Color Change of Selected Wood Species Affected by Thermal Treatment and Sanding

Mária Hrčková,[a,]* Peter Koleda,[a] Pavol Koleda,[a] Štefan Barcík,[a] and Jaroslava Štefková [b]

The aim of the research was to evaluate the impact of various temperatures of thermal modification and sanding treatment on the color change of sessile oak, Norway spruce, and Red meranti. Thermal modification was carried out at various temperatures. Subsequently, one side was sanded. The measurements were recorded using a BFS 33M-GSS-F01-PU-02 color reader. A Konica Minolta CR-10 Plus colorimeter and Nikon D3200 camera were used in conjunction with the Matlab program. The assessments were conducted in the color space of CIE *L* a* b**. The measured values confirmed that the decrease in lightness from natural to thermally modified wood (220 °C) was the largest for non-machined spruce samples (ΔL = 42.47) and the smallest was for sanded spruce samples (ΔL = 31.64). The relative change in sample lightness was the largest for sanded oak samples (51%). The trends of the color values *a** and *b** were different for individual wood species. Overall, the average color change ΔE was the lowest for the non-machined meranti species (ΔE = 33.06), and the largest for the non-machined spruce (ΔE = 43.06). Comparing the individual methodologies, it was found that all methodologies provided relevant results and can be used in practice.

*Keywords: Color; Thermal modification; Temperature; Lightness; L*a*b* color values; Oak; Spruce; Meranti*

*Contact information: a: Department of Manufacturing and Automation Technology, Faculty of Environmental and Manufacturing Technology, Technical University in Zvolen, Studentska 26, 96053 Zvolen, Slovakia; b: Institute of Foreign Languages, Technical University in Zvolen, T. G. Masaryka 24, 96053 Zvolen, Slovakia; * Corresponding author: hrckova@tuzvo.sk*

INTRODUCTION

Wood is an important natural renewable material (Dos Santos *et al*. 2016), and the possibilities for its use are tremendous. It is as important a building material for the interior as it is for the exterior. Wood is used in the furniture industry, and it is an important raw material in the paper industry as well as the power industry. As a natural material, wood is a chemical compound of mostly organic substances. It is mainly composed of organic macromolecular substances: cellulose (35% to 50%), hemicelluloses (20% to 35%), and lignin (15% to 35%) (Geffert 2013). All together, these components make up 90% to 97% of the absolute weight of dry wood. Furthermore, wood also contains extractive substances: carbohydrates, starch, and oils; proteins, inorganic salts, waxes, tanstuffs, and resins; and turpentine, ethereal oils, and colorants, as well as others that influence the wood color (Geffert 2013). The content of extractives ranges up to 10% (Čunderlík 2009). Wood is a readily machinable and mechanically resistant material. However, it has some unfavorable properties, such as hygroscopicity, anisotropy, and poor resistance to biological degraders. Currently, the need is increasing to improve the properties of wood and especially its durability and resistance towards biological agents. Thermal modification seems to be a suitable solution for this requirement.

The color of wood is an important component of its appearance (Babiak *et al*. 2004), and therefore it figures crucially in the final decision of a customer (Sahin *et al*. 2011; Jankowska and Kozakiewicz 2014; Kubovský and Igaz 2014; Barcík *et al*. 2015). Color is one of wood's basic physical properties (Čunderlík 2009; Dzurenda 2018). The color is determined by the chemical components of wood. Besides genetic factors, the color of the wood is influenced by the environmental conditions (the humidity, solar radiation, pollution, and wind) where the tree and the wood grew (Čunderlík 2009; Valverde and Moya 2013). The color is also one of the parameters of the quality of the surface assessment.

At present, color and shade are measured by colorimetry, which is based on the standards and technical requirements stated and issued by the International Commission on Illumination (Commision Internationale de l`Éclairage). The color space CIE *L*a*b** is the closest to the human perception. Its construction is based on the theory of opposite colors. The color space CIE *L*a*b** is characterized by three parameters: *L**, *a**, and *b**. The vertical axis L* represents the lightness (100 = white, 0 = black). The chromatic axes are represented by the *a** and *b** components. The *a** axis represents the shift from green (-) to red color (+), and the b* axis represents the shift from blue (-) to yellow (+) (Babiak *et al*. 2004; Tuong and Li 2010; Dzurenda 2013). The CIE *L*a*b** is the most frequently used color space for measuring wood surface color (Brischke *et al*. 2007). The color measurement is executed by apparatuses called spectrophotometers or colorimeters (Babiak *et al*. 2004) or optic color readers.

Thermal modification of wood is the process by which wood is modified by high temperatures (Barcík *et al*. 2015). This technology is considered an ecological wood treatment because it does not use any chemical substances (Boonstra 2008; Tuong and Li 2010; Aydemir *et al*. 2012). It is crucial to carefully determine the conditions of modification, including maximum temperature, exposure time, wood dimensions, and suitable equipment. The changes to wood and its chemical composition occur based on set conditions (Kučerová *et al*. 2016). The properties of thermally modified wood have been investigated for a rather long time. Thermally modified wood is more resistant to microorganisms, and it has greater dimensional stability, durability, and insulating and hygroscopic properties (Johansson 2005; Reinprech and Vidholdová 2008; Mitani and Barboutis 2014). Based on the newly-established properties, the interest in its use in various areas, *e.g*., floorings, sauna furniture, garden furniture, exterior and interior siding, windows, doors, roofing systems, *etc*., is constantly growing (Vančo *et al*. 2016).

Thermal modification uses the thermal and hydrothermal effects of high temperatures (150 to 260 °C) and in various environments (vacuum, inert atmosphere, air, water, or oil) (Reinprecht and Vidholdová 2008; Kačíková and Kačík 2011). In several countries in Europe and in Canada, different methodologies of thermal modification have been patented, for example Thermo Wood in Finland, which uses air, PlatoWood in Germany, which uses oil, and Rectification in France, which uses inert gases (Tuong and Li 2010).

Changing the chemical composition of wood due to thermal modification also determines the color change of the wood. The change in color is a function of temperature and time (ITWA 2003; Hill 2006). The increase in temperature and treatment time leads to darker colorification (Brischke *et al*. 2007; Klement and Marko 2008; Esteves and Pereira 2009). Under the effect of high temperature, the wood takes the color of yellow-brown to brown-black and often resembles that of tropical wood species. The wood acquires darker shades due to the changes in the basic constituents of wood and extractive substances (Tuong and Li 2010). The degree of color change may indicate the quality of the thermal modification (Hill 2006; Kamperidou and Barmpoutis 2015). After mechanical machining (cutting, planning, milling, or sanding), the wood retains the original shade acquired by the thermal modification. The measurement of the wood surface color is a quick, precise, and reproducible process (Brischke *et al*. 2007; Hrčka 2008). The acquired information about a color of a thermally modified wood together with the knowledge of the temperature used can provide a wide range of possibilities for further use. They can serve as the foundations for monitoring the quality of thermally modified wood, as well as the input parameter to determine the temperature of modification, reflecting the demands for the wood appearance for further processing.

The aims of the present experiments are as follows: first, to determine the color change in the CIE $L^*a^*b^*$ color space of selected wood species, namely, of Sessile oak, spruce, and Red meranti, under the influence of thermal modification at 160, 180, 200, and 220 °C, second, to assess the influence of sanding on the color of the wood species, and third, to verify whether the use of other methods of wood color evaluating demonstrates significantly different results compared to the Conica Minolta CR-10 Plus. This sensor is normally used to detect the color of wood species as well.

