The Impact of Drying Conditions on the Surface Color Changes of Pine Wood

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The article presents the impact of drying process and selected parameters on the color changes on the surface of pine wood (*Pinus sylvestris* L.). Three predetermined process conditions (modes), mild, normal, and intensive, were investigated. The experiments were conducted using a semi-industrial scale dryer designed at the Gdańsk University of Technology with a loading capacity of 0.55 m^3. The drying process was applied to pine wood grown in the northern part of Pomeranian region in Poland. The specimens were selected taking into consideration the radial angle of the growth rings. During each drying mode, 25 pieces of wood with dimensions (thickness, width, length) of 0.03 m, 0.2 m, and 1.5 m, respectively, were dried. The total color change (ΔE) after drying process and color saturation (h^*) before and after drying processes of the wood surface was determined using the normalized CIELAB methods. The obtained results indicated that the color change of the pine wood surface increased simultaneously with the intensification of the drying process. However, the normalized wood quality after drying under intensive drying process conditions remained within the standard limits. The application of intensive drying process conditions remarkably changes the surface color of the obtained material, while remarkably reducing the drying process duration.

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Keywords: Wood drying; High temperature wood drying; Drying conditions; Pine wood; Surface color changes; Moisture content

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INTRODUCTION

The wood color changes that occur during the drying process are a well-known fact. The development of kiln drying schedules for the industrial drying of timber has resulted in a general increase of drying temperatures. It is also connected with advantages such as shorter drying time, fewer cracks, and less deformation. The main consequences of higher drying temperatures are color changes and darkening of wood, but also an increase of resin flow, especially around knots. The color of wood is one of the main criteria for assessing its quality, which impacts how wood products are perceived by customers, particularly in furniture, decorative products, decorative veneers, and flooring; thus, accurate matching of the color of different samples is required (Torres *et al*. 2010). Drying temperature, time, time in the capillary drying phase, and water content are parameters that influence the color change (Sundqvist 2000). Sundqvist (2002) discovered that the coloration of the wood had the same intensity during drying when there was moisture content above the fiber saturation point (FSP) even when there was moisture content in the wood under the FSP. Another feature of the drying process is that the color change in pine wood increases markedly at drying temperatures above 70 °C, probably depending on the resin content (Tarvainen *et al.* 2001). According to Abrahão (2005) the color uniformity in wood is significantly important in its quality evaluation as it determines the final appearance of the wood product. The color expression often means a subjective experience dependent on the available light source, surface properties, and the individual viewer's eye. To study color changes, color must be measured in an objective way. Objective color measurement is performed instrumentally in a way that corresponds to visual assessment, using spectrophotometers or colorimeters and is defined numerically based on the standardized colorimetric calculation developed by the International Commission on Illumination (CIE) (Barański *et al.* 2017, 2020). During processing, wood undergoes mechanical treatment, as well as drying or thermal modification, both of which substantially influence on changes in its natural color and chemical composition (Gonzalez de Cademartori *et al.* 2013; Gonçalez *et al.* 2014; Barcík *et al.* 2015). Significant changes in wood structure occur after exceeding a temperature of 180 °C, while the carbonization process begins at a temperature of 250 °C (Kačíková and Kačík 2011).

Instrumental methods for determining colorimetric parameters, color differences are subject to ISO standards, which are also applicable in Poland. These standards include definitions of basic concepts, requirements for colorimetric systems, the fundamentals of colorimetric calculation, and information for correctly conducting instrumental color measurement (Kazimierska 2014).

Colorimetric measurement is valuable in wood quality control and in evaluating the color of end wood products subjected to high-temperature drying process (Klement and Huráková 2015). The mechanism behind color change is a complex process influenced by various factors (Kudra *et al.* 2003; McCurdy *et al.* 2005; McDonald *et al.* 2010).

The aim of the conducted experimental research was to determine the impact of selected parameters of drying process (modes), such as: relative air humidity, temperature etc. on the surface color changes (ΔE), and color saturation (h^*) on the pine wood (*Pinus sylvestris* L.), which was dried to the final moisture content about 8%.

MATERIALS AND METHODS

The drying modes were conducted in the experimental facility of semi-industrial kiln of 0.55 m^3 load capacity, specially designed at the Gdańsk University of Technology, Poland (Figs. 1 and 2).

