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Wood discoloration patterns depending on the light source

Dace Cirule*, Edgars Kuka, Ingeborga Andersone and Bruno Andersons

Abstract

The wood photodegradation, including discolouration caused by exposure to UV and solar radiation, has been intensively studied, while the effect of artificial lighting on wood has been little investigated. In the present study, the effect of three types of artificial light sources (LED, incandescent, and fluorescent lamps) on the colour changes of wood was evaluated. LEDs with high (6500 K) and low (3000 K) correlated colour temperature were employed in the experiments. Wood colour was assessed by spectrophotometric measurements of reflectance spectra, which were converted into colour parameters of the CIELAB colour system. The total discolouration as well as the changes in colour lightness, chroma (saturation), and hue were evaluated for two hardwood species (birch, oak) and two softwood species (spruce, pine - sapwood and heartwood) depending on the irradiation dose. Visually perceivable changes in colour of all woods were observed already at relatively low irradiation doses, indicating a high sensitivity of the wood to radiation emitted by artificial light sources. Comparing the softwoods and hardwoods included in the study, the latter proved to be more resistant to discolouration caused by the tested light sources. Overall, greater colour changes in long-term exposure were caused by incandescent and fluorescent lamps, although more rapid discolouration developed in the early stage irradiation with LEDs. A substantial difference between the effect of the tested LEDs was only observed in the initial phase, when the cool LED (6500 K) caused more discolouration. The changes in the colour parameters were complex and varying in directions, including a reversal with the accumulation of the irradiation dose, indicating that the exposure to artificial light sources resulted in continuous alteration in the shade of the wood colour.

Keywords: Wood, Discolouration, Artificial lighting, LED

Introduction

Lighting plays a dual role in museums and galleries. On the one hand, it is an essential player for decent display of exhibits. On the other hand, the innate energy of photons, which is transferred to the lit object by the radiation of lighting, can trigger chemical transformations in light sensitive materials ultimately leading to deterioration of the object. In addition, photo-chemical processes are irreversible and cumulative, which means that even a low daily dose of light can lead to serious damages over time. Therefore, achieving a balance between the quality of display lighting and prevention of photo-deterioration is always a topical issue for light sensitive exhibits/materials [1, 2]. Today, the sustainability of the light source is another important aspect in the designing of the lighting strategy [3].

The process of photodegradation depends on both the spectral composition of the incident radiation as well as the chemical composition of the irradiated material. According to CIE (Commission Internationale de l'Eclairage) technical report [4], wood is classified as a material of low responsivity to visible light, while it is recognized as a moderately or even highly sensitive to UV (ultraviolet) material [5]. Wood photodegradation has been quite intensively studied and it is well recognized that photodegradation processes are localized only in a

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thin layer of the exposed wood making them exclusively surface phenomena [6, 7]. Alongside other chemical changes, photodegradation includes transformations in the wood chromophoric composition, manifesting in discolouration that leads to changes in aesthetic properties. Lignin and phenolic extractives have been recognized to be the most sensitive wood components to photo-discolouration, as they contain many chromophoric groups, which can undergo chemical transformations when exposed to light, leading to colour change of wood [6, 8–11]. In addition, discolouration is found to be the first sign of wood photodegradation, as colour changes are more pronounced than other indicators at the initial phase of exposure [12]. The UV radiation is well recognized to be the main cause of the photochemical changes in wood [6]. Accordingly, studies of the interaction of wood and UV dominate in the literature. However, it is detected that visible light of the shorter wavelength also can cause wood discolouration [6, 13–16]. In addition, these results demonstrate that the changes in the colour parameters of the CIELAB colour system [17] depend on the spectral composition of the incident light. This indicates that the shade of the wood colour generated by the irradiation can vary depending on the light source.

Another cause of wood discolouration is the natural ageing process, which is mainly caused by the inevitable mild thermal oxidation reactions that occur in the whole bulk of wood even without any assistance of light [18]. Although this is an unavoidable process in environment containing some oxygen, the rate of colour changes due to ageing is relatively low when compared with the wood photo-discolouration [19].

Wood discolouration indoors can be caused by different light sources including various types of artificial lighting as well as solar radiation both directly through an open window and indirectly through window glass. When wood is exposed to both solar and artificial light, the effect of the former will predominate due to the high content of UV in it, which readily causes transformations in the chemical structure of wood. Extensive information on the potential processes of wood photodegradation caused by exposure to solar radiation can be found in the literature, including various aspects related to discolouration [e.g. 6, 7, 12–16, 20]. Much less attention has been paid to the processes in wood caused by artificial lighting.

