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IMPACT OF TEMPERATURE AND ULTRAVIOLET RADIATION ON CHANGES OF COLOUR OF FIR AND SPRUCE WOOD

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ABSTRACT

This study deals with the investigation of impact of temperature and ultraviolet (UV) radiation on spruce wood (*Picea abies* (L.) H. Karst.) and fir wood (*Abies alba* Mill.) colour changes. Samples of investigated woods species were loaded by temperatures of 110, 130, and 150°C and UV radiation (with 253.7 nm wavelength and 40 W m^{-2} intensity) during 72, 168, 336 and 672 hours. Colour changes were evaluated in the CIE Lab colour space. The neural network for prediction of both colour coordinates and total colour difference of spruce and fir wood was trained by data regarding exposure conditions (temperature, UV radiation and time) and by obtained results. Coefficient of determination (R^2) of the neural network was above 0.99 for training, validation and testing. Average colour coordinates (± standard deviation) of the spruce and fir wood before exposure were L^* = 80.08 ± 3.70, a^* = 7.55 ± 2.13, b^* = 21.56 ± 1.79, L^* = 80.46 ± 1.91, a^* = 6.84 ± 0.97, and b^* = 18.90 ± 1.26, resp. Total colour differences after thermal loading were in the interval from $_{\Delta}E_{ab}^*$ = 3.76 ± 1.95 (spruce wood at 110°C) to $_{\Delta}E_{ab}^*$ = 45.37±1.46 (fir wood at 150°C). Total colour differences of both wood species exposed by UV radiation were approximately in intervals from $_{\Delta}E_{ab}^*$ = 12 to 13 (after 72 h) up to $_{\Delta}E_{ab}^*$ = 16 to 20 (after 168 to 672 h). Obtained results proven that both temperature and UV radiation have significant impact on the colour changes of the investigated woods.

KEYWORDS: CIE Lab, colour change, fir wood, neural network, spruce wood, thermal modification, ultraviolet radiation.

INTRODUCTION

Colour is the basic (aesthetic) property of every surface. Colour spaces (models) are used for exact expression of colour. Among the most famous and used colour spaces are RGB (red, green, blue), CIE Lab, HSB or HSL (hue, saturation, brightness or lightness), CMY(K) (cyan, magenta, yellow - key black), YCbCr (luma, blue, red) and RAL (acronym of Institute for Quality Assurance and Labelling in German language). Each colour space is used in a certain area (e.g. CMY(K) in printing, YCbCr in digital image processing, etc.). The mentioned colour spaces are mutually convertible, details about conversions between colour spaces are described in e.g. Ji et al. (2006) and Mu et al. (2005). The colour of the wood is most often expressed by the CIE Lab colour space, as evidenced by e.g. scientific works of Dzurenda and Dudiak (2021), Varga et al. (2021), Reinprecht et al. (2018) and Timar et al. (2016). Less often, the colour of wood was also expressed in other colour spaces by Awoyemi and Jarvis (2007).

The CIE Lab is a three-dimensional colour-space consisting of three axes (L^*, a^*, and b^*). The L^* axis is lightness (grayscale) from 0 (black) to 100 (white). The a^* is axis of red (positive)/green (negative) and the b^* is axis of yellow (positive) / blue (negative) (Ly et al. 2020, Soares, Alves 2018, and Dzurenda 2014). According to STN EN ISO/CIE 11664-4: 2020, the difference between the colours of two surfaces can be expressed as colour difference (the absolute value of the differences between the coordinates L^*, a^*, and b^* of these surfaces $_\Delta L^*$, $_\Delta a^*$, and $_\Delta b^*$) or as total colour difference according to Eq. 1 defined by the cited technical standard:

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

where: $_\Delta E_{ab}{}^*$ is the total colour difference between colour of two compared surfaces (-), $_\Delta L^*$ is lightness differences between these surfaces (-), $_\Delta a^*$ is differences in red/green colour coordinates between these surfaces (-) and $_\Delta b^*$ is differences in yellow/blue colour coordinates between these surfaces (-).

Since wood is heterogeneous material with surface texture (the texture shows colour variability), the values of L^*, a^*, and b^* are determined as average value obtained by measure at several points. The average values are usually reported with the standard deviation or with the combined standard uncertainty of the measurement, which is calculated according to Eq. 2, given by Dzurenda (2014):

$$u_{C_{L^*}} = \sqrt{\frac{\sum_{i=1}^{n}(L_i - \bar{L})^2}{n(n-1)} + u^2_{B_{L^*}}}, \quad u_{C_{a^*}} = \sqrt{\frac{\sum_{i=1}^{n}(a_i - \bar{a})^2}{n(n-1)} + u^2_{B_{a^*}}}, \quad u_{C_{b^*}} = \sqrt{\frac{\sum_{i=1}^{n}(b_i - \bar{b})^2}{n(n-1)} + u^2_{B_{b^*}}} \quad (2)$$

where: u_{CL^*}, u_{Ca^*} and u_{Cb^*} (-) are the combined standard uncertainties of L^*, a^*, and b^* (-), L_i, a_i, and b_i are measured values of colour coordinates (-), $\bar{L}, \bar{a}$, and $\bar{b}$ are average values of colour coordinates (-), n is number of measurements (-) and $u^2_{BL^*}$, $u^2_{Ba^*}$ and $u^2_{Bb^*}$ (-) are colourimeter standard deviations.