Steam production was implemented using a steam generator. The provision of necessary heat was supplied to kiln, thanks to hot flue gas, by a heat exchanger placed inside the drying kiln. The heat exchanger was supplied by exhaust gas generated during natural gas combustion process in the combustion chamber. The heat exchanger and electric steam generator made it possible to keep a constant temperature and relative humidity, respectively, inside the kiln during experiments.

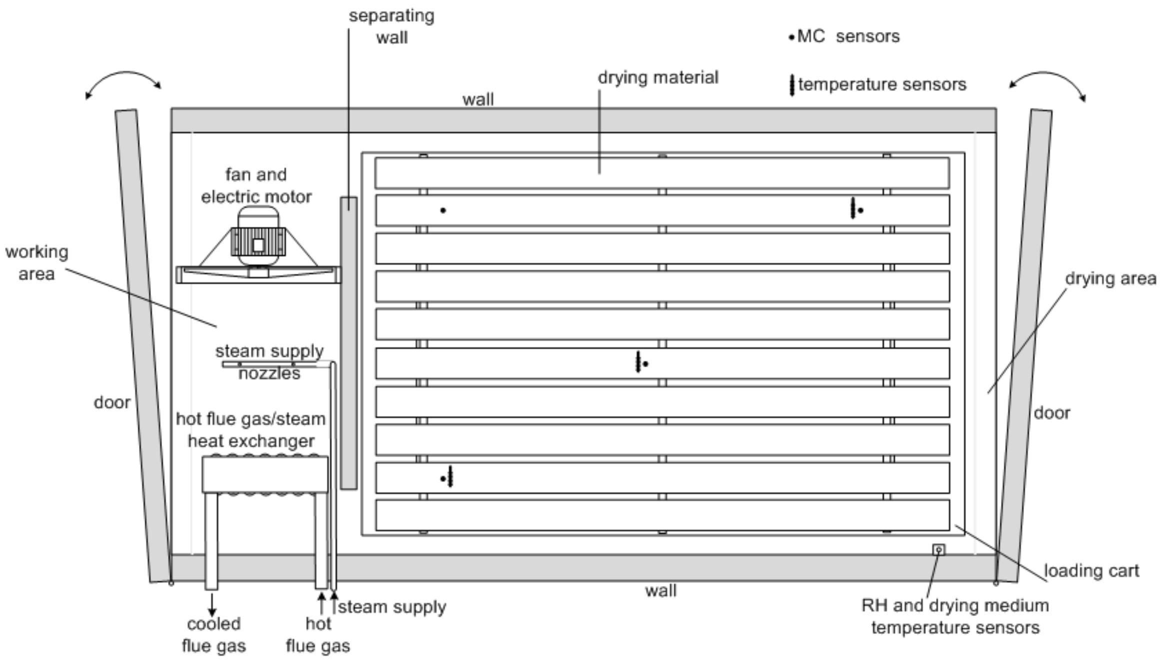

Fig. 1. Semi-industrial drying kiln - top view

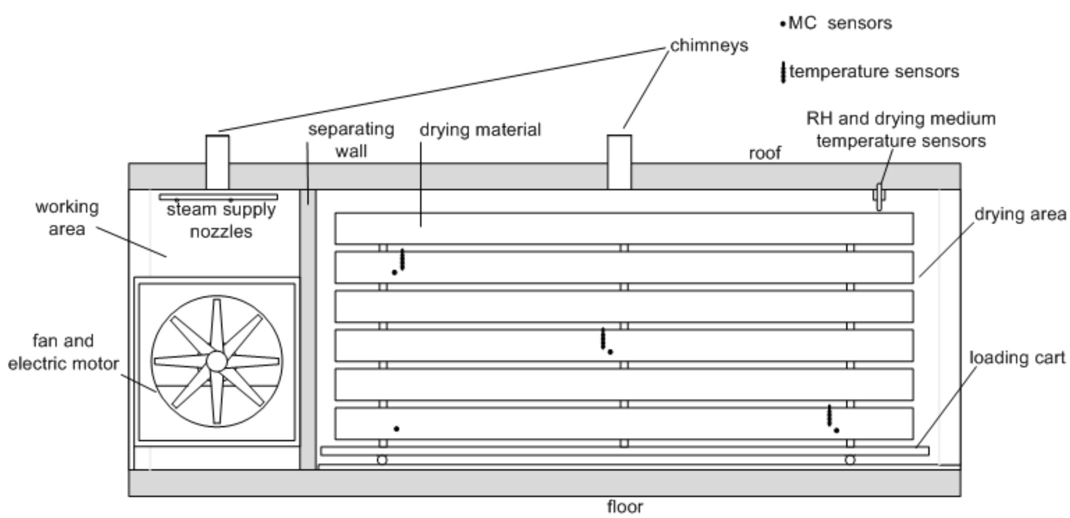

Fig. 2. Semi-industrial drying kiln - side view

Steam circulation inside the drying kiln was forced *via* a circulating fan with drying medium's velocity regulation up to 5.0 m/s. Fan and heat exchanger were located in the working area of kiln separated from the drying area by the wall. The two chimneys on the roof of the kiln controlled the drying conditions inside. The drying kiln was customized to dry all timber types and to obtain the final moisture content not exceeding 8%. The control system, which controls and monitors the drying process, was located outside the kiln. It contains four thermocouples to measure temperature inside the kiln and the wood in three chosen locations in dryer, respectively. The system also monitored the level of wood moisture content in eight different locations inside the stack of the drying material such as the midsection and outer layers, and the humidity of the environment inside the kiln, respectively.

The drying medium parameters inside the kiln were measured using E+E humidity and temperature sensor type EE31 with accuracy of ± 1.3% for humidity and 0.2 °C for temperature, respectively. The drying procedure was conducted using a two-stage process, overseen by the control system (Barański 2018; Klement *et al.* 2019).