EXPERIMENTAL

Materials

The choice of the three wood species corresponded to the requirements of the VEGA project 1/0315/2017 "The Research of the Relevant Properties of Thermally Modified Wood in the Contact Processes of Machining Addressing the Optimal Surface Achievement". The samples were prepared from both traditional European and exotic wood species (Sfarra *et al*. 2017). To make generalizations, the emphasis was placed upon the heterogeneity of the selection of species and colors – wood species native to Slovakia – deciduous, coniferous, and an exotic wood species. The color of the wood of these trees was also considered; they were divided into three groups according to color of wood – pale wood (spruce), brown wood (oak), and red wood (meranti) (Čunderlík 2009). The three wood species used for the experiment were sessile oak *(Quercus petraea)*, which has a distinct grain and interesting wood texture, Norway spruce *(Picea abies)*, which has a pale wood color and minimal colour differences, and Red meranti *(Shorea acuminata)*, which has an exotic grain and wood of various shades of color. The exotic wood species meranti resembles a wood species native to Slovakia of oak in its appearance as well as in its properties. The wood species of sessile oak and Norway spruce were harvested in Slovakia, in the locality of Vlčí jarok (440 meters above sea level) near Budča. The samples of the wood were made in the Research and Development Workshops of the Technical University in Zvolen. Radial boards 25-mm-thick were cut out of heartwood of the logs by a MEBOR HTZ 1000 (Mebor d.o.o., Železniki, Slovenia) saw and then dried to 8% moisture content. The 8% moisture selection was based on the environment properties (interior) in which the wood will be used. The test samples, with dimensions 20 mm × 100 mm × 700 mm, were made from these boards. Red meranti wood species in Slovakia was imported from Malaysia and Indonesia. The red meranti used in the research was purchased from the importer (Wood Store, Prague, Czech Republic) in the requested dimensions. The country of origin was not specified by the importer. The density of the studied wood species is in Table 1.

Table 1. Densities of the Studied Wood Species

Temperature (°C)	Density (kg.m^{-3})		
	Sessile oak	Norway spruce	Red meranti
N	776	442	639
160	720	431	617
180	687	409	580
200	618	372	559
220	609	363	549

The prepared samples were divided into five groups. The first group was left in their natural state. The other groups of samples were thermally treated using the ThermoWood® technology, each at a different temperature (160 °C, 180 °C, 200 °C, and 220 °C). The process of the thermal treatment was executed in the Arboretum of the Faculty of Forestry and Wood Sciences (Czech Agricultural University, Prague, Czech Republic) in Kostelec nad Černými lesy in a LAC S 400/03 type chamber (Katres s.r.o., Říčany, Czech Republic), (Fig. 1). The basic parameters are given in Table 2.

Fig. 1. Chamber S400/3

Table 2. Parameters of LAC S 400/03 Chamber

Maximum Temperature (°C)	300
Volume (l)	380
Outer Dimensions (mm)	1400 × 1850 × 1200
Inner Dimensions (mm)	800 × 800 × 600
Weight (kg)	350
Number of Fans	1
Performance (kW)	6
Maximum Bottom Load (kg)	70

The samples were stored at the temperature of 10 °C. The process of thermal modification was managed by the program. The samples remained in the chamber until they had cooled to 60 °C, and then they were removed. The process of the temperature change itself (heating, temperature exposure, and cooling) in time is illustrated in Fig. 2.

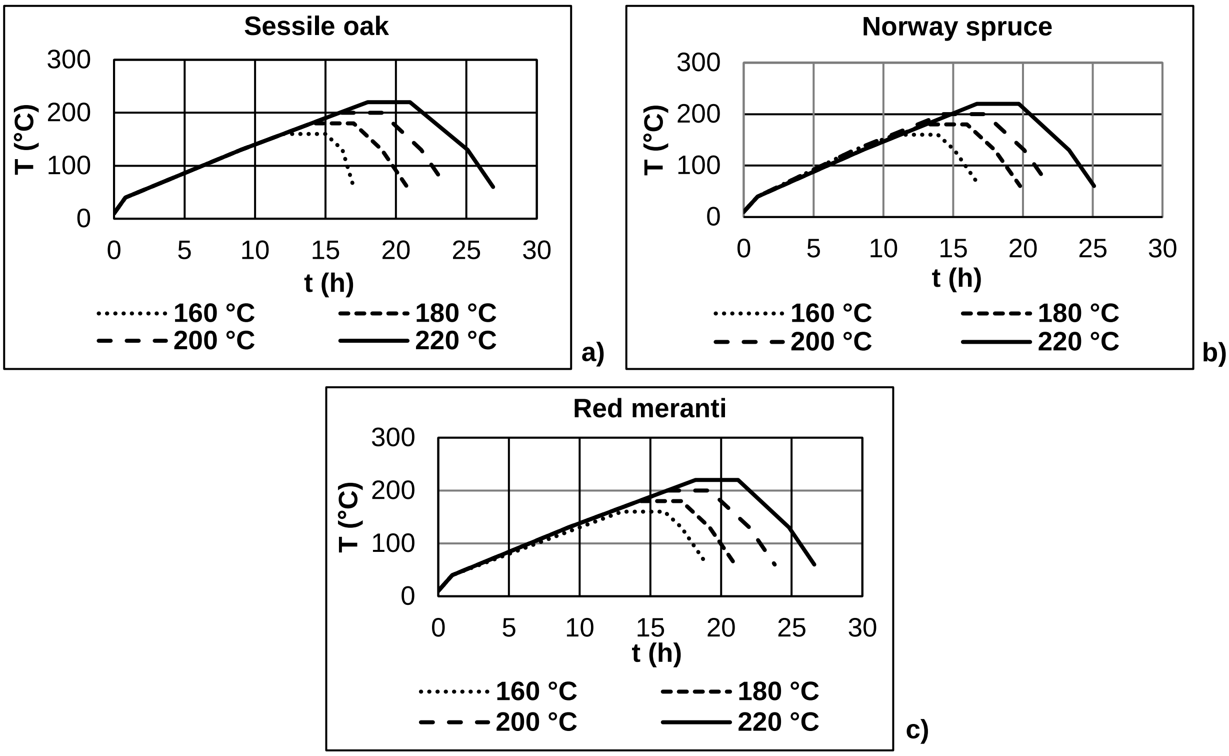

Fig. 2. The stages of thermal modification of wood species: a) sessile oak, b) Norway spruce, and c) red meranti

Fig. 3. Samples with marked areas for measuring the color

The final treatment of the samples was sanding of one side of the sample. The grinding was carried out with band grinder DZJC 200 (Slupska Fabryka Obrabiarek, Slupsk, Poland). A grinding belt of grain size 80 was used. The appearance of the samples is shown in Fig. 3.

The measurement of the color coordinates was performed in three different ways that are discussed below.

Methods

Color sensor BFS 33M-GSS-F01-PU-02

An optical-electrical color sensor BFS 33M-GSS-F01-PU-02 (Balluff Slovakia s.r.o., Bratislava, Slovakia) works in two modes. In the first mode, it enables the user to distinguish the color of the scanned objects based on the patterns recorded in advance. The maximum number of patterns is seven. The sample is identified in a binary form *via* three light-emitting diodes (LED) outputs. In the second mode, the sensing device can be used as a color sensor. The sensor enables the measurement of the color coordinates of the CIE $L^*a^*b^*$ model. The resulting values are formed by averaging 64 values obtained by the sensitive part of the sensor at every measurement. The sensitive part of the sensor was installed beneath a lampshade to eliminate the effects of daylight. The sensor has its own built-in illumination source with a diode at a temperature of 5600 K. The diode light and light reflected from the object are transferred by optic cables.