The colour of the wood is primarily determined by the type of wood, but even with the same type of wood, its colour depends on a large number of factors. The mentioned factors are divided into natural (occurring without exposure of wood to physical, chemical or biological agents) and external (caused by exposure of wood to physical, chemical or biological agents). The most important natural factors include water content, wood cut (tangential, radial and transverse) and type of wood (spring and summer wood; sapwood and heartwood) and possibly wood defects (e.g. knots). The most important physical factors include primarily exposure to increased temperature and ultraviolet radiation. Chemical and biological factors include the exposure of wood to a chemical substance (chemical modification of wood) or biological pests (e.g. wood decay fungi and moulds).

The impact of changing the colour of wood as a result of the action of external factors depends on the specific (area) of application. The same change may be desirable for certain applications while undesirable or irrelevant for others. An example can be the darkening of wood as a result of the effect of increased temperature or ultraviolet (UV) radiation. In the production of thermally modified wood, this change is usually desirable (it creates the impression of exotic wood). An example of an undesirable change in the colour of wood is its (direct or indirect) exposure to germicidal radiation (especially UV radiation with a wavelength of 253.7 nm) due to the sterilization of pathogenic agents on the surface. Intentional exposure of surfaces (including wood) to germicidal UV radiation has increased especially in the last two years due to the use of this type of radiation to inactivate SARS-CoV-2 virus. Growing interest in SARS-CoV-2 virus inactivation by the UV radiation documents (Schuit et al. 2022).

The dependence of the change of the average colour coordinates of wood on temperature, the intensity of ultraviolet radiation and the time of exposure is of significant use in science and research, as well as in technical practice. Among the most important is the backward estimation of the conditions of thermal modification (temperature and time) of wood, which was described in detail by Martinka et al. (2018). Another method of retrospective estimation of thermal modification conditions was described by Korosec et al. (2017). This retrospective estimate can be used e.g. when checking the temperature program of the wood modification declared by the manufacturer and when determining the causes of fires (estimation of temperatures in the adjacent fire compartment). This method is only applicable for adjacent fire compartment, where the wood was exposed to temperatures up to 150°C (short-term 200 to 220°C) and did not flame burn. If the wood burned in a flame way, the change in colour is not used to determine the causes of fires, but the rate of charring. Babrauskas (2005) provides details. The change in the colour coordinates of the wood as a result of exposure to ultraviolet radiation is used, e.g. also for a quick preliminary estimate of the age of a wooden product that was exposed only to sunlight (not to direct atmospheric precipitation). The effect of exposure of wood to temperature or ultraviolet radiation (e.g. during aging) on the change in its properties is described in their scientific works (Severo et al. 2012, Park et al. 2016, Sikora et al. 2018, Mitterpach et al. 2020, Zachar et al. 2017, 2021, Fathi et al. 2021).

The aim of the presented study is to quantify the impact of exposure of spruce wood (*Picea abies* (L.) H. Karst.) and fir wood (*Abies alba* Mill.) to temperatures of 110, 130 and 150°C and ultraviolet radiation (with 253.7 nm wavelength and 40 $W \cdot m^{-2}$ intensity) during 72, 168, 336 and 672 h to change their colour. Another goal of the study is to train a neural network to predict the colour coordinates and total colour differences of the mentioned woods after exposure to increased temperature (between 110 and 150°C) and ultraviolet radiation (with 253.7 nm wavelength and 40 $W \cdot m^{-2}$ intensity) in a time interval of 0 up to 672 h.

MATERIALS AND METHODS

Spruce wood (*Picea abies* (L.) H. Karst.) and fir wood (*Abies alba* Mill.) samples were subjected to research. The samples were sawn to blocks with dimensions (100 × 100 × 20) ± 1 mm (tangential × radial × longitudinal). The surface of the samples was subsequently sanded with a vibrating sander with 120-grit sandpaper. A total of 32 samples were prepared from each type of wood (of which 24 samples were used for research on the effect of temperature and 8 samples for research on the influence of ultraviolet radiation on colour change). The samples were selected without defects on the surface (no cracks, lumps and other anomalies). For each sample, the coordinates of the CIE colour space L^*, a^*, b^* were measured on one surface (100 × 100) mm at 40 points before and after exposure.

The samples used to investigate the effect of temperature were exposed in an ARGOLAB TCN 50 Plus oven (AGROLAB GmbH, Landshut, Germany) to temperatures (110, 130 and 150°C) ± 2°C for (72, 168, 336 and 672 h) ± 2h. The samples were stored in the oven in such a way that they did not touch each other and that the measured side did not touch the grid on which they were stored.

The samples used for research on the effect of ultraviolet (UV) radiation were exposed in a UV chamber set up at the Institute of Integrated Safety of the Slovak University of Technology in Bratislava. The chamber has internal dimensions (1475 × 1150 × 850) mm and is equipped with 20 UV lamps TUV TL-D 15W (Philips, Amsterdam, Netherlands). The samples were stored in the UV chamber not touching each other, that the measured side did not touch the grid on which they were stored, and that they did not shade each other from UV radiation in any way. The samples were exposed to UV radiation with an intensity of 40 ± 1 $W \cdot m^{-2}$, a wavelength of 253.7 nm, for (72, 168, 336 and 672 h) ± 2h.

CIE Lab colour space coordinates were measured with a 3nh NR200 colourimeter (3nh, Shiyan, Public Republic of China). Colourimeter standard deviation is 0.08. Total colour differences were calculated according to Eq. 1 and combined standard uncertainties according to Eq. 2.