The moisture content of each dried wood sample was measured using a TANEL Co. (TANEL) resistance-based moisture content meter type WRD 100, that has a measurement accuracy of ± 2%. Prior to and following the drying procedure, samples were checked for the absolute moisture content through the gravimetric method (Eq. 1). This method relied on the use of RADWAG Co. (RADWAG) precision balance type PS 510.R1, that has a measurement accuracy of 0.005 g. The achievement of absolute dryness for the samples occurred within a laboratory kiln operating at a controlled temperature of 103 ± 2 °C. The moisture content was computed using the Eq. 1,

$$w = \frac{m_{w-} m_0}{m_0} \times 100, \tag{1}$$

where w is the moisture content (%), m_w is the weight of the wet sample (g), and m_o is the weight of the absolute dry specimen (g).

To be able to dry the wood well and quickly, it is necessary to set the drying parameters correctly to set a lower equilibrium moisture content (EMC) than the moisture content (MC) of wood. This relation is called the drying gradient (U) and is calculated according to the Eq. 2:

$$U = \frac{MC}{EMC}, \tag{2}$$

where U is the moisture gradient, EMC refers to equilibrium moisture content (%), and MC is moisture content (%).

In general it can be said that a higher moisture gradient causes faster drying, but on the other hand more defects will be present in the wood as a result of faster drying. The drying gradient is decisive for both the quality of the dried wood and economy.

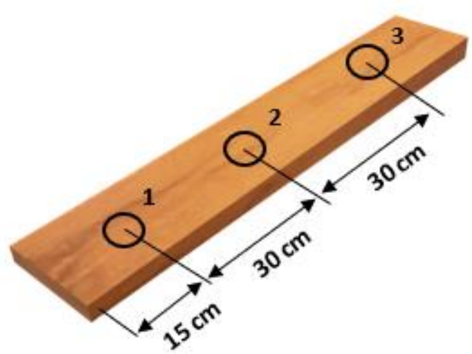

Fig. 3. The explanatory figure of the wood sample used for measuring color changes

Materials used for experiments were 75 pieces of pine samples (*Pinus sylvestris* L.) originating from the same location of northern part of Pomeranian region in Poland. The specimens were selected based on the radial angle of the growth rings. During each drying mode 25 pieces of samples were dried. The dimensions of the tested samples were as follows: 30 mm thickness, 200 mm width, and 1500 mm length. Numerical values of color coordinates for a specified light source were then expressed in three-dimensional (3D) color space according to the CIE standard. The color parameters (L, a^*, b^*) were measured in three chosen locations before the drying and after the drying on each of tested samples, respectively shown in Fig. 3. The color was measured in distance from the edge of the sample was 15 cm and every 30 cm. All together, three measurements were done.