Color difference reader Konica Minolta CR-10 Plus

The color difference reader Konica Minolta CR-10 Plus (Konica Minolta, Tokyo, Japan) is a compact portable device powered by batteries that measures the color coordinates of the CIE $L^*a^*b^*$ model and assesses also the ΔE (the color difference between two samples). It is designed for manual use and, due to its ergonomic construction, can be used for a longer time period. A software application that enables the user to change the device’s settings, set the measurement tolerance limits, and assess the data directly in the device is a part of the package. The measurements were recorded *via* an optic scanning opening of 8 mm diameter and a standard source of light of D65 (temperature 6500 K). The light source in the device is a Xenon lamp, guaranteeing longer lifetime.

Camera Nikon D3200 and application in Matlab

The camera Nikon D3200 (Nikon, Tokyo, Japan) is a single-lens reflex that is equipped with a 4.2 mega pixel sensor complementary metal-oxide-semiconductor (CMOS) and an effective image processor EXPEED 3. The images were produced in full high definition quality; the overall number of pixels was 24.7 million. The reference standard with the precise color value of the sample in CIE XYZ (Y = 83.7) was aligned with the assessed sample to eliminate the mistakes caused by the change in color conditions during the production of the photographs. The photographs were processed using Matlab 2010b (MathWorks, Natick, MA, USA). According to the reference standard, the application first calculates the coefficients, which are used to treat the color of the whole image. Subsequently, the color coordinates of all points in the marked area were processed. The results express the color coordinates in the color model of RGB. These values can then be recalculated into the color space of CIE $L^*a^*b^*$ and CIE XYZ. The calculated values were exported into an MS Excel program (Microsoft, Redmond, WA, USA).

The measurements were recorded at the temperature of 22 °C. To measure the color we used five boards from each wood species (one untreated, four thermally modified at 160 °C, 180 °C, 200 °C, and 220 °C). The boards were non-machined on one side, sanded on the other side. The measurements were made on a radial area of section. To determine the color of every sample, five places were chosen based on the homogeneity of the whole sample. Their position was marked by a circle, and each one was given an ordinal number so that the order was consistent in measurements by different methods. Each measurement was made at the selected location by each method. The results of the measurements were the values of the individual coordinates in the color space of CIE $L^*a^*b^*$. The measurements of the individual coordinates of the color space were executed according to ISO 11664-2 (2007), ISO 11664-4 (2008), and ISO 11664-6 (2014) standards. The measured color values in the CIE $L^*a^*b^*$ space on 5 different places were averaged (Table 4). Table 5 presents the statistical deviations of the measured values. The processing of the values retrieved from the three methodologies was executed in the programs of Statistica 12 (StatSoft, Tulsa, OK, USA) and MS Excel. The statistical analysis was performed using basic statistics and analysis of variance. The similarity of measured values of color was compared by post-hoc Duncan's and Tukey's tests, which express the probability of similarity of data sets.

To assess the color change for the individual samples, the color space CIE $L^*a^*b^*$ was used. The Euclidean distance ΔE, which expresses the total color change (Matušková and Klement 2009), was used to compare the individual color shades. The value for ΔE was calculated according to Eq. 1:

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{1}$$

The classification of the overall color change was carried out based on assessment guidelines by Cividini *et al.* (2007) (Table 3).

Table 3. The Criteria to Assess the Color Change

$\Delta E < 0.2$	Invisible changes
$0.2 < \Delta E < 2$	Small changes
$2 < \Delta E < 3$	Color changes visible by high quality filter
$3 < \Delta E < 6$	Color changes visible by medium quality filter
$6 < \Delta E < 12$	Distinct color changes
$\Delta E > 12$	A different color

RESULTS AND DISCUSSION

The measured values confirmed the primary assumption that the lightness was affected significantly by the thermal treatment in a manner directly proportional to an increase in temperature (Figs. 5 through 7). All wood samples showed general darkening (Todaro *et al*. 2012).

The evaluation was carried out separately for each tree type and for each methodology (Fig. 4). Because the resulting change trends are identical, we used the entire database of the measured values at the final evaluation.

The decrease in lightness of the treated samples compared to the thermally non-treated wood species was recorded for all samples, and at the highest temperature ranged approximately 40% to 50% below its original value. The maximum decrease in the lightness appeared in oak, where the lightness for the sanded samples decreased 51%. Lightness decreased least in the sanded samples of spruce, namely 36.6%. In absolute values, the biggest change in lightness occurred in the non-machined samples of spruce (ΔL = 42.5) and the least change in the sanded samples of spruce (ΔL = 31.6). Based on Duncan's multiple range test, it can be stated that the statistically insignificant changes occurred on sanded oak samples treated at 160 °C and 180 °C. The effect of sanding on oak appeared minimal on the samples thermally treated at 160 °C and 200 °C.