The statistical significance of total colour differences between the studied wood kinds was evaluated by two-factor ANOVA with replication (at the significance level $\alpha = 0.05$). The neural network was created and trained in the MATLAB 2020b program (in the Neural Network Toolbox environment). The three layers Neural Network Fitting (input layer, hidden layer and output layer) was used. The number of neurons in input, hidden and output layer was 5, 10, and 4, respectively. The structure of used neural network is shown in the Fig. 1. The number of values (items) used for training, validation and test was 1792, 384, and 384, resp. The Levenberg–Marquardt algorithm training algorithm was used.

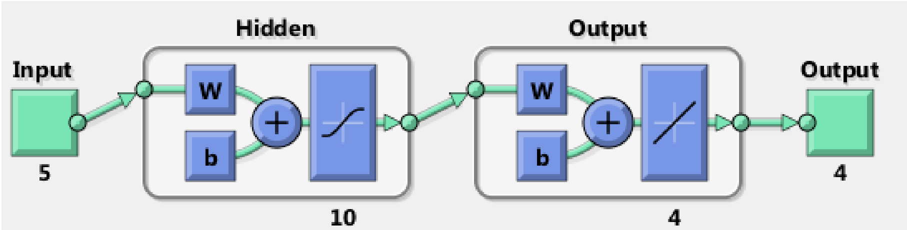

Fig. 1: Structure of neural network for colour coordinates prediction.

Structure of input and output data for neural network training and prediction of colour coordinates of fir and spruce wood is in Tab. 1. The list of 9-tuples (Tab. 1) was used in the phase of neural network training. The list of 5-tuples (Tab. 1) was used in the phase of neural network validation and testing. In the same way a list of 5-tuple is used for the neural network prediction phase (wood species, type of exposure: temperature or UV radiation, time of exposure and temperature are stated as input) and total colour difference together with colour coordinates are predicted as neural network output. The values of time are divided by 672 and temperature by 150 due to data normalization (so that the minimum values correspond to 0 and maximum values correspond to 1).

Tab. 1: Structure of input value for training of neural network and prediction by trained neural network.

Data used for both training and prediction					Data used only for training			
Wood	Exposure to temperature	UV	Time (-)	Temp. (-)	ΔE_{ab} (-)	L^* (-)	a^* (-)	b^* (-)
0 - fir 1 - spruce	0 - No 1 - Yes	0 - No 1 - Yes	Time in h / 672	Temp. in °C / 150	Value	Value	Value	Value

RESULTS AND DISCUSSION

Pre-exposure and post-exposure wood samples are shown in Fig. 2 and Fig. 3. The coordinates of the CIE Lab colour space of fir and spruce wood before exposure are in Tab. 2. Changes in the coordinates of the CIE Lab colour space of the listed woods after exposure to elevated temperatures and UV radiation are in Tab. 3 and 4.

Similar values of the colour coordinates of unexposed fir and spruce wood are given by Kucerova et al. (2016), Sikora et al. (2018), Klement et al. (2019) and Haftkhani et al. (2022). Average values for fir wood from the scientific works of Kucerova et al. (2016) and Haftkhani et al. (2022) are L^* = 81.6, a^* = 3.7, and b^* = 21.6. Average values for spruce wood from the scientific works of Sikora et al. (2018) and Klement et al. (2019) are L^* = 81.1, a^* = 3.6, and b^* = 20.1. The stated values differ slightly from the values in Tab. 2. However, the difference is not significant and is due to the fact that wood is a heterogeneous anisotropic natural material.