The pine wood was dried under different drying modes with various conditions that are outlined in Tables 1, 2, and 3. The distance from the edge of the sample was 15 cm and every 30 cm were the measurement of color.

Table 1. Parameters of the Drying Medium Used for the Mild Drying Process

Absolute Wood Moisture Content	Air Temperature	Equilibrium Moisture Content	Drying Gradient	Psychrometric Difference	Relative Air Humidity
MC	t_s	EMC	U	Δt	φ
(%)	(°C)	(%)	(-)	(°C)	(%)
> 40.0 to 26.0 (FSP)	50.0	11.3	3.5 to 2.3	6.3	70.0
25.9 to 8.0	60.0	9.1	2.3 to 1.1	9.0	62.0

Table 2. Parameters of the Drying Medium for the Normal Drying Process

Absolute Wood Moisture Content	Air Temperature	Equilibrium Moisture Content	Drying Gradient	Psychrometric Difference	Relative Air Humidity
MC	t_s	EMC	U	Δt	φ
(%)	(°C)	(%)	(-)	(°C)	(%)
> 40.0 to 26.0 (FSP)	70.0	9.0	4.4 to 2.9	9.0	65.0
25.9 to 8.0	80.0	7.5	2.9 to 1.3	11.7	60.0

Table 3. Parameters of the Drying Medium for the Intensive Drying Process

Absolute Wood Moisture Content	Air Temperature	Equilibrium Moisture Content	Drying Gradient	Psychrometric Difference	Relative Air Humidity
MC	t_s	EMC	U	Δt	φ
(%)	(°C)	(%)	(-)	(°C)	(%)
> 40.0 to 26.0 (FSP)	90.0	14.1	2.8 to 2.6	2.8	90.0
25.9 to 18.0	90.0	10.0	2.6 to 1.8	7.3	75.0
17.9 to 8.0	120.0	4.0	3.5	20.0	3.0

In this study, the color change of dried wood was assessed using a three-axis system (Fig. 4), measuring the lightness (L^*) and chromaticity coordinates (a^*, b^*), in accordance with ISO 11664-2 (2007) and ISO 11664-4 (2008) standards. The CIE-recommended CIELAB color system consists of two axes with parameters a^* and b^*, positioned at a right angle to each other, defining the color hue. The third axis represents lightness L^*. It is perpendicular to the a^* b^* plane.

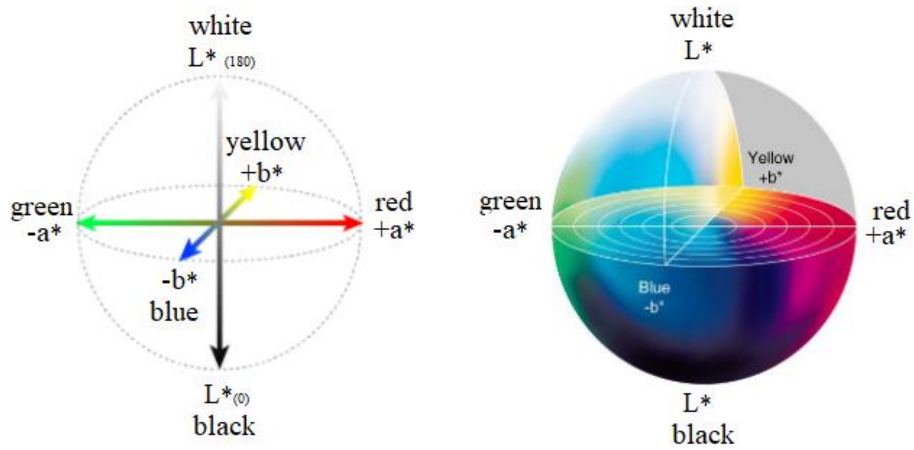

Fig. 4. Schematic of three-axis color change measurement system (Barański *et al.* 2020)

To measure color changes CIELAB Color spaces were determined with the use of the Color Reader CR-10, Konica Minolta Company.