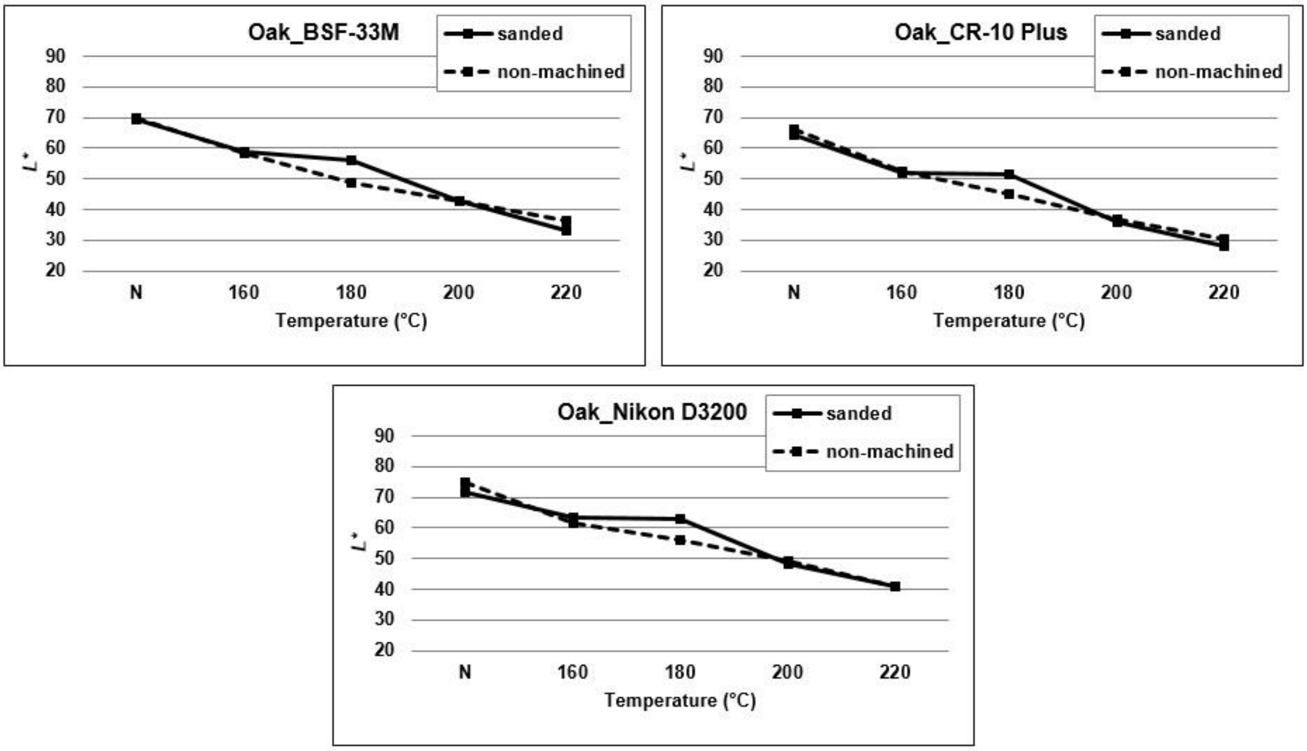

Fig. 4. Lightness *L** (sessile oak) – all methodologies

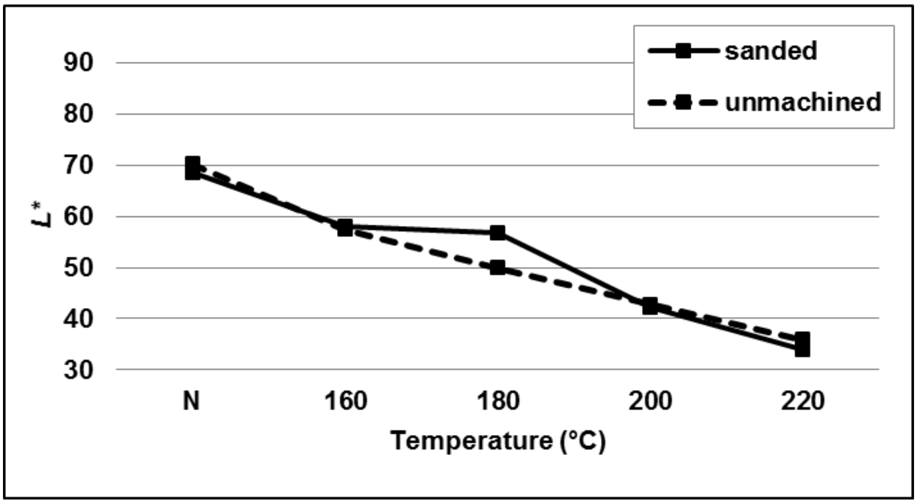

Fig. 5. Lightness *L** – Sessile oak

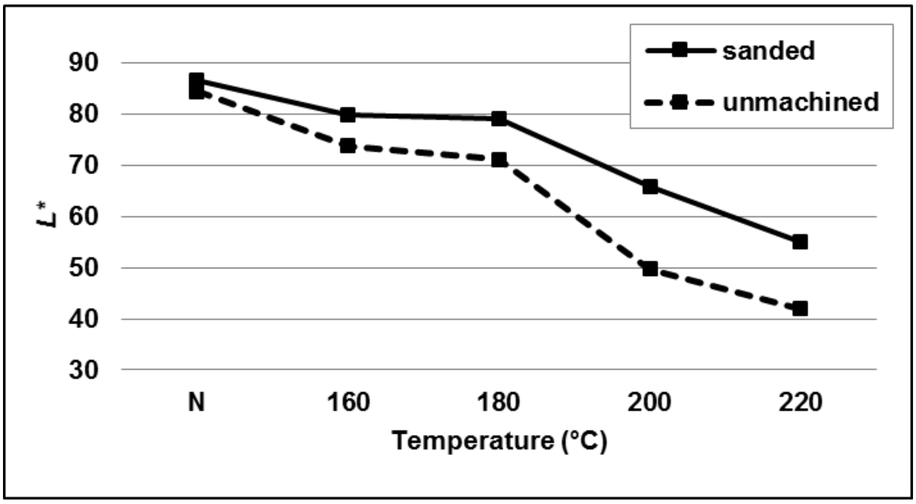

Fig. 6. Lightness *L** – Norway spruce

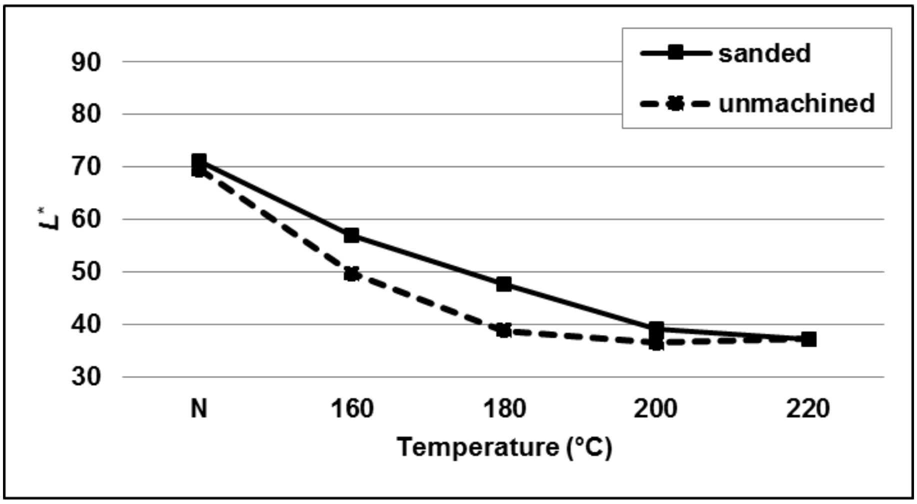

Fig. 7. Lightness *L** – Red Meranti

These results were also confirmed for oak by Čermak and Dejmal (2013), who found lightness for non-machined samples in the range of 69 to 75 and for thermally treated samples at 230 °C ranging from 29 to 35. The authors' thermal treatment was performed only at 220 °C; therefore, the value of lightness in this study reached the value of 34.

The spruce showed statistically insignificant changes of lightness for the sanded samples thermally treated at 160 °C and 180 °C. The lightness of this wood species, whether referring to sanding or thermal treatment, changed distinctly.

Lightness change for samples of meranti under the influence of thermal treatment up to 200 ° C was noticeable, in contrast to samples of meranti exposed the UV radiation treatment, where the lightness changes were small (Laskowska *et al*. 2016). Non-machined meranti thermally treated at 200 °C and 220 °C showed the smallest change in lightness. The change in lightness caused by sanding did not appear in the samples of this wood species modified at 220 °C.

Sanding had a various effect on the lightness of samples. In the case of spruce, the difference in lightness between the sanded and non-machined samples was distinct and increased with an increase in the temperature of modification.

Table 4. Measured Values (S – Sanded)

