Color and Chemical Changes in Teak (*Tectona grandis* L. f.) and Meranti (*Shorea* spp.) Wood after Thermal Treatment

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This paper studied the effect of thermal treatment (160 °C, 180 °C, and 210 °C), based on ThermoWood® principle, on the color and chemical properties of teak (*Tectona grandis* L. f.) and meranti (*Shorea* spp.) wood. The color of the wood was determined using the CIE *L*a*b** system before and after the thermal treatment and was evaluated according to the total color change. The chemical changes were evaluated by wet chemical methods. The lightness of the wood was most affected during treatment. Meranti wood became darker (46.1%) compared with the teak wood (41.8%). The red-green and yellow-blue coordinates were higher in the teak wood, and their values decreased as the thermal treatment temperature increased in both wood species compared with untreated wood. The color change was higher in the meranti wood, and it increased steadily with increasing temperature. The extractives, cellulose, and lignin percentage contents increased in both wood species; however, the highest treatment temperature of 210 °C decreased the lignin in the meranti wood. The least stable component in both wood species was the hemicellulose. The hemicellulose content in the teak wood decreased by 67.7%, while it decreased by up to 80.5% in the meranti wood.

*Keywords: Thermal treatment; Color; Chemical changes; CIE L*a*b*; Temperature; Teak; Meranti*

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INTRODUCTION

The wood color is an essential aspect that affects the overall appearance of wood products. Some products, such as art, furniture, and musical instruments, are highly dependent on their appearance, so their color is an important factor. However, the color of wood changes during processing depending on the treatment, machining processes, and end use. One of the most important wood treatment processes is thermal treatment, which fundamentally affects the physical and mechanical properties of wood, including its color.

Thermal treatment is a process in which wood is subjected to higher temperatures in the range of 160 °C to 280 °C (Militz 2002) or the smaller range of 180 °C to 260 °C (Candelier *et al*. 2016), for a certain time in the presence of oxygen, air, and nitrogen, or in a vacuum. Currently, five common technologies are used for industrial thermal treatment: ThermoWood® (Finland), PLATO® (Netherlands), OHT (Germany), Rétification (France), and Bois Perdue (France) (Shi *et al*. 2007; Esteves and Pereira 2009). In addition to these, WTT (Denmark), Huber Holz (Austria), Firmolin (The Netherlands), and Termovuoto (Italy) are newer technologies that have recently emerged; they are mainly used in research and are not used industrially as much as the previously listed methods

(Esteves and Pereira 2009; Ferrari *et al*. 2013). All of these technologies primarily differ in the thermal treatment conditions, such as the temperature, pressure, duration, *etc*. (Surini *et al*. 2012). The most widely used thermal treatment method in Europe is ThermoWood®, which takes place at temperatures of 180 °C to 215 °C in the presence of air at normal atmospheric pressure and using water vapor for the moistening. This method is used mainly for coniferous (spruce, pine, and larch) and deciduous (birch, aspen, and ash) wood species. Experiments with exotic wood species have also been performed to a lesser extent (Navi and Sandberg 2012). The main objective of thermal wood treatment is to increase the dimensional stability, reduce the hygroscopicity, and increase the biological resistance (Jämsä *et al*. 1999; Jämsä *et al*. 2000; Santos 2000; Kamdem *et al*. 2002). An undesirable factor is a decrease in the mechanical properties, which is why thermally treated wood cannot be allowed for use in structural purposes (Hill 2006). A distinctive and characteristic effect of thermal treatment is a color change, which depends on the wood type and treatment conditions (especially temperature and duration); a general rule applies where increases in the temperature and duration lead to pronounced darkening of the wood (Srinivas and Pandey 2012).

The color of an object is generated when certain parts of its molecules, called chromophores, absorb a certain wavelength of incident light in the visible spectrum, while the remaining part is reflected and perceived by the human eye (Cirule and Kuka 2015). Based on this, it is clear that the wood color depends on the chemical composition of its components (cellulose, hemicelluloses, and lignin) and their interaction with light. The color is determined more by the distinctiveness of the individual wood components than their amount, and the best example of this is cellulose. Cellulose is white in color and its content in wood is the highest, but its color is often overlaid by more distinctive extractives and lignin, whose content in wood is lower (Požgaj *et al*. 1997). The CIE $L^*a^*b^*$ system is usually used to determine the color or color change; it determines the total color change (ΔE^*) using the change in the three color components, which are the lightness (L^*, 0 (black) to 100 (white)), green-red coordinate (a^*, -100 (green shades) to +100 (red shades)), and yellow-blue coordinate (b^*, -100 (yellow shades) to +100 (blue shades)) (Moya and Marín 2011). In some cases, the color change is used as an indicator for assessing the quality of thermally treated wood (Brischke *et al*. 2007). For common temperate wood species, the color changes after thermal treatment, especially in coniferous wood species, have been described sufficiently in previous works. Tropical wood species have a different structure, and thermal treatment may not have the same effect on their properties as on temperate wood species. Additionally, tropical wood species include a large number of wood species whose thermal treatment has not been sufficiently studied yet. This concerns not only the physical and mechanical properties, but also color changes.