The parameter h^* defines the hue of the wood color and is one of the key properties contributing to wood color analysis, defined (in the CIECAM02 model) as "the degree to which a stimulus can be described as similar or dissimilar to stimuli described as red, green, blue, and yellow". Hue can also be quantified (Eq. 3), using a single number, often corresponding to an angular position around the central or neutral point or axis in the color space coordinate system (Fig. 5),

$$h^* = \tan^{-1}\frac{b^*}{a^*} \tag{3}$$

where h^* is the parameter determining the hue of the wood where 0° is red, 90° is yellow, 180° is green, and 270° is blue, b^* is the parameter determining the color of wood in the yellow-blue direction ($-$]), and a^* is the parameter determining the color of wood in the red-green direction ($-$]).

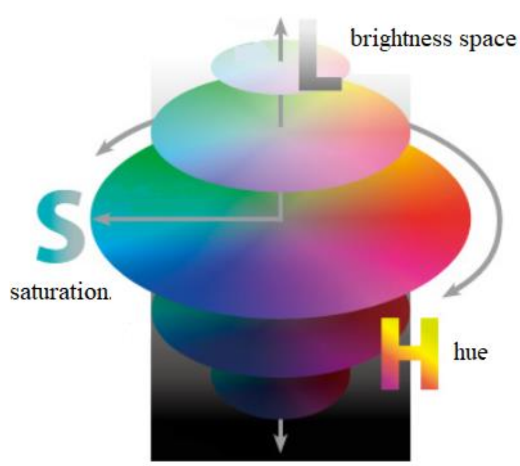

Fig. 5. Description of color change in the hue, saturation, and brightness space (Canon Inc.)

The change in wood color before and after drying (expressed in the CIELAB color space) can be compared using the total color difference ΔE, which represents the distance between these colors in the three-dimensional CIELAB space (Fig. 6).

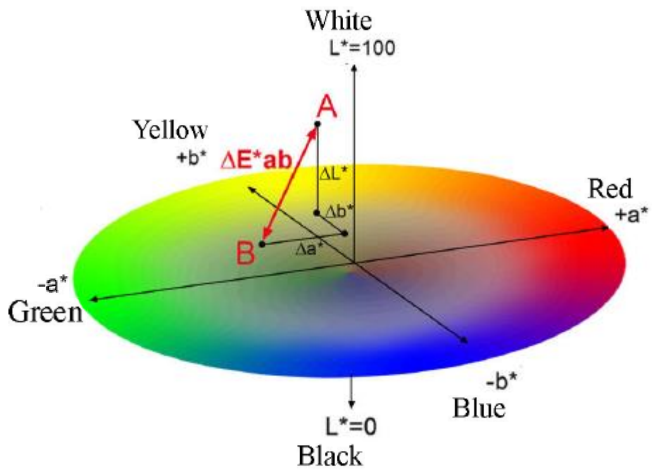

Fig. 6. Schematic of total wood color change evaluation described by the parameter ΔE^* (Barcík *et al.* 2015)

Color differences in the CIE space can be straightforwardly determined by calculating their spatial distance, equal to the square root of the sum of the squares of differences for each of the three coordinates of the two compared colors, according to the relationship (in accordance with ISO 11664-4 (2008) and ISO 11664-6 (2022) standards,

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{4}$$

where ΔE^* is the parameter determining the total wood color change after drying (%), ΔL^* is the difference of the parameter determining the color change after drying in the white-black direction, Δa^* is the difference of the parameter determining the color change after drying in the red-green direction, Δb^* is the difference of the parameter determining the color change after drying in the yellow-blue direction.

The total color change ΔE^* calculated using Eq. 4 was determined according to the criteria described (Cividini *et al.* 2007), concerning the distribution of color changes (Table 4).

Table 4. Criteria for Distribution of Color Change (Cividini *et al.* 2007)

ΔE^* Value (-)	Color Change Description (-)
$\Delta E^* < 0.2$	Undetectable difference
$0.2 < \Delta E^* < 2.0$	Slight difference
$2.0 < \Delta E^* < 3.0$	Color change visible with a high-quality filter
$3.0 < \Delta E^* < 6.0$	Color change visible using a medium-quality filter
$6.0 < \Delta E^* < 12.0$	Significant color changes
$\Delta E^* > 12.0$	Different color

To illustrate the research methodology, a statistical analysis (STATISTICA, file version 12.0.1133.15, StatSoft CR s.r.o., Australia) was conducted for each of the samples, determining mean, maximum, and minimum values as well as standard deviation. Subsequently, a statistical analysis was performed using the Duncan test and box plots.