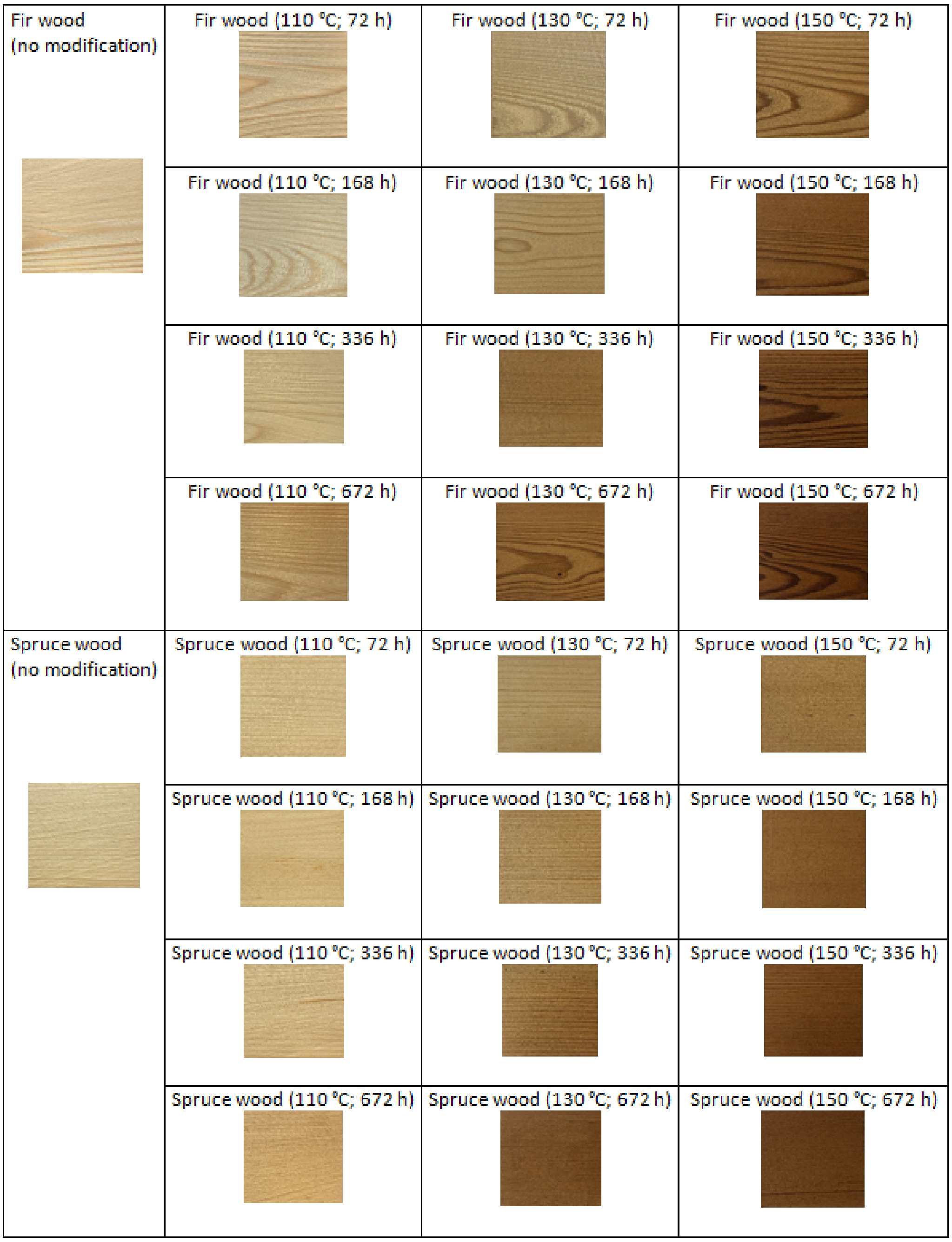

Fig. 2: Samples of fir and spruce woods before and after exposition by temperature in range from 110 to 150°C during 72 to 672 h.

Tab. 2: Average CIE Lab colour space coordinates of fir and spruce wood before modification (L: lightness, a*: axis of red/green and b*: axis of yellow/blue).*

Sample (-)	*L** (-)	*a** (-)	*b** (-)
Fir wood	80.46 ± 0.10 (1.91)	6.84 ± 0.08 (0.97)	18.90 ± 0.09 (1.26)
Spruce wood	80.08 ± 0.13 (3.70)	7.55 ± 0.10 (2.13)	21.56 ± 0.09 (1.79)

Note: Values after sign ± denote combined standard uncertainty of average value and values in round brackets denote standard deviation of average values.

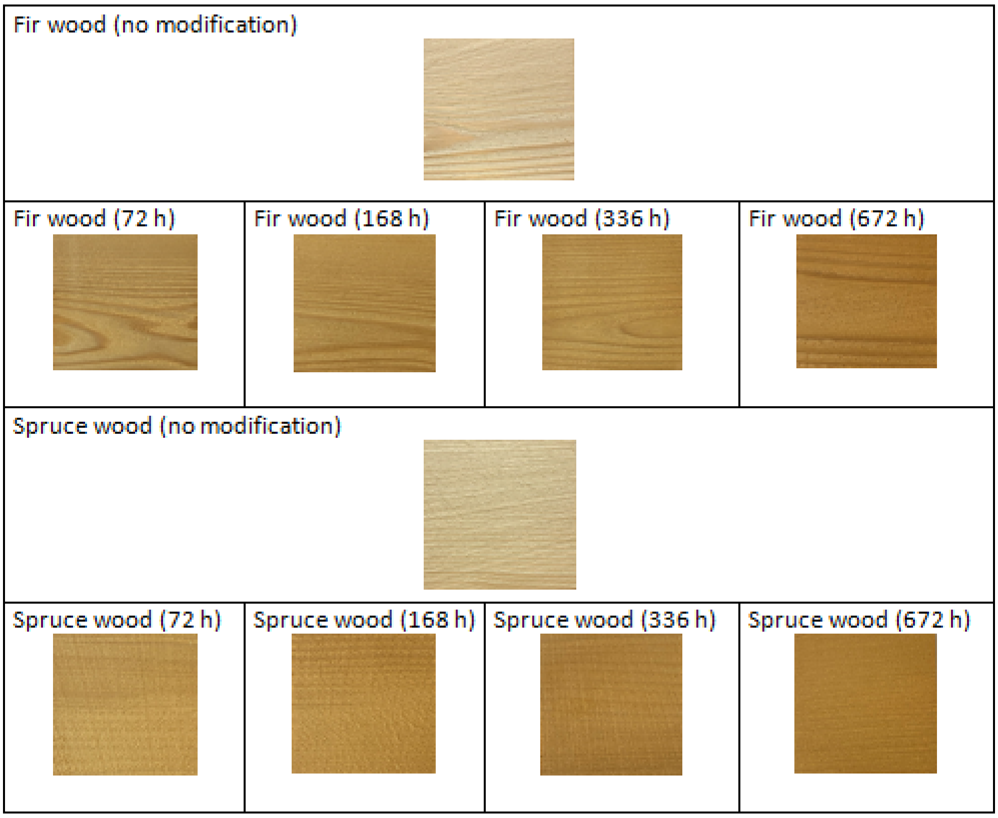

Fig. 3: Samples of fir and spruce woods before and after exposition by ultraviolet radiation with 253.7 nm wavelength and 40 W·m^{-2} intensity during 72 to 672 h.