The types of artificial light sources have significantly changed in recent decades. The incandescent lamps have been the most common artificial light source for a very long period. However, an increasing number of countries have already phased out or are about to phase out this type of lamps because of the very high energy losses. As the next generation, different kinds of fluorescent lamps with considerably improved efficiency (radiation output per electricity input) were introduced. However, the fluorescent lamps have a significant drawback from an environmental point of view because they contain mercury. Today LED (light-emitting diode) lamps are becoming the dominant light source for different indoor environments due to number of advantages such as high efficiency and long lifetime providing considerable energy and maintenance savings, non-toxic materials, low emission of heat radiation, and flexibility in fixture design [21]. Although LED lamps have relatively low emittance in the UV and IR ranges, they typically have an emittance peak in the blue region of visible light [1, 22] which can cause photodegradation in wood surface. The intensity of the emitted energy in this region varies depending on the LED type and typically positively correlates with the correlated colour temperature (CCT) of the LED [23]. Consequently, LEDs of higher CCT could potentially be more harmful because of the relatively high emittance of the more energetic blue light photons as it is observed for certain museum materials [23]. On the other hand, it is found that higher CCT of LEDs not always is associated with higher discolouration of museum materials [22, 24, 25]. It has been implied that, albeit of a low level, the ratio of the emitted UV radiation of LED rather than the composition of visible light can be the determining factor for certain materials [22]. In addition, the higher level of the blue light in the spectrum makes LEDs of higher CCT visually brighter and they can increase the colour contrast of objects [5, 26]. Accordingly, lower irradiation intensity can be used to provide adequate visibility, thus reducing the total irradiation dose, which could compensate for the higher emission of the photons capable of inducing chemical transformations.

The colour changes in wood caused by photodegradation do not evolve linearly with increasing exposure time. It is well documented that the very fast wood discolouration phase at the onset of irradiation is followed by much slower changes in the further course of exposure [e.g. 20, 27, 28]. Consequently, wood that has been on display for a long time is not expected to change its colour significantly in the future. However, a knowledge based lighting strategy may be important to diminish photodegradation of objects that do not have such experience [26].

The aim of the present study was to evaluate and compare colour changes in wood caused by artificial lighting. Different types of artificial light sources and wood species including both softwoods and hardwoods were used in the experiments to obtain information on the peculiarities of wood discolouration depending on the irradiation characteristics and dose. The findings of the present study could be useful in estimating potential risks and designing the display of wooden artifacts from repositories.

Materials and methods

Material

In the study, both hardwood and softwood were represented by two species each: birch (*Betula* spp.), oak (heartwood) (*Quercus robur* L.), spruce (*Pice abies* H.Karst.), and pine (*Pinus sylvestris* L.). In the case of pine, separate specimens were prepared from heartwood and sapwood. The specimens measuring 70 mm⊆70 mm⊆10 mm were prepared from boards sourced from a local sawmill. Six boards were used for each species. A total of four sets of specimens were prepared for irradiation experiments, each containing six specimens (one per a board) for each species. Prior to further testing, all specimens were conditioned for one month in the dark (RH 65%, 20 °C). In preliminary experiments, one month was assessed as sufficient time for ceasing of the main oxidation reactions, which are unavoidable on the freshly exposed wood surface.

Wood exposure to irradiation

The specimens were exposed to three types of artificial light sources: incandescent, fluorescent, and LED lamps. Two LEDs differing in CCT (3000 and 6500 K) were included in the experiments. It should be noted that CCT provides only information about the colour of the emitted light but not about the spectral power distribution [29]. Some characteristics of the light sources including the spectral composition of the emitted light are summarized in Table 1. Spectral power distribution of the light sources is provided in Additional file 1.

The exposure of the specimens was carried out in 24 specially designed chambers (Fig. 1). Six chambers were equipped with each kind of lamps and in each chamber all woods were represented by one specimen. All walls of the chamber were coloured black to avoid additional irradiation of the specimens with the reflected light of unknown spectral composition.

The illuminance on the surface of specimens during the experiments are listed in Table 1. The luminous flux was regularly controlled with a light meter (LX1010B Dr. Meter, Hong-Kong) and adjusted if needed. The chambers used for incandescent lamps were equipped with ventilators to ensure that the temperature on the surface of specimens does not exceed 30 °C. In preliminary experiments, it was determined that the surface temperature caused by irradiation of other lamps was in the range of 23–27 °C for the used experiment design. The specimens were periodically removed from the chambers for spectrophotometric measurements.