RESULTS AND DISCUSSION

The measurement data presented in Tables 5, 6, and 7 provide a summary of the results of the total color change for the tested samples after drying using three drying programs.

Table 5. Results of Total Color Change Measurement for Mild Drying

Value	Measured Parameters Before Drying			Measured Parameters After Drying			Total Color Change
	*L**	*a**	*b**	*L**	*a**	*b**	ΔE^*
Mean	70.6	9.1	29.9	74.6	6.7	26.5	6.4
Maximum	76.1	12.1	35.6	78.5	9.1	29.9	9.9
Minimum	67.6	7.1	26.1	70.2	4.1	23.5	3.9
Standard Deviation	2.6	1.5	3.3	2.5	1.5	1.7	2.0

Table 6. Results of Total Color Change Measurement for Normal Drying

Value	Measured Parameters Before Drying			Measured Parameters After Drying			Total Color Change
	*L**	*a**	*b**	*L**	*a**	*b**	ΔE^*
Mean	77.0	6.7	25.6	74.3	8.0	29.2	4.8
Maximum	77.9	7.8	28.5	76.0	9.3	31.9	6.9
Minimum	76.1	5.1	23.9	72.1	7.0	26.5	3.1
Standard Deviation	0.5	0.8	1.7	1.3	0.7	1.4	1.1

Table 7. Results of Total Color Change Measurement for Intensive Drying

Value	Measured Parameters Before Drying			Measured Parameters After Drying			Total Color Change
	*L**	*a**	*b**	*L**	*a**	*b**	ΔE^*
Mean	74.2	6.6	24.9	65.2	12.0	33.3	13.9
Maximum	76.5	7.5	27.6	69.5	16.5	45.9	27.7
Minimum	72.4	5.7	22.0	59.2	8.5	27.4	7.0
Standard Deviation	1.3	0.5	1.5	3.2	2.3	5.1	5.6

From the results, it was observed that the color change of pine wood after drying, as indicated by the ΔE^* value, increased when the process was performed at temperatures above 100 °C, where the air and superheated steam mixture were used as drying medium. It was found that the temperature of the drying environment had the most remarkable effect on the color change of wood. Temperatures up to 80 °C were used for both mild and normal drying, while the difference in those drying modes was not great. For this reason, a smaller ΔE difference could be measured in normal mode than in mild mode. The wood itself also had a certain influence on the measured values in terms of its natural color and remarkable annual rings. In the intensive drying mode, the temperature of the drying environment from 90 to 120 °C was used, which also caused the greatest change, as indicated by ΔE. This relationship was also observed by other researchers (Unsal *et al.* 2003; Esteves *et al.* 2008; Gonzalez de Cademartori *et al.* 2013), who subjected eucalyptus and pine wood to thermal modification, as well as to the rectification processes (Moura and Brito 2011). These authors also noted that the average values of the a* and b* parameters decreased with increasing drying temperature, which was confirmed by this study. The other way around, the results of (Sundqvist 2002) showed that colorization was most intense at the wood surface, and color homogeneity was not affected by raised temperatures during drying.

Figure 7 presents a bar chart illustrating the color change of pine wood after drying under three conditions mild, normal, and intensive, defined by the ΔE parameter. The color change of pine wood was the smallest for the normal drying process (mean ΔE^* value of 4.81(-), with a standard deviation of 1.1(-)). The most significant color change was obtained during the intensive drying process (mean ΔE^* value of 13.9 (-), with a standard deviation of 5.6(-)).