In general, tropical wood species are naturally more durable because they have a different structure and a higher proportion of extractives. For this reason, thermal treatment is not necessary for commonly used tropical wood species. However, the durability of tropical wood species is strictly dependent on their density, because not all of them have high-density. Meranti (*Shorea* spp.), for example, is a low-density wood that is very difficult to impregnate with protective substances, it has low dimensional stability and its resistance to fungi and insects is very low (Rasdianah *et al.* 2018). Meranti has a pale color that places it behind other dark tropical woods in terms of popularity, because aesthetics prevails in the selection of wood (Esteves *et al.* 2008).

Teak (*Tectona grandis* L. f.) is one of the most commonly used tropical wood species with a wide range of uses because of its high dimensional stability, high durability,

and good aesthetic properties for external use (Garcia *et al*. 2014). The brown color and high durability of teak heartwood is caused by two basic chemical substances: the caoutchouc, responsible for good water repellency, and tectoquinone, a natural protective substance. On the contrary, teak sapwood is paler and significantly less durable than the heartwood; therefore it is most often treated with protective substances. Due to climate change and high demand for teakwood, the 80-year harvesting cycle has been significantly reduced to 15-25 years. For this reason, teak wood from traditional plantations (*e.g.* in Brazil) has a pale color and a higher amount of sapwood (Tsukamoto Filho *et al.* 2003). Products made from teak sapwood are less resistant to UV radiation when exposed to weathering conditions. There is a pronounced color difference between teak heartwood and sapwood, which increases by the wood aging. Thermal treatment is one of the best ways to increase the durability of the sapwood and unify the color of the teak wood, as confirmed by the research of various authors, such as George *et al.* (2005), Lopes (2012), and Garcia et al. (2014). Therefore, thermal treatment could be an ecological way to obtain the color of wood without coatings and their disadvantages (emissions of volatile organic compounds, surface cracking).

Another property that is positively affected by thermal treatment is surface roughness. In general, the surface roughness of wood (after cutting or milling) is reduced by thermal treatment in both temperate wood species and tropical woods. The surface roughness of thermally treated wood affects its use in three ways:

- reducing surface roughness results in higher workability, because the wood has a smoother surface that does not require further processing (sanding), leading to less material loss (Korkut 2012),
- wood with a smoother surface, even without additional coatings, is less susceptible to trapping impurities, moisture, and fungi and mold spores from the air, leading to lower degradation (Nuopponen *et al.* 2003; Yildiz *et al.* 2011),
- a smoother wood surface is more suitable for surface treatment with coatings that protect wood from fading due to UV radiation, as well as from weathering and biological pests.

The influence of thermal treatment on surface roughness of temperate and tropical wood species has been verified in various experiments. For example, Korkut (2012) thermally treated sapele, limba, and iroko wood, and he showed that surface roughness of milled wood was reduced after thermal treatment at 160 °C and 180 °C. Tomak *et al.* (2014) found that thermal modification reduced the surface roughness of spruce, pine, and ash wood in comparison with unmodified wood.

In this study, the effect of thermal treatment on the color and chemical changes of teak (*Tectona grandis* L. f.) and meranti (*Shorea* spp.) wood was evaluated. The thermal treatment was performed according to the ThermoWood® principle at various temperatures (160 °C, 180 °C, and 210 °C). The color changes of the wood were measured on a tangent surface of the samples before and after thermal treatment using the CIE *L*a*b** model. The chemical changes were assessed by the amount of individual wood components (cellulose, hemicellulose, lignin, and extractives) in each temperature group.

EXPERIMENTAL

Materials

Teak trees (*Tectona grandis* L. f.) were harvested from the Bhumo district in Myanmar, while meranti trees (*Shorea* spp.) were harvested from Indonesia. Samples with the dimensions 20 mm × 100 mm × 200 mm were prepared. All of the samples were air-conditioned in a conditioning room (relative humidity of 65% ± 3%, and temperature of 20 °C ± 2 °C) for more than six months to achieve an equilibrium moisture content of 12%.

Air-conditioned samples of both wood species were divided into two groups, namely reference (control) and thermally treated samples. Each wood species had 20 samples, *e.g.*, 5 samples per treatment temperature. A separate group of samples was prepared for determining the density and moisture content of the untreated and thermally treated wood according to ISO 13061-1 (2014) and ISO 13061-2 (2014), respectively.