Data in Tabs. 3 and 4 accurately express the effect of exposure of wood to temperature (Tab. 3) and UV radiation (Tab. 4) on their colour change. The influence of factors on the colour change is more visually expressed in Figs. 4 and 5, which illustrate the effect of temperature/UV radiation on both minimal and maximal values (without extremes and outliers), fist quartile (25%), third quartile (75%) and median of total colour difference. Data in Tab. 3 and Fig. 4 prove that the total colour difference increases with increasing temperature and exposure time. Tab. 3 and Fig. 4 shows several anomalies, primarily that spruce wood shows a higher value of total colour difference at a temperature of 110°C for 72 h than for 168 h. A similar trend that one or more colour coordinates of wood when exposed to increased temperature (or UV radiation) with increasing temperature or exposure time first increases, then decreases and then starts to increase again (or shows the opposite trend) is in published scientific works (Goktas et al. 2009, Schnabel et al. 2009, Kucerova et al. 2016, Park et al. 2016, Sikora et al. 2018, Zeniya et al. 2019). If there is a small difference, the cause may be the heterogeneity of the wood surface (and the resulting variability of the measured values). However, the main cause of the mentioned trend in the presented study is the migration of the resin to the surface of the examined samples.

When exposed to UV radiation (Tab. 4, Fig. 5), the colour change occurs mainly in the first 72 h (the subsequent change between 72 and 168 h is already significantly smaller). With spruce wood exposed to UV radiation for 672 h, the dispersion of total colour differences values (compared to exposure for 72 to 336 h) is minimal (Fig. 5). From the above, it follows that with increasing spruce wood exposure time, the dispersion of total colour differences decreases.

The cause of the change in the colour of wood as a result of exposure to temperature and UV radiation is a change in the chemical composition. There is a significant difference between the colour change of wood as a result of exposure to temperature and UV radiation. The difference is the fact that exposure to temperature causes a change in the chemical composition throughout the cross section, while according to Fengel and Wegener (1983) and Geffertova et al. (2018) exposure of wood to UV radiation causes primary changes only to a depth of tens of nanometers and secondary changes up to 0.15 mm.

According to Dudiak et al. (2022) the colour of the wood is formed by chromophores: functional groups of the type >C=O, -CH=CH-CH=CH-, -CH=CH-, aromatic nuclei found in the chemical components of wood (lignin and extractives), which absorb some wavelength of the light and thus create the colour of the wood surface.

According to Fengel and Wegener (1983), Melcer et al. (1990), Funaoka et al. (1990), Bucko et al. (1994) and Kacikova et al. (2006), wood decomposes very slowly even at a temperature below 100°C and it is not possible to determine the lower limit from which it starts to decompose.

Tab. 3: Average differences of CIE Lab space coordinates of fir and spruce wood between pristine wood and temperature exposed wood ($_{\Delta}L^*$: lightness difference, $_{\Delta}a^*$: axis of red/green difference, $_{\Delta}b^*$: axis of yellow/blue difference and $_{\Delta}E_{ab}^*$: total colour difference).

Sample (-)	Temp. (°C)	Time (h)	$_{\Delta}L^*$ (-)	$_{\Delta}a^*$ (-)	$_{\Delta}b^*$ (-)	$_{\Delta}E_{ab}$ (-)
Fir wood	110	72	-8.45 ± 0.17 (1.29)	2.06 ± 0.11 (0.67)	0.96 ± 0.16 (1.25)	8.86 ± 0.17 (1.30)
		168	-8.67 ± 0.14 (1.05)	4.53 ± 0.11 (0.64)	6.23 ± 0.12 (0.83)	11.62 ± 0.16 (1.28)
		336	-11.78 ± 0.16 (1.24)	5.33 ± 0.10 (0.55)	9.50 ± 0.11 (0.62)	16.07 ± 0.15 (1.18)
		672	-10.56 ± 0.21 (1.71)	5.50 ± 0.13 (0.86)	10.22 ± 0.15 (1.08)	15.72 ± 0.24 (2.05)
	130	72	-10.68 ± 0.21 (1.71)	2.79 ± 0.14 (1.07)	5.49 ± 0.23 (1.91)	12.48 ± 0.24 (1.98)
		168	-15.11 ± 0.13 (0.96)	7.15 ± 0.10 (0.52)	11.30 ± 0.11 (0.64)	20.19 ± 0.14 (1.03)
		336	-27.92 ± 0.18 (1.44)	9.53 ± 0.10 (0.60)	11.00 ± 0.16 (1.24)	31.52 ± 0.17 (1.37)
		672	-27.05 ± 0.31 (2.64)	5.96 ± 0.24 (1.99)	7.17 ± 0.38 (3.26)	28.84 ± 0.33 (2.86)
	150	72	-20.77 ± 0.20 (1.62)	7.03 ± 0.12 (0.79)	9.09 ± 0.14 (1.06)	23.76 ± 0.21 (1.73)
		168	-29.69 ± 0.29 (2.37)	8.36 ± 0.14 (1.03)	7.87 ± 0.21 (1.62)	31.88 ± 0.31 (2.63)
		336	-34.49 ± 0.24 (2.02)	7.77 ± 0.12 (0.77)	7.77 ± 0.16 (1.27)	36.24 ± 0.22 (1.84)
		672	-44.23 ± 0.19 (1.42)	8.11 ± 0.13 (0.87)	5.74 ± 0.19 (1.56)	45.37 ± 0.18 (1.46)
Spruce wood	110	72	-8.41 ± 0.15 (1.15)	3.34 ± 0.10 (0.50)	5.26 ± 0.22 (1.80)	10.53 ± 0.23 (1.87)
		168	-3.23 ± 0.22 (1.80	0.45 ± 0.10 (0.60)	1.70 ± 0.13 (0.92)	3.76 ± 0.23 (1.95)
		336	-7.47 ± 0.18 (1.40)	3.02 ± 0.12 (0.82)	7.18 ± 0.13 (0.91)	10.81 ± 0.22 (1.78)
		672	-12.64 ± 0.21 (1.69)	6.49 ± 0.10 (0.50)	8.87 ± 0.10 (0.57)	16.79 ± 0.19 (1.53)
	130	72	-11.13 ± 0.17 (1.37)	3.44 ± 0.10 (0.56)	5.91 ± 0.13 (0.85)	13.14 ± 0.14 (1.01)
		168	-10.53 ± 0.35 (3.04)	4.77 ± 0.11 (0.69)	7.28 ± 0.11 (0.61)	13.75 ± 0.32 (2.78)
		336	-23.27 ± 0.14 (1.01)	7.73 ± 0.09 (0.42)	10.63 ± 0.13 (0.96)	26.74 ± 0.14 (1.06)
		672	-29.61 ± 0.21 (1.72)	8.49 ± 0.08 (0.24)	7.06 ± 0.10 (0.56)	31.61 ± 0.19 (1.55)
	150	72	-21.00 ± 0.20 (1.65)	8.40 ± 0.09 (0.31)	9.59 ± 0.09 (0.41)	24.59 ± 0.18 (1.44)
		168	-28.05 ± 0.35 (3.04)	9.49 ± 0.09 (0.33)	9.24 ± 0.15 (1.10)	31.08 ± 0.31 (2.62)
		336	-32.60 ± 0.22 (1.81)	8.39 ± 0.11 (0.66)	6.17 ± 0.13 (0.90)	34.24 ± 0.21 (1.75)
		672	-37.89 ± 0.16 (1.21)	7.16 ± 0.10 (0.55)	2.49 ± 0.16 (1.19)	38.67 ± 0.16 (1.22)