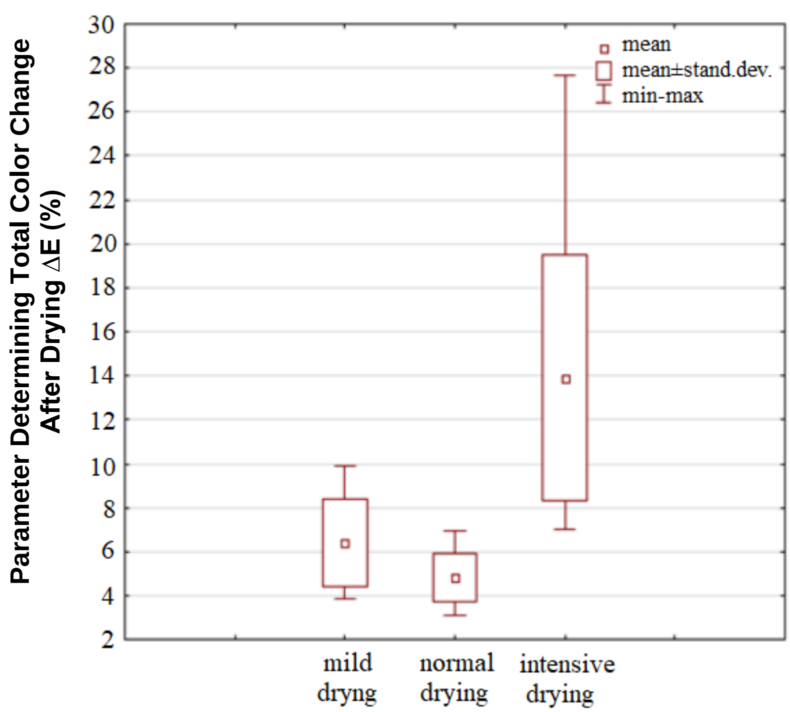

Fig. 7. Bar chart depicting the color change of wood after drying under three programs: mild, normal, and intensive, defined by the parameter ΔE*

Table 8 presents a quantitative summary of the dried pine wood boards showing specific quality criteria considering the total color change resulting from the application of three different drying conditions. All types of drying contributed to the total color change of the wood surface, which is visible using a medium-quality or higher-grade filter.

Table 8. Distribution Percentages of the Dried Pine Wood Batch Based on the Total Color Change for the Utilized Drying Methods

		Mild	Normal	Intensive
$\Delta E^* < 3.0$	Invisible or small or visible with a high-quality filter	0.0%	0.0%	0.0%
$3.0 < \Delta E^* < 6.0$	Visible with a medium quality filter	56.7%	76.7%	0.0%
$6.0 < \Delta E^* < 12.0$	Noticeable color change	43.3%	23.3%	56.7%
$\Delta E^* > 12.0$	Different color	0.0%	0.0%	43.3%

Based on the obtained results, an increase in the intensity of the drying process led to a more pronounced color change in the dried material. The obtained results indicate a strong statistical dependence ($p \approx 0$). Duncan's test (Table 9) confirmed a significant statistical difference in the total color change of wood after drying using intensive drying conditions compared to the other conditions (mild and normal). The drying program involving a mixture of air and superheated steam at temperatures above 100 °C requires an increased relative air humidity in the initial stage of the process and its significant reduction as the drying medium temperature exceeds 100 °C. This can lead to an increase in the ΔE^* parameter value, which translates to a more pronounced color change.

Table 9. Duncan's Test for the Total Color Change of Pine Wood Depending on the Used Drying Program

		Mild	Normal	Intensive
		ΔE_1^*	ΔE_2^*	ΔE_3^*
Mild	ΔE_1^*	-	0.083619	0.000114
Normal	ΔE_2^*	0.083619	-	0.000053
Intensive	ΔE_3^*	0.000114	0.000053	-

Figures 8, 9, and 10 provide a visual interpretation of the change in hue and color saturation of wood in a 2-dimensional space resulting from the drying process.

Mild and normal wood dryings resulted in a slight change in hue (h^*) and color saturation (C_{ab}^*) of pine wood compared to intensive drying (Table 10). The chosen parameters for gentle and normal drying led to a change in the hue of the tested pine wood towards the red spectrum (Figs. 8 and 9). For intensive drying of pine wood, both the hue and color saturation underwent a more substantial change towards the yellow spectrum (Fig. 10). Gonçalez *et al.* (2014), showed that drying of tropical wood species appeared to inversely reduce wood lightness.

