.481C_2 + 0.002C_4 + 0.478C_6 + 1.005W_{15} + 1.145W_{30} + 0.140W_{45} \quad (3)$$

$$\Delta E_{poplar} = 17.479 - 0.385D_{radial} + 0.385D_{tangential} + 0.322UV_{0.50} - 1.510UV_{0.75} + 1.188UV_{1.00} + 1.075C_2 - 0.334C_4 - 0.741C_6 + 1.262W_{15} - 0.777W_{30} - 0.485W_{45} \quad (4)$$

Here, the color change (ΔE) is a dependent variable, whereas direction (D), UV-irradiance (UV), conditioning (C), and water (W) are independent variables. The R^2 value of this model was 58.02% for Scots pine and 63.74% for poplar wood. These values are acceptable for estimation. The correlation coefficient (R) for Scots pine was 0.76 and 0.80 for poplar, which showed the relationship between the variables to be linear and above the accepted limits of 0.60 to 0.70 outlined in the literature (Cabuk *et al.* 2011; Kurt *et al.* 2016).

There have been many studies on the changes on wood material caused by outdoor weather conditions. UV radiance creates free radicals on the wood surface; these free radicals produce hydrogen peroxide, which is easily broken down by the effect of oxygen and water (Feist and Hon 1984). These free radicals cause the degradation of lignin and the photooxidation of these structures by breaking down the chains of cellulose and hemicelluloses (Pandey 2005).

CONCLUSIONS

In this study, the effect of accelerated weathering factors on the total color change of the wood surfaces of Scots pine (*Pinus sylvestris* L.) and poplar (*Populus x euroamericana*) were investigated. Four parameters thought to be effective on the color change were optimized using the L_{18} Taguchi orthogonal array. The experimental results were then evaluated *via* ANOVA analysis.

1. In both tree species, a minimum total color change was obtained with a process of 0.75 W/m^2 UV-irradiance and 30 min of water spraying. The use of different tree species led to different behaviors in the specimens against the factors of accelerated weathering. The minimum total color change values were achieved on the tangential surfaces in the Scots pine specimens and on the radial surfaces in the poplar specimens. The ANOVA analysis showed the UV-irradiance to be the most effective factor on the total color change.
2. All results showed that the Taguchi method was generally very effective both in decreasing the number of experiments and in determining the optimum parameters that affected color change. In addition, this demonstrates that the Taguchi method could be used to optimize and forecast processes to determine the best results from other combinations that were not tested.

3. There are a great number of parameters that affect color change in wood. In particular, this was thought to be the origin of the high error value (attributed to "uncontrollable factors") obtained in the ANOVA results in this study. Therefore, in future studies it is believed that better results could be obtained by including different parameters which might affect color change in the model.

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