Thermal Treatment

The thermal treatment was performed according to the ThermoWood® method, using a S400/03 thermal chamber (LAC Ltd., Rajhrad, Czech Republic) in three phases:

- Heating and drying – the temperature in the chamber was first increased rapidly to 100 °C and then increased slowly to 130 °C. During this phase, the wood was dried to a nearly 0% moisture content.
- Heat treatment – after heating and drying, the temperature was gradually increased from 130 °C to the desired final temperature of 160 °C, 180 °C, or 210 °C, which lasted 3 h. During heat treatment, water vapor was introduced to the chamber, which served as a protective medium against ignition and favorably influenced the ongoing chemical reactions.
- Cooling and moistening – after heat treatment, the wood was slowly cooled. At 80 °C to 90 °C water was sprayed into the chamber, which increased the moisture content of the wood to 4% to 7%. The chamber was opened at a temperature of 40 °C to avoid thermal shock in the treated wood.

Methods

Determination of the physical properties

Table 1 shows the average density for both wood species before and after the thermal treatment. The average moisture contents of both wood species are shown in Table 2.

Table 1. Wood Density

Wood Species	Treatment	Wood Density (kg/m³) (for each group according to the TT temperature)			
		Reference (Untreated)	160 °C	180 °C	210 °C
Teak	Before TT	711	666	679	735
	After TT	711	603	598	638
Meranti	Before TT	526	462	534	482
	After TT	526	425	508	450

Table 2. Moisture Content of the Wood

Wood Species	Moisture Content (%) (for each group according to the TT temperature)			
	Reference (Untreated)	160 °C	180 °C	210 °C
Teak	10.5	6.8	6.2	5.8
Meranti	10.2	6.9	6.4	5.6

Color measurement

Color measurements were performed on reference (control) and thermally treated samples with a portable spectrophotometer (CM-600d, Konica Minolta, Tokyo, Japan) (10° standard observer, D65 standard illuminate, and color difference format of Δ*E*ab*). Measurements were taken on three locations on each sample, and the arithmetic mean of these measurements was calculated. The *L**, *a**, and *b** measured on the reference and thermally treated wood surfaces were used to determine the Δ*L**, Δ*a**, and Δ*b** (for example: $\Delta L^* = L^*_{\text{treated}} - L^*_{\text{reference}}$). The color change (Δ*E**) was calculated using the CIE *L*a*b** color system according to ISO 11664-2 (2007), ISO 11664-4 (2008), and ISO 11664-6 (2014).

The color change was calculated according to Eq. 1,

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

where Δ*E** is the color change between the color of treated and untreated samples, and Δ*L**, Δ*a**, and Δ*b** are the differences in the lightness, red-green coordinates, and yellow-blue coordinates, respectively, between the treated and untreated samples.

The color change was assessed using evaluation criteria from Cividini *et al*. (2007) and Cui *et al*. (2004). Both studies used a five-level evaluation of the color change in the wood with a different description for each level (Table 3).

Table 3. Evaluation Criteria of the Color Change

Evaluation	Reference	Color Change	Description
A	Cui *et al.* (2004)	0 < Δ*E** < 0.5	Negligible color change
		0.5 < Δ*E** < 1.5	Slightly perceivable color change
		1.5 < Δ*E** < 3.0	Noticeable color change
		3.0 < Δ*E** < 6.0	Appreciable color change
		6.0 < Δ*E** < 12.0	Very appreciable color change
		Δ*E** > 12.0	Total color change
B	Cividini *et al.* (2007)	0 < Δ*E** < 0.2	Invisible difference
		0.2 < Δ*E** < 2.0	Small difference
		2.0 < Δ*E** < 3.0	Color change visible with high-quality filter
		3.0 < Δ*E** < 6.0	Color change visible with medium-quality filter
		6.0 < Δ*E** < 12.0	High color changes
		Δ*E** > 12.0	Different color

Chemical changes

The reference (untreated) and thermally treated samples were mechanically processed into sawdust, and a 0.5 mm to 1.0 mm fraction size was extracted with a Soxhlet apparatus using a mixture of ethanol and toluene according to ASTM D1107-96 (2013). The lignin content was determined according to ASTM D1106-96 (2013). Briefly, the samples were hydrolyzed in a two-stage process. In the first stage, 72% (w/w) H_2SO_4 at a temperature of 30 °C was used for 2 h, and in the second stage, the samples were refluxed after dilution to 4% (w/w) H_2SO_4 for 4 h. The holocellulose content was determined using the method by Wise *et al*. (1946), and the cellulose content was determined according to the method by Seifert (1956) using a mixture of acetylacetone, dioxane, and hydrochloric acid (6:2:1.5) under reflux for 30 min for delignification of the wood samples. The hemicellulose content was calculated as the difference between the holocellulose and cellulose contents. All of the measurements were performed on four replicates per sample. The data was presented as percentages of the oven-dried weight of the wood per that of the unextracted wood.