Note: Values after sign ± denote combined standard uncertainty of average value and values in rounds brackets denote standard deviation of average values.

Tab. 4: Average differences of CIE Lab space coordinates of fir and spruce wood between pristine wood and ultraviolet radiation exposed wood ($_{\Delta}L^*$: lightness difference, $_{\Delta}a$: axis of red/green difference, $_{\Delta}b$: axis of yellow/blue difference and $_{\Delta}E_{ab}$: total colour difference).

Sample (-)	Time (h)	$_{\Delta}L^*$ (-)	$_{\Delta}a^*$ (-)	$_{\Delta}b^*$ (-)	$_{\Delta}E_{ab}$ (-)
Fir wood	72	-5.42 ± 0.27 (2.25)	2.22 ± 0.14 (1.07)	10.75 ± 0.14 (0.97)	12.44 ± 0.19 (1.53)
	168	-17.98 ± 0.18 (1.42)	6.52 ± 0.14 (0.97)	8.32 ± 0.15 (1.13)	20.89 ± 0.20 (1.67)
	336	-8.07 ± 0.17 (1.32)	4.15 ± 0.11 (0.73)	13.23 ± 0.15 (0.55)	16.42 ± 0.20 (1.58)
	672	-9.22 ± 0.22 (1.83)	6.10 ± 0.15 (1.11)	15.70 ± 0.18 (1.41)	19.28 ± 0.23 (1.91)
Spruce wood	72	-6.06 ± 0.30 (2.53)	3.11 ± 0.16 (1.20)	11.02 ± 0.16 (1.23)	13.10 ± 0.28 (2.36)
	168	-8.35 ± 0.23 (1.88)	4.41 ± 0.16 (1.22)	13.65 ± 0.20 (1.66)	16.64 ± 0.29 (2.51)
	336	-9.99 ± 0.19 (1.58)	6.23 ± 0.10 (0.52)	15.88 ± 0.14 (0.98)	19.79 ± 0.20 (1.61)
	672	-9.24 ± 0.12 (0.82)	6.71 ± 0.08 (0.25)	15.65 ± 0.09 (0.42)	19.39 ± 0.10 (0.49)

Note: Values after sign ± denote combined standard uncertainty of average value and values in round brackets denote standard deviation of average values.

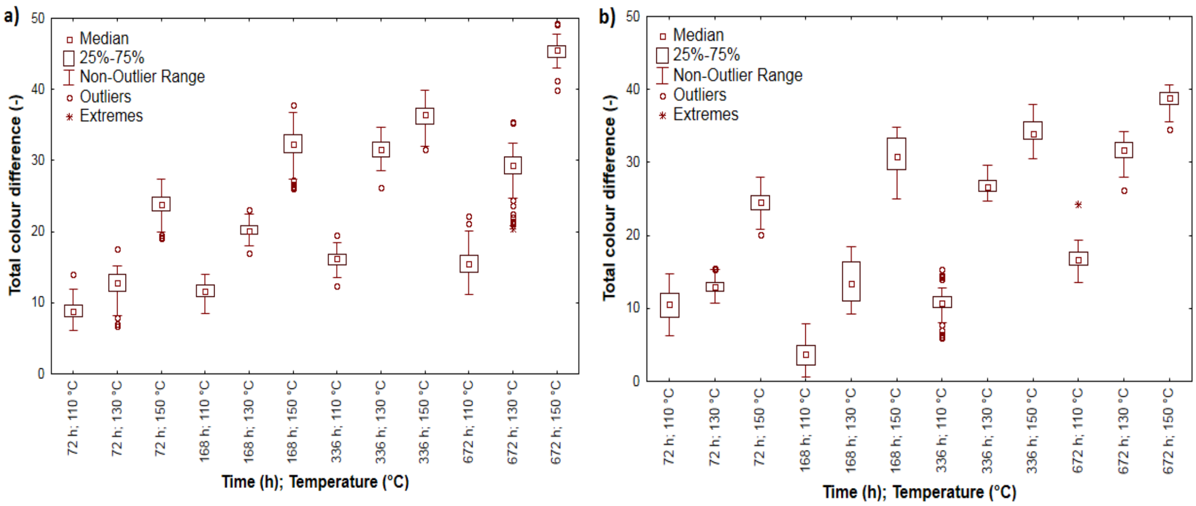

Fig. 4: Impact of temperature and time of exposure on total colour differences of fir wood (a) and spruce wood (b).