Table 1 Characteristics of light sources used in experiments

Light source	Radiant power distribution (%)			Correlated colour temperature (CCT) (K)	Luminous efficacy (lm/W)	Illuminance on surface (lx)	Irradiance on surface (400-1100 nm) (W/m^2)
	300–400 nm (UV)	400–520 nm	520–800 nm				
LED (warm)	0.23	19.7	80.1	3000	100	2350	6.7
LED (cool)	0.21	40.7	59.1	6500	103	3100	5.8
Incandescent	0.61	7.1	92.3	2700	11	2200	97.5
Fluorescent	1.43	15.7	82.9	2700	65	1900	5.1

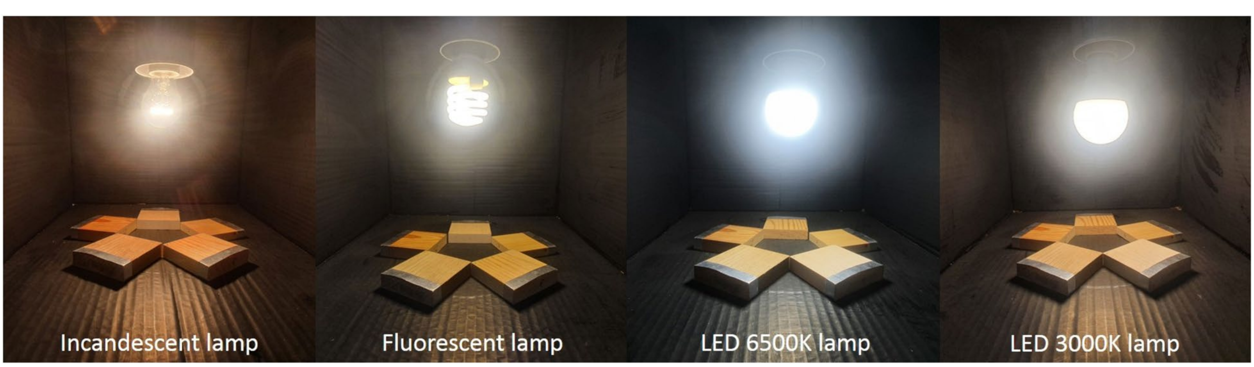

Fig. 1 Test chambers for wood exposure

Evaluation of colour changes

To avoid the highly subjective visual perception inherent to humans, instrumental measurements providing numerical quantification of colour are widely used for assessment and comparison of object colour. Measurements of reflectance spectra in the visible range (360–740 nm) and conversion of these data into the CIE colour system CIELAB were performed with a spectrophotometer Konica Minolta CM-26dG (standard illuminant D65, d/8° measuring geometry, 10° standard observer, measuring area Ø 8 mm). The measurements were always performed on the same five spots on a specimen surface, which was ensured by using a template with cut holes. CIELAB is a three-dimensional system consisting of an achromatic lightness axis L^*, and chromaticity axes a^* (red – green) and b^* (yellow – blue) in which each colour is represented by a point with three coordinates. The CIELAB is acknowledged as a useful tool for evaluating perceived colour differences, although certain limitations have been identified related to its development for definite standard viewing conditions and deviations from absolute uniformity across its space [30]. The difference between two colours DE is the Euclidean distance between the points corresponding to these colours and is calculated from the corresponding colour parameter differences DL^*, Da^*, Db^* according to the formulas:

$$DL^* = L_d^* - L_o^*$$

$$Da^* = a_d^* - a_o^*$$

$$Db^* = b_d^* - b_o^*$$

$$DE = \sqrt{(DL^*)^2 + (Da^*)^2 + (Db^*)^2}$$

$$DC^* = C_d^* - C_o^*$$

$$Dh^* = h_d^* - h_o^*,$$

where $L_o^*, a_o^*, b_o^*, C_o^*, h_o^*$- colour parameters of unexposed specimens;

$L_d^*, a_d^*, b_d^*, C_d^*, h_d^*$- colour parameters of specimens exposed to definite illumination dose

Although Cartesian coordinates (a^* and b^*) are more often applied in the literature to analyse changes in wood chromaticity, transformation of these coordinates into polar coordinates C^* and h^* (Fig. 2) was used in this study to provide data that are more adapted for the description of colour shades as they better correspond to human visual experience [30].