S	Temperature (°C)	BSF-33M			CR-10 Plus			Nikon D3200		
		Color coordinates			Color coordinates			Color coordinates		
		*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**
Sessile oak										
YES	N	69.53	4.92	16.13	64.16	7.84	19.68	71.82	4.98	17.52
	160	58.72	6.54	16.19	51.92	8.72	17.80	63.37	7.53	19.83
	180	56.22	6.59	15.73	51.48	8.66	17.58	62.96	7.10	18.37
	200	42.74	8.33	13.83	35.92	8.42	12.56	48.38	8.69	14.07
	220	32.94	5.21	6.47	28.06	3.94	4.82	41.00	4.63	6.64
NO	N	70.01	4.71	16.18	65.90	7.34	19.36	74.81	3.92	16.59
	160	58.17	7.50	15.03	52.54	9.50	16.86	61.54	10.15	22.02
	180	48.88	9.20	16.34	44.86	11.10	18.06	56.11	9.95	18.12
	200	42.54	9.02	13.49	36.66	9.24	12.86	49.10	10.04	13.51
	220	36.34	3.98	4.32	30.28	2.98	3.00	41.10	4.57	6.19
Norway spruce										
YES	N	86.90	2.77	13.95	86.16	4.82	19.28	86.58	1.45	13.85
	160	79.84	5.10	19.00	77.46	8.76	25.16	82.24	2.55	18.22
	180	79.02	5.19	19.25	76.60	8.66	25.00	81.79	2.28	18.56
	200	66.23	7.18	22.03	61.84	11.32	26.86	69.55	6.58	24.36
	220	54.70	8.73	22.14	49.70	12.18	24.84	60.33	8.63	26.16
NO	N	83.96	2.98	15.03	84.62	5.22	20.76	84.75	1.16	15.75
	160	73.57	7.20	20.87	71.80	10.76	26.42	76.07	7.51	21.23
	180	72.34	7.61	20.86	69.30	11.44	26.60	71.66	6.79	23.92
	200	49.31	11.17	20.39	45.38	13.64	22.38	54.58	12.19	23.39
	220	43.98	7.10	13.65	35.86	8.88	12.62	46.08	8.55	13.82
Red meranti										
YES	N	72.31	8.05	14.13	67.48	10.70	17.26	73.47	7.04	16.13
	160	56.60	8.84	13.11	52.10	10.72	14.54	61.75	9.53	15.99
	180	47.54	7.74	12.95	41.12	8.72	12.92	53.92	8.92	13.80
	200	39.06	9.38	12.78	32.12	7.94	10.36	46.12	8.85	11.81
	220	35.94	9.31	12.44	29.74	8.16	10.70	45.44	7.76	9.92
NO	N	70.43	8.10	13.51	66.76	10.62	16.86	71.07	8.92	16.26
	160	49.30	9.95	15.72	45.48	12.10	17.52	54.32	10.44	16.59
	180	36.97	10.42	12.42	33.02	9.76	11.76	46.23	9.37	11.58
	200	35.43	8.62	10.07	29.32	7.32	8.08	44.51	6.30	7.83
	220	36.49	8.31	11.21	30.32	6.98	9.08	44.74	5.66	7.96

Table 5. Standard deviation values (S – Sanded)

S	Temperature (°C)	BSF-33M			CR-10 Plus			Nikon D3200		
		Color coordinates			Color coordinates			Color coordinates		
		*L**	*a**	*b**	*L**	*a**	*b**	*L**	*a**	*b**
Sessile oak										
YES	N	0.62	0.10	0.48	0.90	0.28	0.46	2.45	0.99	1.34
	160	1.26	0.65	0.39	0.99	0.76	0.37	1.85	0.61	0.52
	180	2.20	0.57	0.35	2.82	0.43	0.63	1.26	0.96	0.50
	200	2.22	0.67	1.03	1.87	0.42	1.15	1.94	0.23	1.23
	220	0.36	0.40	0.69	0.59	0.51	0.93	2.62	0.41	0.26
NO	N	0.69	0.09	0.14	0.91	0.11	0.34	0.84	0.42	0.70
	160	1.00	0.11	0.32	1.71	0.22	0.65	2.42	1.25	1.39
	180	1.09	0.15	0.55	1.09	0.20	0.64	2.16	0.70	1.21
	200	2.33	0.81	0.92	2.40	0.80	1.60	1.34	1.30	1.64
	220	0.81	0.40	0.80	0.75	0.50	0.70	2.97	0.79	1.34
Norway spruce										
YES	N	0.27	0.12	0.06	0.90	0.16	0.13	2.41	0.27	0.44
	160	0.93	0.62	0.81	0.48	0.31	0.54	2.04	0.35	0.84
	180	0.04	0.12	0.15	0.35	0.24	0.21	1.40	0.44	0.35
	200	3.34	0.54	0.23	3.62	0.44	0.72	2.35	1.14	0.94
	220	3.41	0.27	1.23	2.87	0.28	1.66	2.89	0.50	1.77
NO	N	0.54	0.08	0.25	1.19	0.15	0.77	2.25	0.05	0.75
	160	0.90	0.37	0.30	1.45	0.69	0.70	2.59	1.46	0.71
	180	0.93	0.23	0.32	1.08	0.46	0.48	2.41	0.90	0.32
	200	1.33	0.60	1.01	1.61	0.86	1.13	2.60	0.63	1.33
	220	0.52	0.66	1.62	0.76	0.76	1.19	4.15	0.59	1.26
Red meranti										
YES	N	0.83	0.24	0.21	0.83	0.70	0.36	1.75	0.65	0.63
	160	1.23	0.11	0.18	1.04	0.23	0.18	2.93	0.57	0.40
	180	1.47	0.18	0.30	3.35	0.76	1.84	2.24	0.23	0.69
	200	1.51	0.30	0.89	1.66	0.86	1.70	1.56	0.26	1.23
	220	0.81	0.26	0.49	0.87	0.48	0.69	1.95	0.37	0.63
NO	N	1.17	0.65	0.49	0.63	0.94	0.62	2.50	0.94	0.71
	160	1.28	0.21	0.33	1.96	0.20	0.82	1.70	0.20	0.39
	180	1.77	0.45	0.77	1.03	0.32	0.90	2.42	1.67	2.30
	200	0.84	0.44	0.81	1.74	1.10	1.36	1.28	0.58	0.91
	220	0.67	0.30	0.70	0.16	0.37	0.67	2.29	0.50	1.28

The changes in lightness for oak and spruce were smaller and, in some cases, *e.g.*, oak (200 °C) and meranti (220 °C), achieved minimal values. Barcík *et al*. (2015) measured the color of thermally modified oak using the Konica Minolta CM-600d. The comparison of the results was as follows (in parenthesis are the values measured on non-machined samples): natural: *L** = 64.5 (70.2), *a** = 6.8 (5.3), *b** = 20.2 (17.4); 160 °C: *L** = 57.9 (57.4), *a** = 6.8 (9.0), *b** = 18.8 (18.0); and 180 °C: *L** = 46.2 (50.0), *a** = 6.4 (10.1), and *b** = 14.5 (17.5). The authors also measured the color of the thermally modified wood treated at 210 °C and 240 °C. Such material was not available in the authors' research. The deviations might have been caused by the fact that different methodologies were used for measurement. Babiak *et al*. (2004) measured the color of various wood species, including spruce *(Picea abies* L.*)*, using a spectrum-photometer MINOLTA, type CM 2600d. The comparison of the values of the CIE *L*a*b** model measured by their team and the authors' values (given in parenthesis) was as follows: *L** = 82.5 (84.4), *a** = 4.6 (3.1), and *b** = 21.4 (17.2).

The differences in the measured color coordinates were small, and it can be stated that, considering the character of wood and the dependencies of its properties on various factors, these differences were irrelevant. Sahin *et al*. (2011) measured the color of oak at various temperatures and obtained similar results. They state that the oak wood gets darker with increasing temperature because its lightness decreases. Their measurements confirmed that the chrome coordinates change under the influence of temperature. Based on the measured values, they state that the color change could be predicted based on the affecting temperature during the thermal modification. Johansson (2005) investigated spruce, and his results confirm the decrease in lightness with increasing temperature.

Regarding the lightness, the behavior of each wood species was different and influenced by the original colour of the sample. This is also confirmed by Tolvaj's (2006) experiments. Domestic wood species of oak and spruce underwent smaller changes in lightness at lower temperatures and larger changes at higher temperatures. When discussing the exotic wood species, meranti, the contrary can be said: at lower temperatures the lightness changed more distinctly, while at higher temperatures it changed less.