Boundary temperatures, at which a given characteristic starts to change, were determined for color parameters and chemical components. These temperatures were calculated by linear interpolation in graph, where the x-axis is the starting state, i.e. values (percentage content of chemical component or color parameter values) for thermally untreated wood. On this axis, the positive and negative values of the difference of the respective characteristic (the difference in the values between the treated and untreated wood) are plotted at the mentioned thermal treatment temperatures. By interconnecting the last positive and the first negative value of difference (or vice versa) by the line, the x-axis intersection occurs at the specific temperature at which the value decreases (or increases).

RESULTS AND DISCUSSION

Chemical Changes

The chemical components of teak and meranti wood behaved differently under different thermal treatment temperatures. The most pronounced differences were in the extractives and hemicellulose contents in both wood species (Table 4).

Table 4. Percentage Content of the Chemical Components for the Untreated and Thermally Treated Wood

Wood Species	Treatment Temperature	Holocellulose (%)	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	Extractives (%)
Teak	Untreated	62.9	36.9	26.0	35.4	7.0
	160 °C	56.0	39.4	16.6	39.3	8.0
	180 °C	55.2	40.2	15.0	39.5	8.3
	210 °C	49.8	41.4	8.4	40.5	10.9
Meranti	Untreated	71.5	53.0	18.5	32.4	2.5
	160 °C	66.5	51.0	15.5	36.7	3.2
	180 °C	66.1	52.0	14.1	36.3	3.2
	210 °C	62.7	59.1	3.6	35.3	3.9

The chemical composition of the teak wood depends on the location of harvesting, as well as the position within the trunk and testing method, and there can be a wide range. Fengel and Wegener (2003) reported values of 39.1% to 57.2% cellulose, 7.7% to 14.7% pentoses, and 29.3% to 39.1% lignin, which corresponds with the results in this study. The amount of holocellulose determined according to the method used by Wise *et al*. (1946) depends on the number of delignification cycles. According to the original method, four-hour delignification is recommended for deciduous trees, and up to five-hour delignification is recommended for coniferous trees. It should be noted that this method is suitable for wood species from temperate climates. Preliminary analyses showed that four-hour delignification provided high yields, so five-hour delignification was used for the tropical wood samples. According to Lukmandaru (2015), the holocellulose content varies in different parts of the teak wood (sapwood = 79%, outer heartwood = 69.7%, middle heartwood = 71.9%, and inner heartwood = 72.2%). These higher values, compared with our results (62.9%), were probably because of the shorter delignification in their experiment. In this research, the lignin content in the teak wood was higher (35.4%) compared with that reported by Lukmandaru (2015), who obtained a lignin content of 30.3% to 31.0% in different parts of teak wood. Ahmad *et al*. (2016) found the following chemical composition in meranti wood: 41.58% cellulose, 32.8% hemicelluloses, 33.6% lignin, 3.1% extractives, and 0.6% ash; the differences compared with the results of this study (53.0% cellulose, 18.5% hemicelluloses, 32.4% lignin, 2.5% extractives), may have been because of the different growth location, as well as the different methods used for determining the chemical components.

Thermal treatment resulted in an increase of the percentage content of extractives, cellulose, and lignin in both wood species. Similarly, in eucalyptus wood the extractive content increased and almost all of the original extractives disappeared and new compounds were formed resulting from degradation of hemicelluloses and lignin (Esteves *et al.* 2008). In meranti, the highest thermal treatment temperature caused a decrease in the lignin. The increased extractives content was mainly because of the degradation of lignin macromolecules (Wikber and Maunu 2004; Čabalová *et al.* 2018). The increase of the lignin content in the thermally treated wood corresponds with the generally accepted fact that lignin is more thermally stable than saccharides and also condenses (Nuopponen *et al.* 2005; Inari *et al.* 2007; Windeisen and Wegener 2008). In addition to condensation reactions, high temperatures also cause the degradation of lignin macromolecules (Uribe and Ayala 2015; Kačík *et al.* 2016). The results of this study showed that during thermal treatment of the teak wood, condensation reactions were dominant, which led to an increase in the lignin amount in the wood. In the case of the meranti wood, lignin degradation occurred at higher temperatures and its yields decreased (Table 4). The least stable component in both wood species were the hemicelluloses. In the teak wood, it decreased by approximately 67%, and in meranti wood, it decreased by up to approximately 80%. For comparison, hemicelluloses in thermally treated temperate wood are more stable; in the case of oak wood, the hemicellulose content decreased by 58%, and in spruce wood, the hemicellulose content decreased by only 37% (Sikora *et al.* 2018). This was probably because of the different hemicellulose structures, as shorter hemicellulose chains degrade more rapidly at high temperatures (Kačík *et al.* 2015).