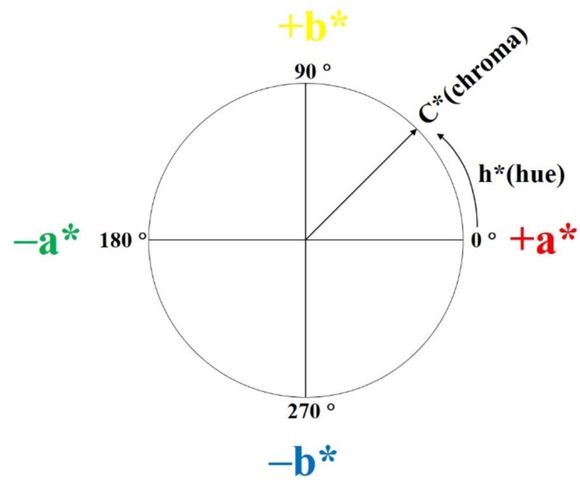

Fig. 2 Schematic representation of chromaticity parameters in CIELAB colour system

C^* is a measure of chroma represented by the distance from the achromatic (L^*) axis and h^* is a measure of hue represented by the angle from the $+a^*$ axis defined as 0°. Changes in C^* (DC^*) characterize alteration in colour intensity or saturation, while changes in h^* (Dh^*) indicate the extent and direction of hue or shade transformation.

Results and discussion

Total discolouration DE

In the CIELAB colour system, the threshold above which the difference between two colours is visually perceivable is between 1 and 2 DE units [31, 32]. Figure 3 shows the results of the total discolouration (DE) observed for the specimens exposed to the irradiation dose of 0.6 Mlx h, which approximately corresponds to an eight-hour daily exposure of one year at illuminance of 200 lx, which is the recommended limit of light level for moderately light sensitive materials [33, 34].

It can be seen that the colour difference visibility threshold of 2 DE units was reached by almost all woods with an exception of the oak exposed to the warm LED (CCT 3000 K). It is well documented that discolouration due to exposure to UV radiation is very fast during the initial phase [e.g. 9, 35, 36]. The results of the present study demonstrate that artificial lighting also initiate quite rapid discolouration and visible colour differences will evolve between unexposed and to artificial light exposed parts of the exhibits in less than a year. Comparing woods, the most pronounced photo-sensitivity to all light sources was observed for the pine heartwood. Overall, a tendency of faster onset of discolouration of the tested softwoods compared to hardwoods was detected. This well agrees with the general observation that

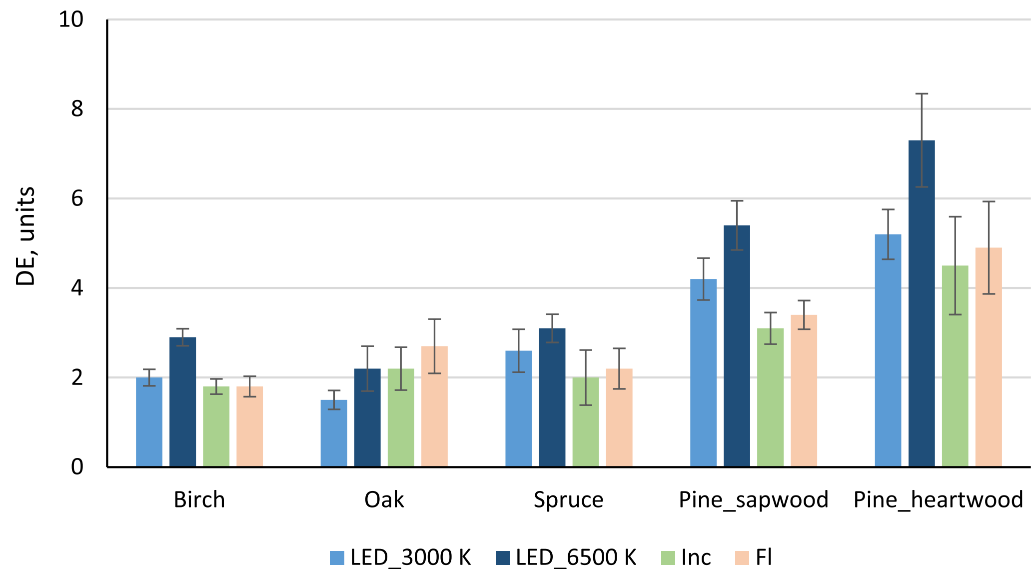

Fig. 3 Total discolouration (*DE*) of woods exposed to artificial light sources for irradiation dose of 0.6 Mlx h: *Inc* incandescent lamp, *Fl* fluorescent lamp

softwoods are more prone to photodiscolouration, which is attributed to the peculiarities of their chemical structure and mainly to their higher lignin content [28, 37, 38].