The sanding had an effect on all samples of spruce, for meranti, on the samples modified at lower temperatures, while for the oak, only on the samples modified at 180 °C. For other samples of oak, the differences were minimal. The temperature effect and heat transfer in the treated samples during thermal degradation could be further specified using holographic interferometry (Černecký *et al*. 2015)

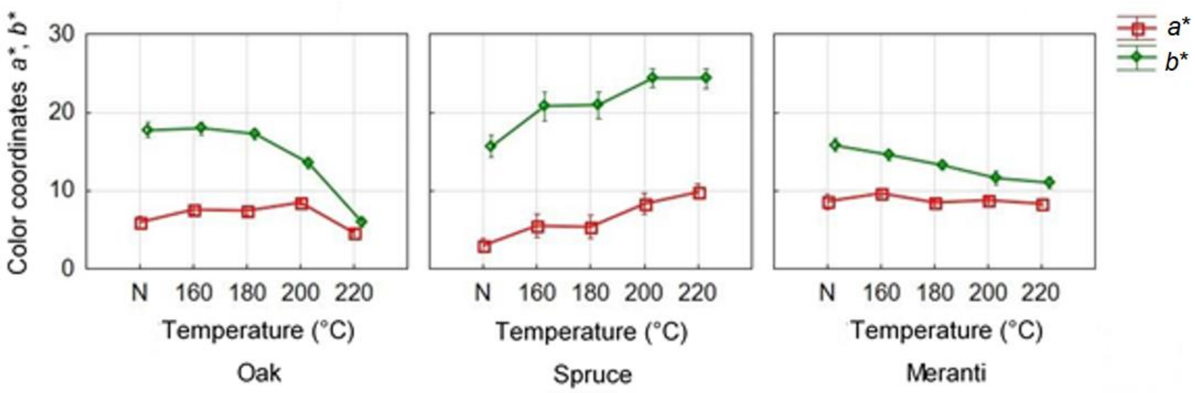

Fig. 8. Color coordinates *a** and *b** for non-machined samples of all wood species

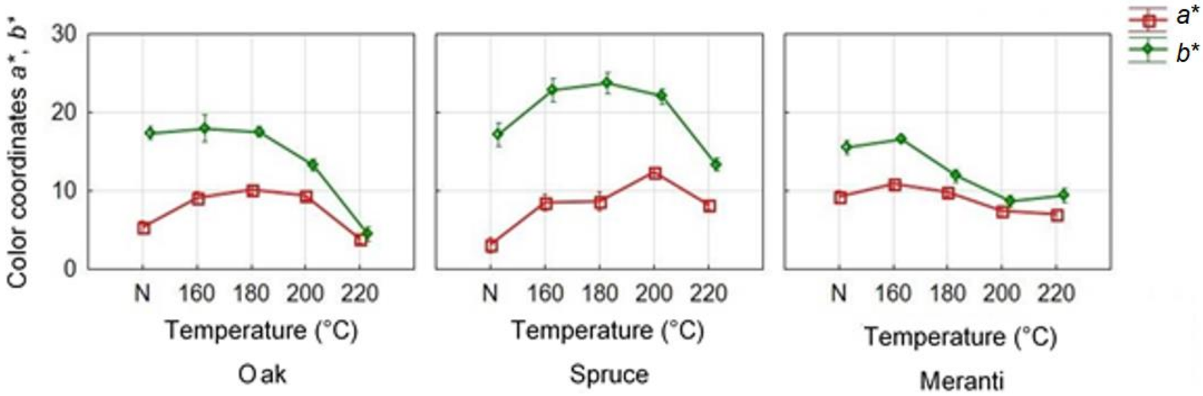

Fig. 9. Color coordinates *a** and *b** for sanded samples of all wood species

The development of the color value *a** was different for the different wood species. For oak, the samples treated at 160 °C showed an increase compared to the untreated samples. The results for oak are presented by Čermák and Dejmal (2013). The changes at the temperatures of 180 and 200 °C were minimal, and on the samples treated at 220 °C there was a decrease. For spruce, the development was different. The color value *a** was constantly growing, except in the case of the sanded samples. This development probably was due to the fact that spruce is a light wood species and, therefore, there occurred a greater color difference during its thermal modification. Meranti, characterized by red coloring even before thermal modification, did not show a greater color difference for the color value *a**, except in the case of thermal modification at the lowest temperature of 160 °C.

For the comparison of the sanded *versus* non-machined samples of the same wood species, it could be stated that the color value *a** decreased for the sanded samples due to the removal of the surface layer affected by the thermal treatment. The sequence of changes to the chrome coordinate *a** were equivalent in the sanded and non-machined samples. A visible exception was provided by spruce, in particular, the sample treated at 220 °C, where the growth of the chrome coordinate *a** was sustained, in contrast to the non-machined sample subjected to identical treatment, where it was not.

The developments in the color value *b** mirrored the changes in the color value *a** with a few small exceptions. The development and the size of the color value *b** were identical (the differences were statistically insignificant) for non-machined and also for sanded samples. The decrease of the *b** component for oak accorded with the results of Čermak and Dejmal (2013). The great decrease for samples modified at high temperatures (200 °C and 220 °C) was rather interesting. The behavior of the color value *b** for spruce was undoubtedly different for high temperatures. For the non-machined sample, at 200 °C the color value *b** started to decrease, and at 220 °C the decrease was so great that the resulting value was lower than for the sample that was not at all modified. For the sanded samples, the *b** component showed a different development at high temperatures. It grew at 200 °C, and at 220 °C there was no statistically significant change. Regarding meranti, it can be said that there was a decreasing trend for the color value *b**. This trend was clear for the sanded samples, while there was a slight growth at 160 °C and 220 °C for the non- machined samples. The different behavior of the color values of wood color after thermal modification could be explained by changes in the chemical composition of the wood samples caused by temperature, which varied depending upon the ratio of individual chemical components constituting the wood species (Cirule and Kuka 2015).

Table 6. Assessment of the Color Change – Sessile Oak

S	Temperature (°C)	Color Change ΔE	BFS-33M Assessment Description	Color Change ΔE	CR-10 Plus Assessment Description	Color Change ΔE	Nikon D3200 Assessment Description
Y	160	10.9	Distinct color changes	12.4	Different color	9.1	Distinct color changes
	180	13.4	Different color	12.9	Different color	9.1	Distinct color changes
	200	27.1	Different color	29.1	Different color	24.0	Different color
	220	37.8	Different color	39.2	Different color	32.7	Different color
N	160	12.2	Different color	13.8	Different color	15.6	Different color
	180	21.6	Different color	21.4	Different color	19.7	Different color
	200	27.9	Different color	30.0	Different color	26.6	Different color
	220	35.7	Different color	39.4	Different color	35.3	Different color

Table 7. Assessment of the Color Change – Norway Spruce

S	Temperature (°C)	Color Change ΔE	BFS-33M Assessment Description	Color Change ΔE	CR-10 Plus Assessment Description	Color Change ΔE	Nikon D3200 Assessment Description
Y	160	9.0	Distinct color changes	11.2	Distinct color changes	6.3	Distinct color changes
	180	9.8	Distinct color changes	11.8	Distinct color changes	6.8	Distinct color changes
	200	22.6	Different color	26.3	Different color	20.7	Different color
	220	33.8	Different color	37.6	Different color	29.9	Different color
N	160	12.6	Different color	15.1	Different color	12.1	Different color
	180	13.8	Different color	17.5	Different color	16.4	Different color
	200	36.0	Different color	40.2	Different color	33.0	Different color
	220	40.2	Different color	49.6	Different color	39.4	Different color