Color Changes

Lightness (L^*) is a basic wood color parameter and in many applications is considered to be the most important parameter. As the thermal treatment temperature

increased, the *L** values gradually decreased in both wood species (Fig. 1), which was confirmed by the characteristic influence of the high temperatures. The most remarkable decrease was achieved at 210 °C. The *L** decrease trend was similar in both wood species, although a certain difference occurred at 180 °C, where there was a slight increase in the teak wood. The overall decrease in the *L**, compared with that in the untreated wood, was 46.1% for the meranti wood and 42% for the teak wood. The decrease in the *L** confirmed that the thermal treatment had the same effect on the *L** of the tropical wood species as it did on that of the temperate wood species, which have been investigated in many studies, such as Kačíková *et al*. (2013), Barcík *et al*. (2015), and Sikora *et al*. (2018). The decrease in the teak wood lightness after thermal treatment was confirmed using the work of Cuccui *et al*. (2017).

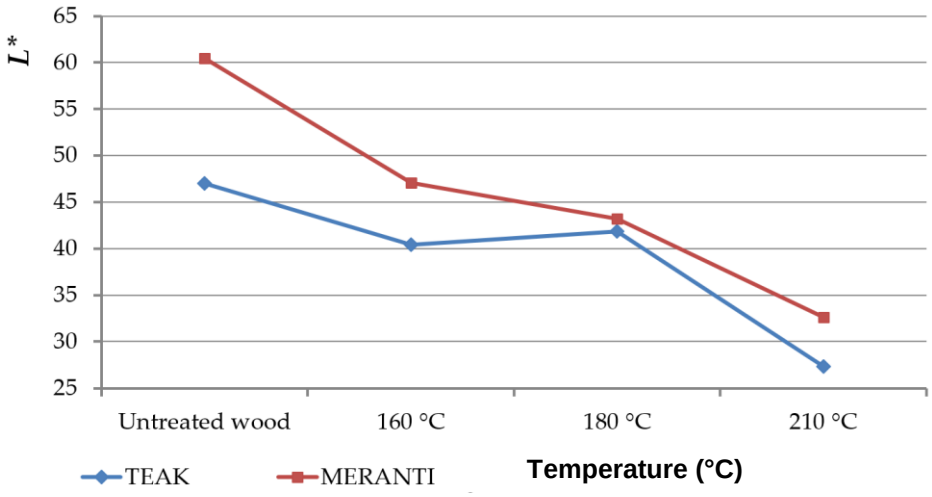

Fig. 1. Dependence of the *L** on the thermal treatment temperature

The red-green coordinate (*a**) was not clearly affected by the thermal treatment, although there was a gradual, but very mild decrease in its values as the temperature increased (Fig. 2). As was the case for the *L**, the lowest values were found at 210 °C. There was also a slight deviation from the trend, where the *a** values in the teak wood increased slightly at 180 °C. The meranti wood achieved a lower decline in the *a** than in the teak wood.

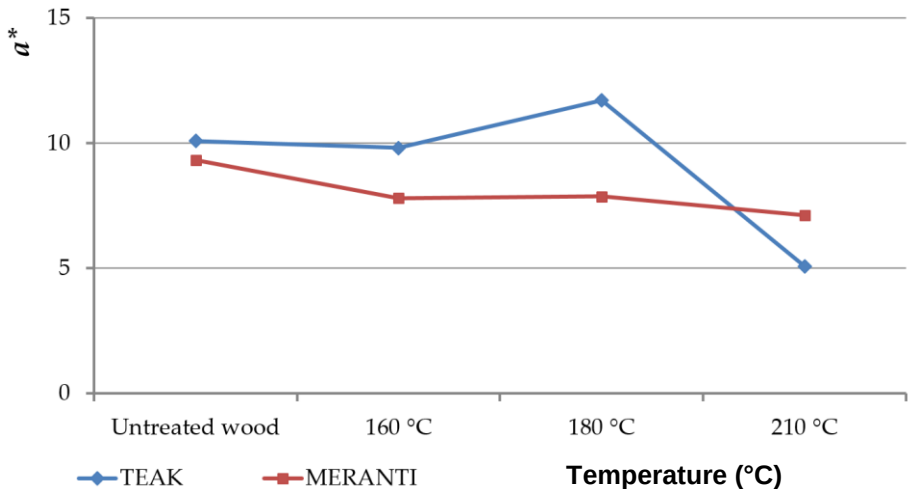

Fig. 2. Dependence of the *a** on the thermal treatment temperature

The yellow-blue coordinate (*b**) was similarly affected by the increasing temperature in the thermal treatment in both wood species (Fig. 3). There was a gradual decrease in its values, with the exception of at 180 °C, where there was a certain increase in both wood species. Cuccui *et al*. (2017) confirmed the same trend; there was a slight increase at 180 °C to 190 °C, which was followed by a major decrease when 200 °C was exceeded. The most remarkable decrease was observed at 210 °C for both wood species. An interesting fact was that the *b** values in the teak wood were higher than those in the meranti wood up to a temperature of 210 °C, after which there was a more pronounced decrease and its value was lower than that of the meranti wood.