An unexpected result was that the LEDs imparted greater colour changes for all woods except the oak in the early stage of exposure compared to the incandescent and fluorescent lamps, which emit more harmful UV radiation. However, similar trend was also observed by Farke et al. [39] for softwood (species not specified) exposed to fluorescent and LED lamps in display cases, when in the initial phase much higher *DE* values were detected for the specimens irradiated with LED lamp. On the other hand, more discolouration caused by exposure to the cool LEDs (CCT 6500 K) corresponds to the higher ratio of the blue light in their emission spectrum. Chang et al. [10] have suggested that extractives might be oxidized primarily after irradiation which could explain the rapid discolouration caused by LEDs, which emit relatively much of radiation that is mainly absorbed by extractives.

Although the LEDs induced an unexpectedly great discolouration of the wood at a relatively low irradiation dose, the colour changes caused by the incandescent and fluorescent lamps developed much more during the subsequent exposure. The maximum values of the total discolouration observed in the course of exposure for the total irradiation dose of 36 Mlx h are shown in Fig. 4.

In some cases, slight (up to 2 *DE* units) decrease in *DE* was observed during exposure, which goes in line with the observations that wood photodegradation is not a straightforward process and may change both rate and direction of discolouration [6, 8, 40]. This phenomenon is associated with generation of different chromophores, which themselves can undergo transformations with progressing of the photodegradation process [41]. However, the maximum values included in Fig. 4 provide basic information to predict the magnitude of the changes in wood colour, which can be expected depending on the species and light source. These results distinctly demonstrate that the LEDs transform wood colour less during long-term exposure. In addition, for the specimens exposed to the incandescent and fluorescent lamps, the maximum values were reached and considerable increase in *DE* ended already at the accumulated irradiation dose of 6–10 Mlx h depending on the species. This could be associated with the relatively higher ratio of UV in the emittance spectra of these lamps. Much higher doses (20–36 Mlx h) were required in the case of the LEDs to reach the discolouration level after which only relatively slight changes in *DE* were observed. Summarizing the results shown in Figs. 3 and 4, it can be seen that the LEDs imparted relatively higher ratio from the maximum discolouration value during the initial phase (Fig. 3) compared with the incandescent and fluorescent lamps, for which, as mentioned above, lower irradiation doses caused the maximum discolouration. Consequently, the discolouration processes caused by the LEDs were faster at the onset but slowed down more considerably as irradiation progressed.

Overall, the tendency of greater discolouration of softwoods than hardwoods observed for the initial phase did

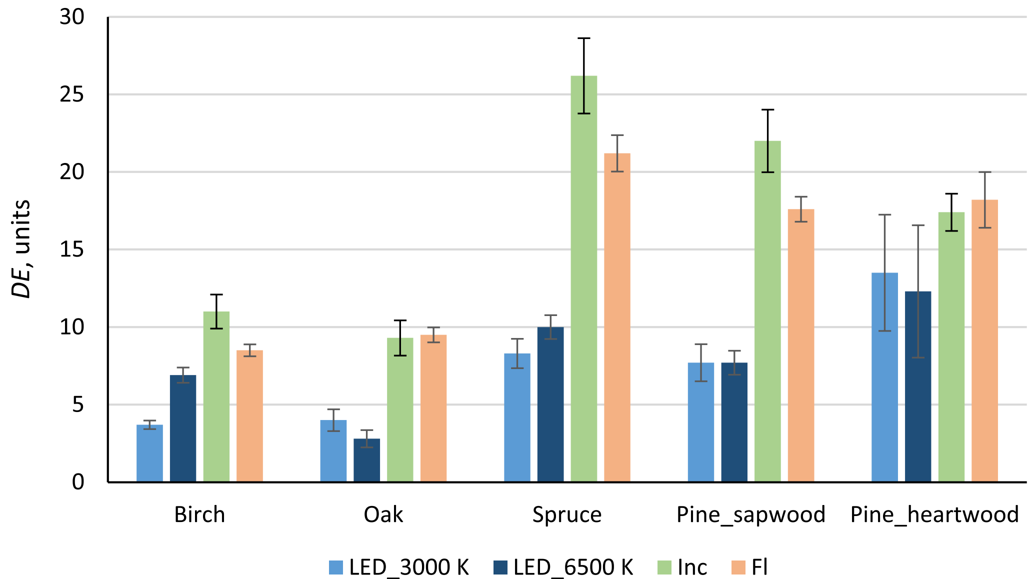

Fig. 4 Maxima total discolouration (*DE*) of woods exposed to artificial light sources during exposure to irradiation dose of 36 Mlx h: *Inc* incandescent lamp, *Fl* fluorescent lamp