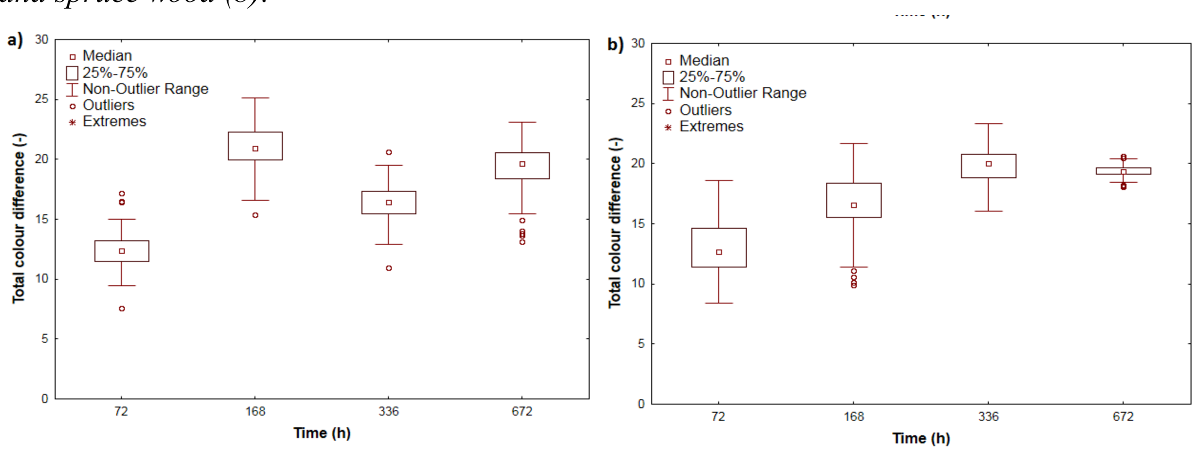

Fig. 5: Impact of exposition time by ultraviolet radiation (at 253.7 nm wavelength and 40 $W \cdot m^{-2}$ intensity) on total colour differences of fir wood (a) and spruce wood (b).

According to Shafizadeh (1984), Kacik et al. (2001) and Kacikova et al. (2006), the decomposition reactions of the main components of wood are divided with respect to the limit temperature of 300°C. According to the cited authors, at temperatures up to 300°C in lignin, mainly following bonds are decomposed: C-C in the aliphatic chain of phenylpropane C_9 units of lignin (240-280°C), ether C-O-C_4 alkyl-acrylic (up to 290°C) and C-O-$(C_6H_{10}O_5)_nH$ phenyl-glycosides that connect lignin with hemicelluloses (270-300°C). The values given are higher than the temperatures in this study. The reason that even at lower temperatures a change in colour was recorded was the long-term exposure of the samples and the decomposition of extractives. According to Nuopponen et al. (2003) and Kacikova et al. (2006), mainly carbonyl groups of fatty acid esters are decomposed from extractives at a temperature of 100 to 180°C.

Two-factor ANOVA with replication (at the significance level α = 0.05) p value for total colour differences caused thermal loading is significantly lower than 0.05 ($1.23 \cdot 10^{-13}$) and for total colour differences caused by UV radiation is 0.85. Thus there are statistically significant differences between Fir and Spruce wood regarding to changes of their colour due to thermal loading. On the other hand the colour differences between investigated woods due to loading by UV radiation are negligible (no statistically significant).

Accuracy of trained neural network was evaluated by both correlation and regression of predicted versus expected values and by errors (differences between expected and predicted values) histogram. Correlation and regression of predicted versus expected CIE Lab colour space coordinates of fir and spruce wood for trained neural network is in the Fig. 6.