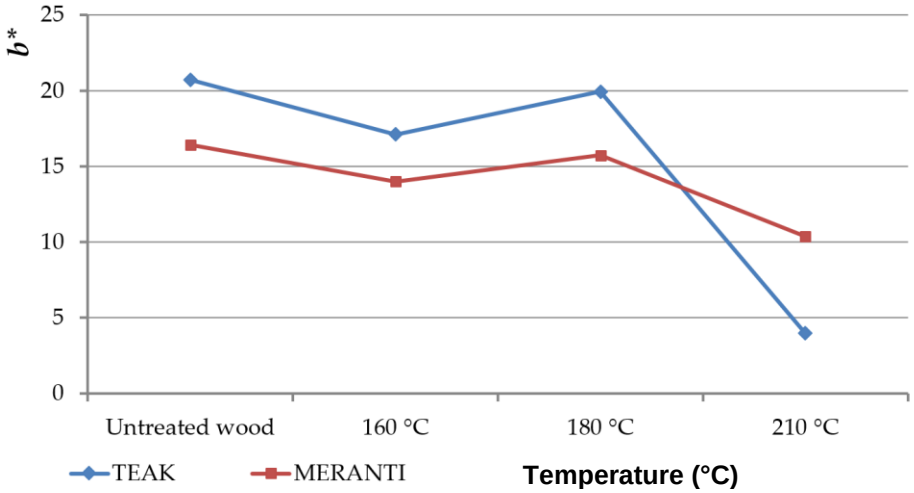

Fig. 3. Dependence of the *b** on the thermal treatment temperature

The color change (Δ*E**) was almost identical in both wood species, where an increase in the temperature resulted in a more pronounced color change (Fig. 4). A more pronounced Δ*E** of 32.54 was found in the meranti wood, while the teak reached a value of 27.03 (Table 5). The Δ*E** was most affected by the thermal treatment effect on the *L** (Cuccui *et al*. 2017). The color change values in the teak wood found in this research corresponds with the results reported by Méndez-Mejías and Moya (2016).

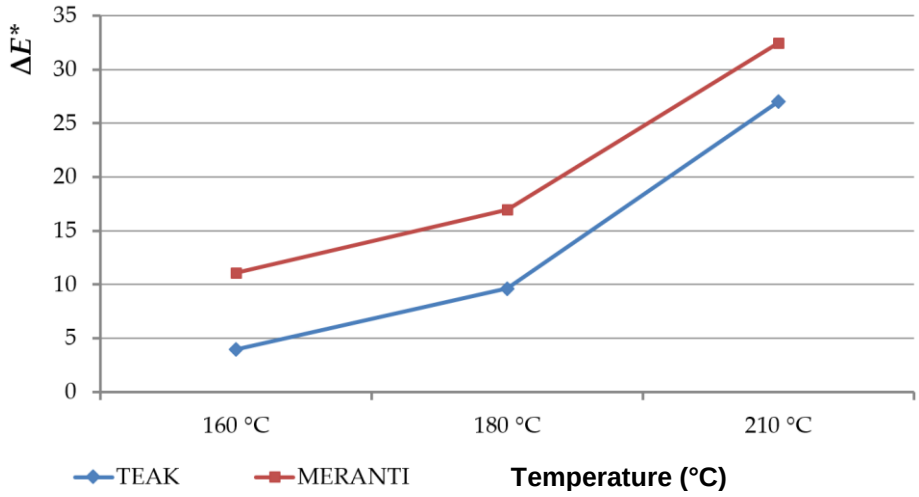

Fig. 4. Dependence of the Δ*E* * on the thermal treatment temperature

The nature of color change is complex, as all essential wood components including the extractives may contribute to the change. Bekhta and Niemz (2003) have reported that the darker color of heat-treated wood was attributed to the formation of degradation products from hemicelluloses, changes in extractives, and the formation of oxidation products such as quinones, *etc*.