not change also for higher irradiation doses and resulted in considerably greater maximum discolouration for all tested lamp types. Greater *DE* of softwood compared to hardwood was also observed for the wood exposed to UV [37]. However, different result was observed between softwoods regarding their sensitivity to the tested light sources. The greatest discolouration because of exposure to the LEDs was found for pine heartwood, while the incandescent lamps caused considerably more colour changes for pine sapwood and spruce than pine heartwood. In the case of the fluorescent lamps, the highest discolouration was observed for spruce whereas both types of pine wood discoloured less and to approximately equal extent. Although lower average values of discolouration were detected for pine heartwood exposed to the LEDs than other lamps, the *DE* values for various light sources were not different from each other at a significance level of $\alpha = 0.05$, which was mainly due to the high variation in the LED results. Since mostly wood extractives are attributed to absorption of visible light [40] and formation of pine heartwood is associated with an accumulation of extractives [42, 43], the high *DE* variation for the specimens exposed to the LEDs could be related to the variations in extractive content. To verify that, additional experiments were carried out by extraction of wood of the same boards, which were used to prepare the specimens that showed the highest variations in *DE* after exposure to the LEDs (Additional file 3). A close positive correlation ($r = 0.98$) was observed between the content of extractives and *DE* values. High variation in pine heartwood extractives is reported not only between trees but also within a stem [44]. Our preliminary result of the extraction experiment corroborates that exposure of pine heartwood to LEDs could lead to very high variations in *DE* depending on the content of extractives.

The different response to light of sapwood and heartwood can be another concern for wood, since it can result in a changed overall appearance of objects that contain both wood types [33]. To evaluate this aspect depending on the light source, colour difference between colour of pine sapwood and heartwood was calculated for the maximum irradiation doses. Colour difference, which was about 8 *DE* units for unexposed wood, remained at the same level for the wood exposed to the incandescent and fluorescent lamps while doubled for the specimens exposed to the LEDs indicating considerable increase in colour difference between sapwood and heartwood. This could be another consequence of relatively high content of pine heartwood extractives, which are rich in chromophores that are sensitive to visible light. However, more research is needed to really understand the processes and relations underlying these results.

Contribution of colour parameters into DE

DE provides information on the magnitude of colour changes without specifying its characteristics for which an analysis of changes in colour parameters is used [e.g. 16, 19, 27]. Sensitivity of human visual perception to differences in colour parameters is not uniform and is arranged as hue > chroma > lightness [45]. To evaluate the contribution of each colour parameter in *DE* value, corresponding ratios were calculated. These ratios varied considerably between woods and were not constant during the exposure, as it is demonstrated by stacked bar charts in Fig. 5, which show inputs of changes in lightness (*DL**), chroma (*DC**), and hue (*Dh**) in *DE* for the irradiation dose of 0.6 Mlx h (a) and for the maxima observed *DE* (b).

In the initial phase, *DC** was the main contributor to discolouration for the woods exposed to the LEDs whereas *DL** dominated in the case of the incandescent and fluorescent lamps. The exceptions were pine heartwood exposed to the LEDs, for which the input of *DL** prevailed over that of *DC**, and spruce exposed to the incandescent lamps, for which the *DL** contributed only 20%. Comparing the results of the initial phase with those calculated for the maxima discolouration, a common tendency of a decrease in the contribution of *DC** can be seen for the wood exposed to the LEDs while an increase for the wood exposed to the other light sources. In general, the contribution of *Dh** was relatively smaller than that of the other parameters, which indicates that the alteration in wood shade was mainly due to the changes in its lightness and colour intensity rather than hue. However, *Dh** considerably contributed to the discolouration of spruce regardless of the light source in the initial phase, as well as to the maximum colour changes of birch and oak exposed to LEDs.

Changes in colour parameters

As a general trend, a decrease in lightness is reported for light-coloured wood due to light-irradiation [13, 15, 37, 46], while opposite changes have been observed for dark-coloured tropical woods [8, 47]. Although much less common, positive values of *DL** due to irradiation have also been reported, for example for oak [40]. However, it should be noted that in these experiments UV or solar radiation were used as the irradiation source. An increase in lightness has been also detected for wood exposed to certain region of visible light [14]. In the present study, a tendency of wood darkening was observed in the great majority of experiments (Additional file 2). The exception was birch and oak exposed to LEDs, for which a reversal of *DL** values was observed when a slight darkening in the initial phase was followed by an increase in the lightness.

More complex transformations were observed for the changes in *DC** and *Dh**. Hue angle depends on the ratio of colour parameter *b** and *a** values [30]. On the chromaticity plane, red (+*a**) and yellow (+*b**) axis correspond to the hue angles of 0° and 90°, respectively (Fig. 2). Accordingly, for colours with positive chromaticity coordinates *a** and *b**, which is the case of light-coloured wood, a positive *Dh** value corresponds to an increase in yellowness, while a negative value is associated with a shift towards the red hue. The development of changes in hue and chroma is plotted in Fig. 6. At the moment of starting the experiments, the values of *Dh**and *DC** were zero (the intersection of the coordinate axes). Since the general trend of changes in the case of both tested LEDs was similar, only results of the cool LED (CCT 6500 K) are included in Fig. 6.