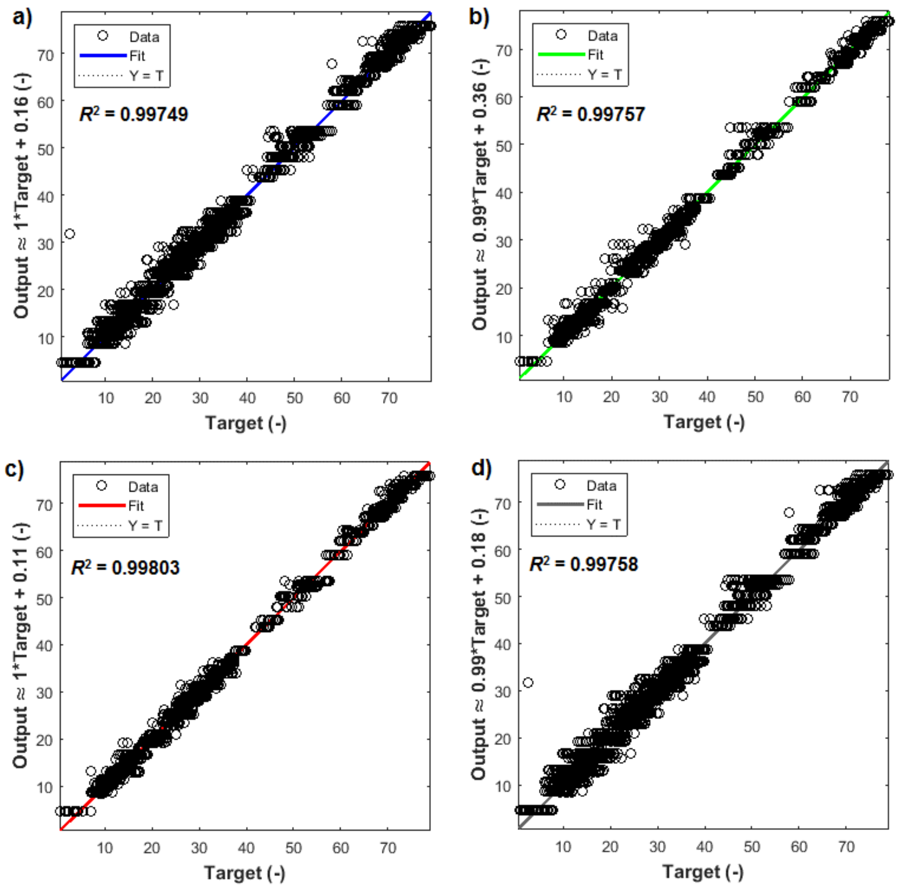

Fig. 6: Correlation and regression of predicted versus expected CIE Lab colour space coordinates of fir and spruce wood for a) training, b) validation, c) test, and d) all data used in training, validation and test of neural network.

The error histogram is in the Fig. 7. Achieved accuracy of trained neural network (R^2 > 0.99 in Fig. 6; and fact that differences between measured and predicted value is in interval -0.7589 to 1.079 for most cases, Fig. 7) is sufficient for virtually all future applications (both in science and technical practice). Trained neural network in MATLAB file is available upon request. Command for prediction in trained network "Y = sim(net_color, input')", where input represent 5-tuple in structure according to Tab. 1, e.g. (1, 1, 0, 0.5, 0.87) and Y represent output 4-tuple (ΔE_{ab}, L^*, a^*, b^*).

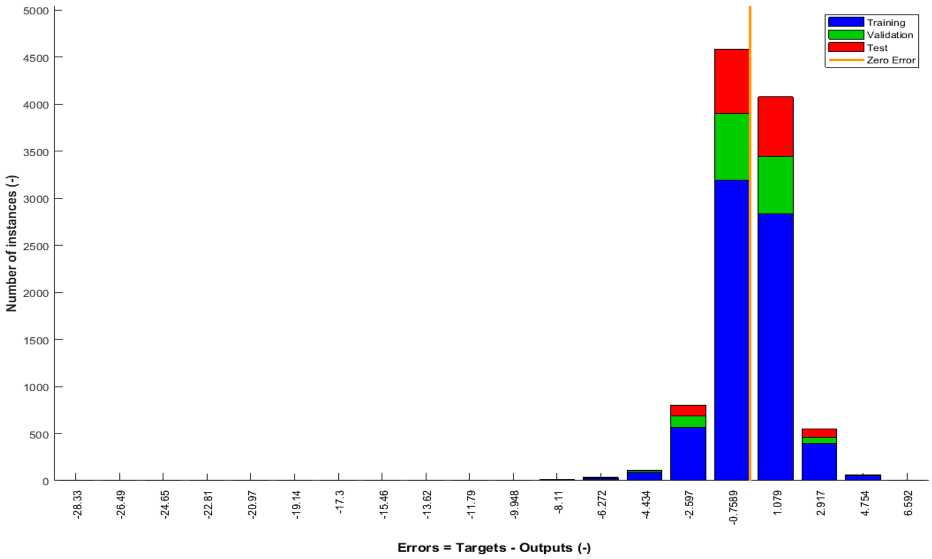

Fig. 7: Error (differences between targets and predicted outputs of CIE Lab colour coordinates) histogram for trained neural network.

CONCLUSIONS

The presented study dealt with research on the effect of exposure of fir and spruce wood to temperature (in the interval from 110 to 150°C) and ultraviolet radiation (with a wavelength of 253.7 nm and an intensity of 40 W·m^{-2}) for 72 to 672 h on the change of colour coordinates in CIE Lab colour spaces. The study was further devoted to training a neural network to predict the colour coordinates of the mentioned woods from the exposure conditions (temperature, UV radiation and time). CIE Lab average colour coordinates before exposition of fir wood were approx. L = 80.5, a^* = 6.8, b^* = 18.9; and the coordinates of spruce wood were approx. L = 80.1, a^* = 7.6, and b^* = 21.6. Total colour differences of fir wood exposed by temperature lay in the intervals from 8.9 to 16.1 (at 110°C) up to 23.8 to 45.4 (at 150°C). Total colour differences of spruce wood exposed by temperature lay in the intervals from 3.8 to 16.8 (at 110°C) up to 24.6 to 38.7 (at 150°C). Total colour differences of fir and spruce woods exposed by UV radiation lye in intervals approx. from 12.5 to 13.1 (during 72 h) up to 16.4 to 20.9 (during 168 to 672 h). The most significant colour change due to exposure to ultraviolet radiation was recorded in the first 168 hours, subsequent changes were only minor. The coefficient of determination of trained neural network during the test was above 0.998 (this means that the trained neural network is able to 99.8% to predict colour changes from the exposure conditions). The most data predicted by trained neural networks differed from expected in interval from approx. -0.76 to 1.08 (negligible difference). These parameters of the neural network allow it to be used for highly accurate colour coordinate prediction and colour change of fir and spruce wood.

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