The thermal treatment temperature and wood species are the most important factors that affect the final color. When the thermal treatment temperature is higher, the wood shade is darker (Huang *et al*. 2012). The color change is less pronounced in darker wood species than in lighter wood species. Thermal treatment causes a number of changes in the chemical components of wood (cellulose, lignin, hemicelluloses, and extractives), depending on their content according to the wood species. The degradation of polysaccharides, especially hemicelluloses, caused by high temperatures is responsible for the most color changes. For this reason, the content of heat-stable components, such as lignin and cellulose, slightly increased. Extractives are degraded under high temperatures, but new extractives are produced by the degradation of the main wood components (Kačíková *et al*. 2013; Sikora *et al*. 2018).

Table 5. Color Parameters for the Untreated and Thermally Treated Wood

Wood Species	Treatment Temperature		Color Coordinates			ΔE
			L	a	b	
Teak	Untreated	Mean	47.0	10.1	20.7	-
		SD*	5.10	1.78	3.36	-
		CV**	10.9	17.7	16.2	-
	160 °C	Mean	40.4	9.8	17.1	3.97
		SD	3.37	0.72	2.78	1.33
		CV	8.3	7.4	16.2	33.6
	180 °C	Mean	41.82	11.7	19.9	9.62
		SD	2.72	0.48	2.04	3.72
		CV	6.5	4.1	10.2	38.7
	210 °C	Mean	27.35	5.1	3.9	27.03
		SD	1.21	1.22	1.66	5.04
		CV	4.4	24.0	41.7	18.7
Meranti	Untreated	Mean	60.5	9.3	16.4	-
		SD	5.63	1.75	1.42	-
		CV	8.7	18.7	8.7	-
	160 °C	Mean	47.1	7.8	14.0	11.08
		SD	6.90	1.45	1.30	3.61
		CV	14.7	18.7	9.3	32.5
	180 °C	Mean	43.2	7.9	15.7	16.95
		SD	5.19	1.06	2.08	4.25
		CV	12.0	13.4	13.2	25.1
	210 °C	Mean	32.6	7.1	10.4	32.54
		SD	3.50	1.62	3.65	3.75
		CV	10.7	22.8	35.2	11.6

**SD – standard deviation, **CV – coefficient of variation (%)*

From the comparison of the color differences according to the two evaluation criteria (Table 6), it was clear that there is no universal method for comparing the color change. A pronounced color change according to both criteria was assessed as a different color compared with the original color before thermal treatment. However, a mild or moderate color change is differently characterized by the description of the given degree of change; this was because of the subjective views of the person who created the evaluation method and the person using the evaluation method. Unfortunately, a high or pronounced change means something different to each person.

Table 6. Evaluation of the Color Change for the Thermally Treated Wood

Wood Species	Treatment Temperature	ΔE^*	Evaluation of the Color Change	
			A	B
Teak	160 °C	3.97	Appreciable color change	Color change visible with medium-quality filter
	180 °C	9.62	Very appreciable color change	High color change
	210 °C	27.03	Total color change	Different color
Meranti	160 °C	11.08	Very appreciable color change	High color change
	180 °C	16.95	Total color change	Different color
	210 °C	32.54	Total color change	Different color

To optimize thermal treatment and achieve the desired wood color, it is important to know at what temperature the chemical components of the wood change, which causes the transition from one shade to another. These changes are illustrated by the following graphs in Figs. 5 and 6, which show at what temperature a chemical component or color parameter changed remarkably.