Table 8. Assessment of the Color Change – Red Meranti

S	Temperature (°C)	Color Change ΔE	BFS-33M Assessment Description	Color Change ΔE	CR-10 Plus Assessment Description	Color Change ΔE	Nikon D3200 Assessment Description
Y	160	15.8	Different color	15.6	Different color	12.0	Different color
	180	24.8	Different color	26.8	Different color	19.8	Different color
	200	33.3	Different color	36.1	Different color	27.8	Different color
	220	36.4	Different color	38.4	Different color	28.7	Different color
N	160	21.3	Different color	21.3	Different color	16.8	Different color
	180	33.6	Different color	34.1	Different color	25.3	Different color
	200	35.2	Different color	38.6	Different color	28.0	Different color
	220	34.0	Different color	37.4	Different color	27.8	Different color

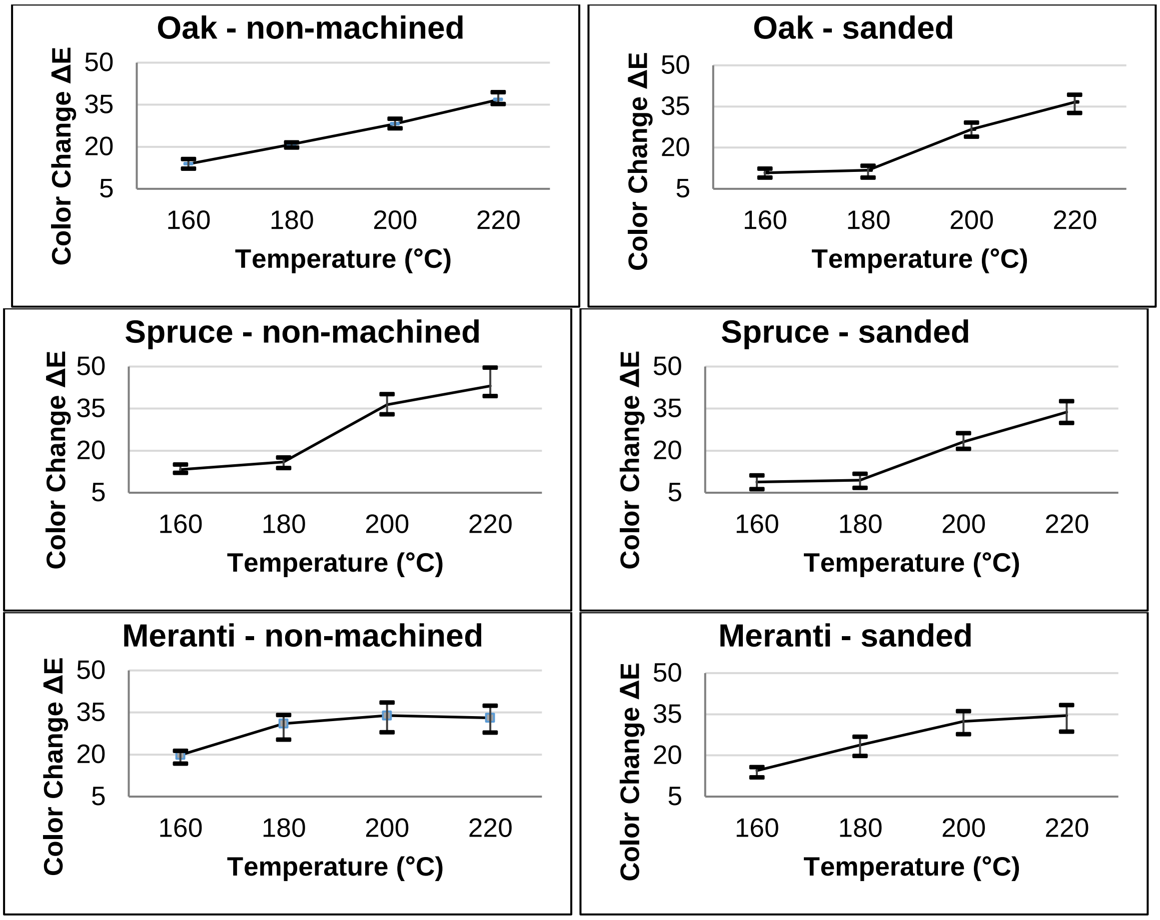

Fig. 10. Overall color change Δ*E* for all wood species

The overall color change, Δ*E*, was assessed for all thermally modified samples related to the thermally non-modified samples. The influence of all components of the color space CIE *L*a*b** was considered during the calculation. The biggest color change appeared on the spruce samples (Δ*E* = 43.1), while the smallest appeared on the meranti samples (Δ*E* = 33.1). The reason behind this lies in the original color of the wood species before thermal modification. The spruce belongs to light wood, while meranti belongs to red wood. For spruce, the overall color change at the lower temperatures of 160 °C and 180 °C was small, while at 200 °C and 220 °C the color change was rather distinct. For meranti, the color change appeared also at 160 °C and 180 °C, and at 200 °C and 220 °C the temperature stabilized, and the changes were minimal. For oak, the overall color change increased with increasing temperature. The exceptions were the sanded samples modified at 160 °C and 180 °C, where the changes were minimal. Overall color was also assessed by Barcík *et al*. (2015). The obtained results were divergent. The overall color change was higher at all temperatures for the authors' measurements.

Three methodologies to collect the data on color and its change were used in the current experiments. The devices that were used included the color sensor BFS 33M-GSS-F01-PU-02, colorimeter Konica Minolta CR-10 Plus, and the camera Nikon D3200 interlinked with the application Matlab. Their comparison is given in Fig. 11, which includes the measured values of the oak wood species. The colorimeter CR-10 Plus measured the lowest values of lightness. The highest measured values came from the application assessing the Nikon D3200 data, which applied to all measured samples.