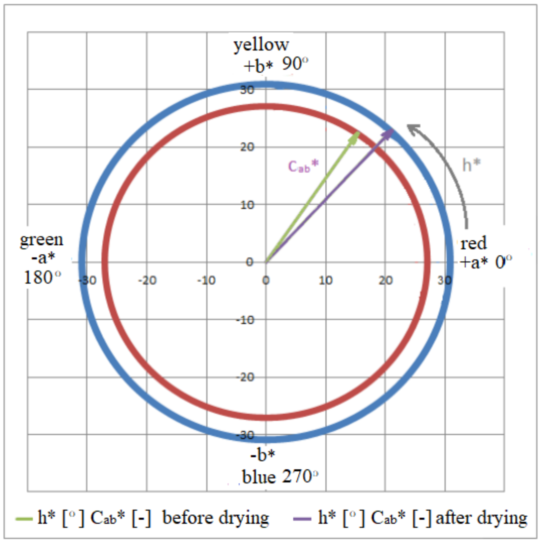

Fig. 8. The average change in hue (h^*) and color saturation of pine wood (C_{ab}^*) after mild drying

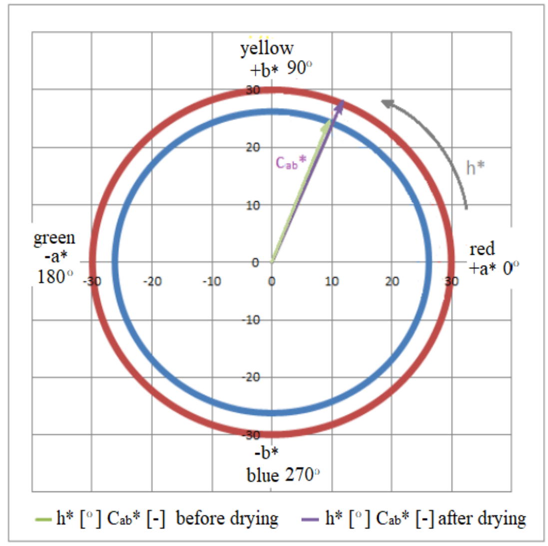

Fig. 9. The average change in hue (h^*) and color saturation of pine wood (C_{ab}^*) after normal drying

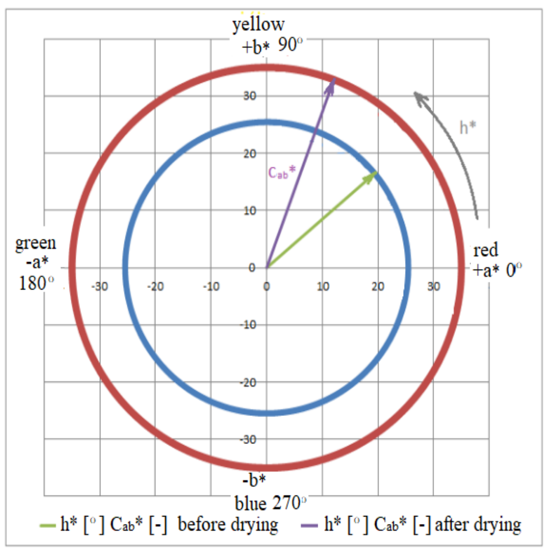

Fig. 10. Average change in hue (h^*) and color saturation of pine wood (C_{ab}^*) after intensive drying

Table 10. Average Values of the Coefficients Describing Hue (h^*), Color Saturation (C^*_{ab}), and Lightness of Saturation (S_{ab}) of Pine Wood Before and After Drying

	Average Values of the Parameters Before Drying			Average Values of the Parameters After Drying		
	h^*	C^*_{ab}	S_{ab} (%)	h^*	C^*_{ab}	S_{ab} (%)
Mild	73.0	31.3	40.4	76.0	27.4	34.5
Normal	75.3	26.5	32.5	74.7	30.3	37.3
Intensive	75.0	25.7	32.8	70.1	35.4	47.6

CONCLUSIONS

1. Results indicated a much stronger negative effect of intensive drying on the lightness (L) value. It seems important that lower intensities of drying had much less effect on L value.
2. The obtained results showed a significant difference in the total color change (ΔE) of wood after drying using intensive drying conditions comparing to other drying modes (mild and normal).
3. The drying schedule involving an air and superheated steam mixture at temperatures above 100 °C require a higher relative air humidity value in the initial stage of the drying process and its significant reduction as the drying medium temperature exceeds 100 °C. That leads to an increase in the ΔE^* value.
4. Mild and normal drying modes of wood resulted in a slight change in the hue (h^*) and color saturation (C_{ab}^*) of pine wood (towards red color) in relation to intensive drying. After the process, the wood had changed its hue (h^*) and saturation (C_{ab}^*) towards a more yellow color.

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