In general, Fig. 6 demonstrates that the shade of wood colour altered differently depending on both the wood and the light source. Regarding the changes in hue, although a general tendency of positive *Dh** values was

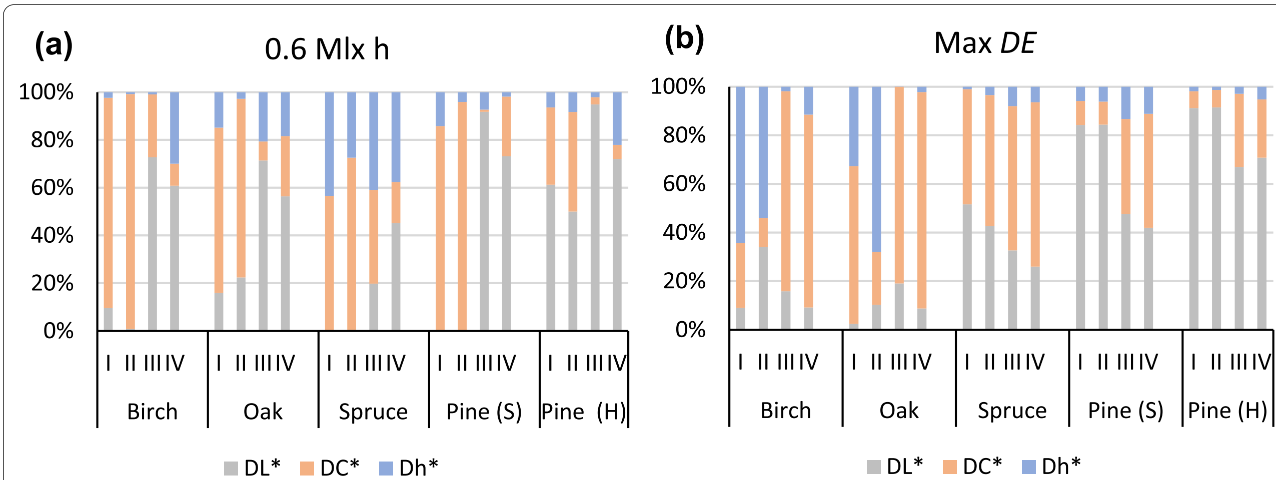

Fig. 5 Input ratio of colour parameters into total discolouration of woods exposed to artificial light source for irradiation dose of 0.6 Mlx h (**a**) and maxima observed discolouration (**b**): I—LED 3000 K, II—LED 6500 K, III—incandescent lamp, IV—fluorescent lamp; *S* sapwood, *H* heartwood

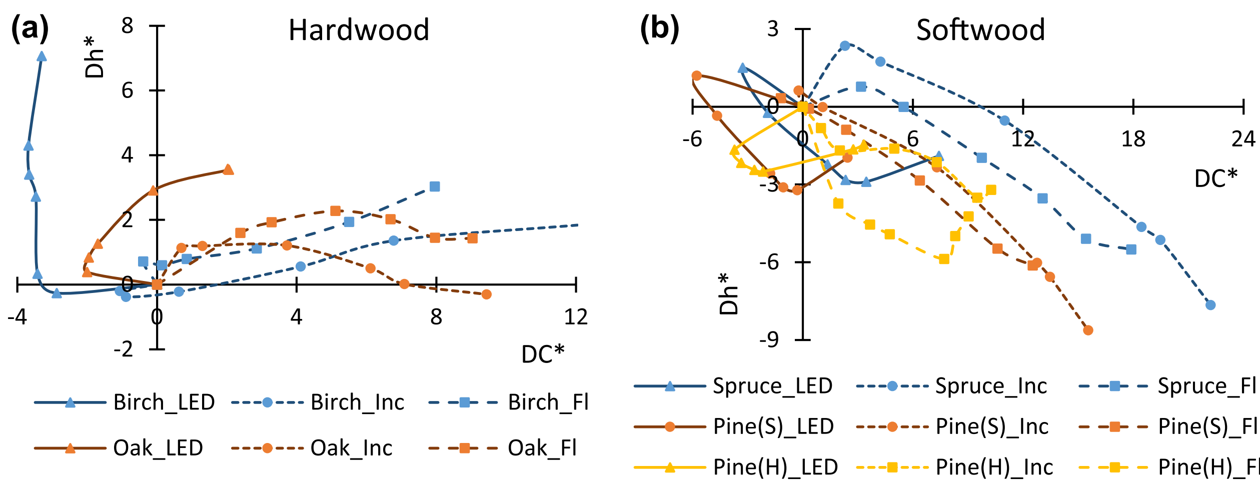

Fig. 6 Changes in chroma (*DC**) and hue (*Dh**) during exposure of hardwoods (**a**) and softwoods (**b**) to artificial light sources: *Inc* incandescent lamp, *Fl* fluorescent lamp, *S* sapwood, *H* heartwood