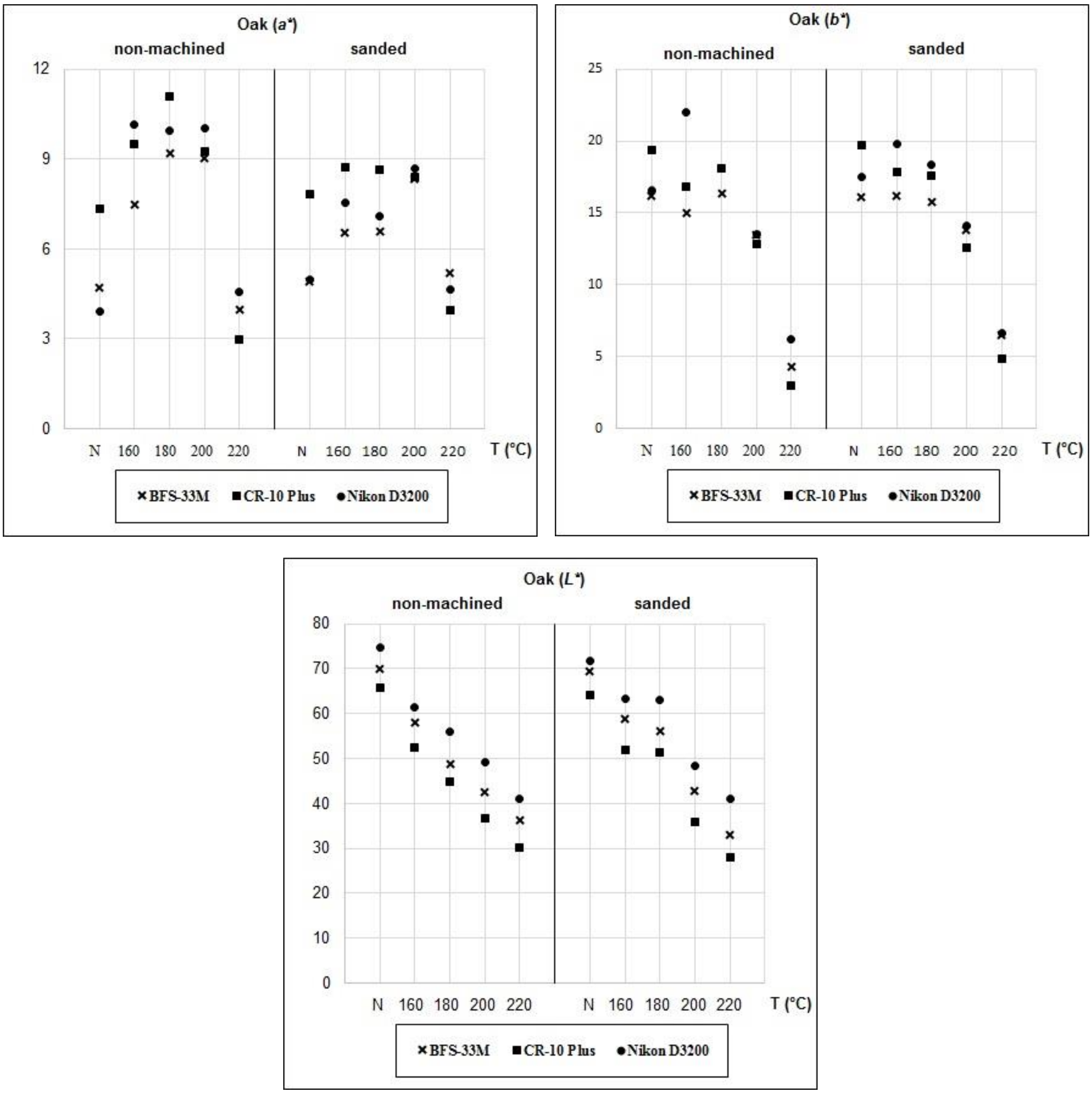

Fig. 11. Comparison of the measurement methodologies

The expected deviations appeared due to the fact that various methodologies use different area sizes to determine color components. Because wood colour is not homogeneous, various area sizes caused variations in the measurements in each specific methodology. The differences between values measured for the same sample using different procedures are theoretically possible to eliminate through calibration of the apparatuses at the first measurement, which eliminates the obvious additive error of the measurement method. However, nonhomogeneous color shades of wood might nevertheless influence evaluation and the difference in the assessed area would not appear. When the color values *a** and *b** were measured, the measured values were varied, yet their scattering was small. This could result in significantly lower values than in lightness; therefore, even a small change in the position of the apparatus during measurement would cause the results to deviate from the trend that appeared in the lightness. The smallest difference between the values of the components *a** and *b** was found for the non-machined and sanded samples modified at 200 °C. Based on the distribution of the measured values, it can be stated that the methodologies used in this experiment were correct and could be used in practice. None of the methodologies used caused a significant error in measurement. No method of measuring generated values that did not correspond with the values measured by other methods.

Tukey's range test of the means of measured data sets by various methods is given in Table 9. These means were different, even though the significance level was set to 5%. Considering the non-homogeneity of the wood shades, all methods were found to be correct.

Similarity tests (Table 9 and 10) largely demonstrated the differences in measured data sets in terms of statistical significance. Measurement of color components of wood color and subsequent evaluation of color changes is dependent on many factors. Their unambiguous determination is controversial with regard to the type and structure of the wood surface, the area and the growth period, and the chemical and mechanical changes occurring in its processing. There is no clear standard with which the measured values could be compared. Due to the different measurement methods and deviations, it can be stated that any method of color evaluation can be used in future experiments as well.

Table 9. Tukey's Range Test of the Means of the Data Sets

Apparatus	*L* Mean	Apparatus	*a* Mean	Apparatus	*b* Mean
CR-10 Plus	51.5987	Nikon D3200	7.0678	BFS-33M	14.9741
BFS-33M	56.2005	BFS-33M	7.3245	Nikon D3200	15.9993
Nikon D3200	60.8476	CR-10 Plus	8.8813	CR-10 Plus	16.7193

Table 10. Duncan's Test of the Similarity of the Data Sets

	Device	Wood	1	2	3	4	5	6	7	8	9
1	BFS-33M	Oak		0,000004	0,000009	0,000011	0,000003	0,000003	0,000011	0,000004	0,000009
2		Spruce	0,000004		0,000004	0,000004	0,000009	0,000005	0,000011	0,000009	0,000003
3		Meranti	0,000009	0,000004		0,000009	0,000004	0,000011	0,000003	0,000004	0,000011
4	CR-10 Plus	Oak	0,000011	0,000004	0,000009		0,000004	0,000009	0,000004	0,000005	0,000003
5		Spruce	0,000003	0,000009	0,000004	0,000004		0,000004	0,000009	0,000011	0,000011
6		Meranti	0,000003	0,000005	0,000011	0,000009	0,000004		0,000004	0,000001	0,000004
7	Nikon D3200	Oak	0,000011	0,000011	0,000003	0,000004	0,000009	0,000004		0,000003	0,000009
8		Spruce	0,000004	0,000009	0,000004	0,000005	0,000011	0,000001	0,000003		0,000004
9		Meranti	0,000009	0,000003	0,000011	0,000003	0,000011	0,000004	0,000009	0,000004	

CONCLUSIONS

1. The lightness value L^* decreased after thermal modification for all samples. The greatest decrease was shown by the sessile oak wood species and was 51% for the samples sanded. The lowest decrease in L^* of 36.56% was recorded for the sanded samples of Norway spruce. The sanded samples of red meranti showed a decrease in L^* of 48%. For the wood species that were not machined after thermal modification, the decreases were measured as follows: oak, 49%; spruce, 50%; and meranti, 47%.
2. The behavior of the color value a^* was different for each wood species. For oak and spruce, the a^* value grew at lower temperatures, but there was a decrease at 220 °C. One exception was the sanded samples of spruce, where a^* grew at 220%.

For the meranti samples, the value of this parameter was stable, except at 160 °C when there was a slight decrease, leading to the lowest value.

3. For the most part, the development of the *b** component mirrored the development of the color value *a**. However, a significant difference was present for oak and spruce on the samples treated at 180 °C and 200 °C, when color value *a** grew or stagnated, the color value *b** decreased.
4. The overall color change Δ*E* was the smallest for meranti and the largest for spruce. The color changes for the sanded oak samples treated at 160 °C and 180 °C were minimal, but subsequently, there was a gradual increase. Such growth was continuous for the unmachined samples at all temperatures. For spruce, the smallest changes appeared at 160 °C and 180 °C. For meranti, the smallest color changes appeared at 200 °C and 220 °C.
5. The comparison of the results by the color sensor BFS 33M-GSS-F01-PU-02, colorimeter Konica Minolta CR-10 Plus, and the camera Nikon D3200 in conjunction with Matlab brought no significant differences except those that were caused by the nonhomogeneous color structure of the wood. All methodologies performed the measurements correctly: all deviations between the measured values by the individual methodologies were minimal, and their impact on the Δ*E* value was irrelevant. The differences could be eliminated by the calibration of individual apparatuses at the beginning of the measurements.

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