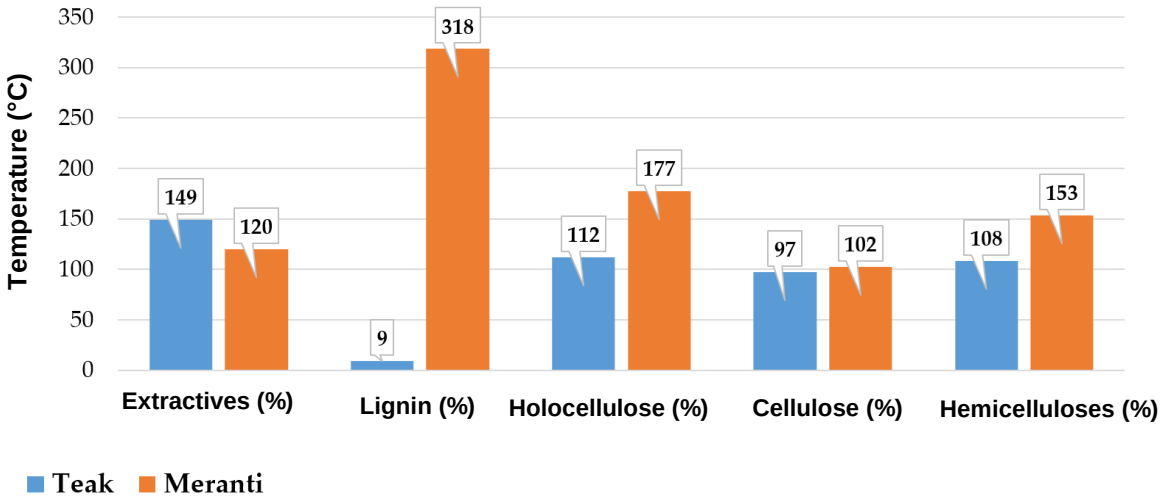

Fig. 5. Boundary temperature at which chemical components began to change

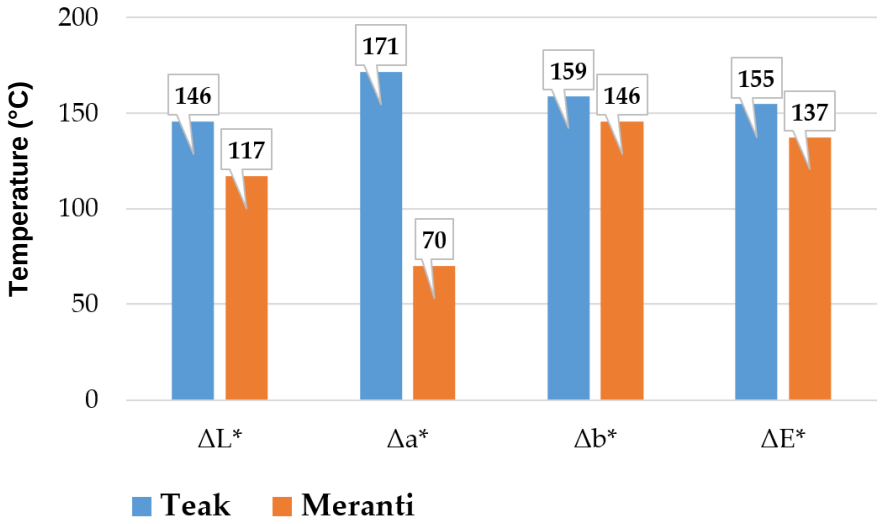

Fig. 6. Boundary temperature at which color parameters began to change

Table 7 shows the Spearman's correlation between the color parameters, thermal treatment temperature, and chemical components found in the teak wood. The values in the table showed a high degree of dependence between the monitored characteristics.

Table 7. Spearman's Correlation of the Color Parameters and Chemical Components for Teak Wood

Variable	TT (°C)	*L**	Extractives (%)	Lignin (%)	Holocellulose (%)	Cellulose (%)	Hemicelluloses (%)
TT (°C)		-67	96	96	-92	97	-96
L*	-67		-66	-65	66	-65	65
Variable	**TT (°C)**	***a****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		-33	96	96	-92	97	-96
a*	-33		-33	-31	38	-31	32
Variable	**TT (°C)**	***b****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		-48	96	96	-92	97	-96
b*	-48		-48	-46	51	-46	47
Variable	**TT (°C)**	**Δ*E****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		97	96	96	-92	97	-96
Δ*E**	97		93	94	-91	95	-94

Table 8 shows the Spearman's correlation between the color parameters, thermal treatment temperature, and chemical components measured in the meranti wood. The values in the table showed a high degree of dependence between the compared characteristics.

Table 8. Spearman's Correlation of the Color Parameters and Chemical Components for Meranti Wood

Variable	TT (°C)	*L**	Extractives (%)	Lignin (%)	Holocellulose (%)	Cellulose (%)	Hemicelluloses (%)
TT (°C)		-85	85	19	39	-92	-96
L*	-85		-76	-19	-33	85	84
Variable	**TT (°C)**	***a****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		-32	85	19	39	-92	-96
a*	-32		-27	-22	-2	24	28
Variable	**TT (°C)**	***b****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		-46	85	19	39	-92	-96
b*	-46		-51	-14	-22	48	45
Variable	**TT (°C)**	**Δ*E****	**Extractives (%)**	**Lignin (%)**	**Holocellulose (%)**	**Cellulose (%)**	**Hemicelluloses (%)**
TT (°C)		95	85	19	39	-92	-96
Δ*E**	95		84	21	35	-91	-93

CONCLUSIONS

1. The results confirmed that thermal treatment affects the color of meranti and teak wood in the same way as for temperate wood species.
2. The *L** was the most affected color parameter. As the thermal treatment temperature increased, the *L** decreased. The meranti wood had a more pronounced decrease in the *L** (46.1%) compared with the teak wood (41.8%). The *a** and *b** values decreased in both wood species as the temperature increased compared with those of the untreated wood. A more pronounced Δ*E** was found in the meranti wood, which had a lighter color before the treatment. The color change increased steadily as the temperature increased.
3. The extractives, cellulose, and lignin percentage contents increased in both wood species. The hemicelluloses decreased remarkably with an increasing temperature; in the teak wood, it decreased by 67.7%, and in meranti wood, it decreased by up to 80.5%.

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