observed for all light sources in the case of the hardwoods, more pronounced shift to yellowness was associated with exposure to the LEDs, especially in the case of birch. It is suggested that the yellowing of wood is governed mainly by photochemistry of lignin [27]. Contrary, only negative *Dh** values indicating shift towards the redness axis *a** were detected for the pine heartwood which could be associated with the relatively high content of extractives, since an increase of the ratio of the redness (*a**) component is associated with transformations in wood extractives [27]. Reversion in *Dh** was observed for pine sapwood and spruce with an initial increase followed by decrease for all light sources. A similar reversion with initial yellowing followed by shift toward red was observed for softwoods also by Tolvaj and Mitsui [9]. Here it should be noted, that the hue angles of the initial colour of all tested woods were in the range of 70°–85° (Additional file 2) indicating strong dominance of yellowness. Therefore, the new hue of the colour resulting from an angle shift even of 10° to the red axis (negative *Dh** values) may still be characterised by yellow rather than red hue.

Regarding the changes in colour saturation, although slight fluctuation was observed for birch in the early stage of irradiation, overall positive *DC**values for all woods exposed to the incandescent and fluorescent lamps indicate that irradiation with these light sources resulted in evolution of a more saturated colour than the initial one. Regardless of wood species, exposure to LEDs led to considerably lower changes in chroma compared to the counterparts exposed to the other lamps. For all woods, except birch, reversion in *DC** during exposure to LEDs can be seen, where the decrease was changed by an increase, resulting in positive *DC** values at the end of the experiments. In the case of birch, moderate decrease was observed during the early stage, which was ensued by virtually constant *DC** for the further irradiation.

Conclusion

The results of the experiments in which the wood was exposed to different types of artificial light can be summarized as follows:

- Although greater discolouration was caused by LEDs in the initial phase of exposure, less colour changes were observed in wood exposed to LEDs than incandescent and fluorescent lamps for higher irradiation doses, suggesting that the LEDs are more acceptable to keep wood discolouration at a lower level. An exception was pine heartwood, for which LEDs caused much greater colour changes than for other woods. In addition, high variation in total discolouration values was observed between pine heartwood exposed to LEDS, which could be caused by differences in the content of light sensitive extractives, however, further research is needed to verify that. Comparing the effect of warm and cool LEDs, notably lower discolouration posed by warm LEDs was observed only at low irradiation dose, while the difference practically levelled off with increasing doses.
- The tested softwoods were more sensitive to discolouration caused by all tested artificial light sources than the hardwoods included in the study. More substantial difference in discolouration between softwoods and hardwoods was found for incandescent and fluorescent lamps.

- The changes in wood shade depend on both the wood substrate and the light source, which varies considerably depending on the accumulation of the irradiation dose. The difference in chromaticity changes indicates that the overall appearance of wooden objects composed of different woods, including sapwood and heartwood of the same species, may be irreversibly altered by exposure to artificial light.

Abbreviations
CCT: Correlated colour temperature; CIE: Commission Internationale de l'Eclairage (International Commission on Illumination); IR: Infrared; LED: Light-emitting diode; UV: Ultraviolet.

Supplementary Information
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Additional file 1: Fig. 1. Spectral power distribution for the light sources used in experiments: Inc – incandescent lamp, Fl – fluorescent lamp.

Additional file 2: Table 1. Colour parameters (CIELA colour space) of unexposed wood with standard deviations in parentheses. **Table 2**. Average colour parameters corresponding to the highest DE values observed during the experiments. **Fig. 1**. Reflectance spectra of unexposed wood

Additional file 3: Fig. 1. Discolouration caused by exposure of pine heartwood to LED 6500 K versus content of extractives in wood from these boards.

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Author contributions
DC: conceptualised the research, designed the methodology, wrote the main manuscript text; EK: curried out the experiments, processed the data, analysed the results; IA: reviewed and edited the manuscript; BA: supervised the research, ensured the funding acquisition. All authors contributed to the final draft. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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