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Homogenization of the Color of Beech Sapwood and False Heartwood by the Steaming Process

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Abstract: This work presents the results of the homogenization of the color of sapwood and false heartwood *Fagus sylvatica* L. into a uniform color shade due to the influence of the temperature of saturated moist air and saturated water steam in individual steaming modes. The results of analyses of the influence of temperature within 24 h point out the different changes in the color of the sapwood and the wood of the false heartwood when the uniform color of the beech wood is achieved by the steaming process. By steaming beech wood with a false heartwood saturated with moist air at a temperature of t_I = 95 °C during τ = 24 h, the color of the sapwood does not merge with the color of the wood of the false heartwood. The sapwood darkens and, on the other hand, the wood of the false heartwood slightly lightens, while the significant color contrast is removed, but the color homogenization in the individual zones does not occur. The unification of the colors in individual zones occurs during the steaming process at a temperature of saturated water steam $t_{II} \approx 105$ °C in 18 h, where the resulting brown color is identified in the color space CIE L*a*b* by the values of the lightness L* = 61.3 ± 2.2 and of the red color a* = 12.4 ± 1.3 and yellow color b* = 19.5 ± 1.4. The most pronounced homogenization of the color occurs through the steaming process at a temperature of saturated water steam $t_{III} \approx 120$ °C, where the wood acquires a uniform dark brown–gray color in a time of $\tau \approx 9$ h steaming. The coordinates of the color-homogenized steamed beech wood are L* = 55.9 ± 1.9, a* = 12.3 ± 1.2, and b* = 19.6 ± 1.3. The unification of the colors by the steaming process is achieved by darkening both the sapwood and the wood of the false heartwood. In the overall color homogenization, the sapwood and the wood of the false heartwood do not participate equally in the steaming process. While the total color difference between the sapwood and a color homogenized state is quantified by the value ΔE_{tI}* = 8, ΔE_{tIII}* = 22.7, the total color difference in the wood with a false heartwood is only ΔE_{tI}* = 1.9, ΔE_{tIII}* = 11.8.

Keywords: beech wood; sapwood; false heartwood; wood steaming; wood color; homogenization of wood color

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1. Introduction

Among the coreless woods with the possibility of forming a false heartwood during the growth of the tree is beech wood, which is included in the group of scattered-porous woods. The most common occurrence of brown–red wood, referred to as false heartwood, is in older trees. Air that penetrates into the trunk oxidizes the soluble carbohydrates and starches found in living or dead parenchymal cells, while the formation of polyphenolic compounds occurs, which penetrate into the neighboring tissue and color the wood [1–7].

The different shapes and positions of the wood of the false heartwood in the cross-section of the trunk led authors [8,9] to divide the false heartwoods in beech wood into the following types: Round, Mosaic, Star, and Flame (centric, eccentric).

The steaming of wood is a technological process in which wet wood is heated by the action of heat in the form of saturated moist air or saturated water steam and changes its physical, mechanical and chemical properties. While temporary physical-mechanical

changes are used in the production of veneers, plywood, bent furniture, or pressed wood, permanent chemical changes manifested by, among other things, a change in color are used to modify the color of the wood into other shades. Recently, the attention of research in the field of thermal treatment of wood has focused on targeted changes in the color of the wood of individual trees to more or less distinct color shades, or wood imitations of domestic trees for exotic woods [10–21].

The color of beech sapwood and mature wood is light white–gray or pale-ochre to white–pink [2,21–25] and brown–red in the zone of false heartwood [2,24,26–28]. The author of [29] numerically documented the visual color differences between the color of sapwood and heartwood through the values of the coordinates of the color space CIE L*a*b* and the total color difference ΔE*. The color difference between sapwood and heartwood ΔE* = 14.1 is classified within the categorization of color differences in the category of significant color changes. The color differences of the wood of the false heartwood from the sapwood are in real practice the reason for the rejection of sawmill assortments with a share of wood of the false heartwood from the production of bent furniture, sports tools and parts for construction and carpentry products.

The aim of this work is based on experimental research aimed at analyzing the changes in the color of sapwood and the color of the heartwood in the color space CIE L*a*b during the process of wood color homogenization by evaporation of atmospheric saturated moist air with temperature t_I = 95 ± 3 °C and saturated water steam with a temperature of t_{II} = 105 ± 3 °C and with a temperature of t_{III} = 120 ± 3 °C to achieve homogenization of the color of the wood after the cross-section.

2. Materials and Methods

Test material in the form of blanks with dimensions of 32 × 50 × 800 mm were produced by longitudinal and transverse sawing from central lumber of thickness h = 32 mm with wood of false heartwood from Pol'ana (Slovakia). A total of 380 sapwood blanks and 380 false heartwood blanks were randomly selected. The blanks were divided into 19 groups so that each group contained 20 sapwood blanks and 20 false heartwood blanks. The cuttings of the first group in number were unsteamed. The other blanks were steamed with saturated moist air at a temperature of t_I = 95 ± 3 °C, or with saturated steam in Mode II with a temperature of saturated water steam $t_{II} \approx 105 \pm 3$ °C and Mode III with a temperature of saturated water steam $t_{III} \approx 120 \pm 3$ °C. Individual cages with steamed wood were removed from the steaming autoclave after steaming τ = 4 h, τ = 8 h, τ = 12 h, τ = 16 h, τ = 20 h and τ = 24 h. The steaming of the wood was carried out in a pressure autoclave APDZ 240 (Himmasch AD, Haskovo, Bulgaria) installed at Sundermann s.r.o. Banská Štiavnica (Slovakia). The steaming conditions of beech wood with a false heartwood with saturated water steam with marked time intervals of sampling during thermal treatment v are shown in the diagram in Figure 1.

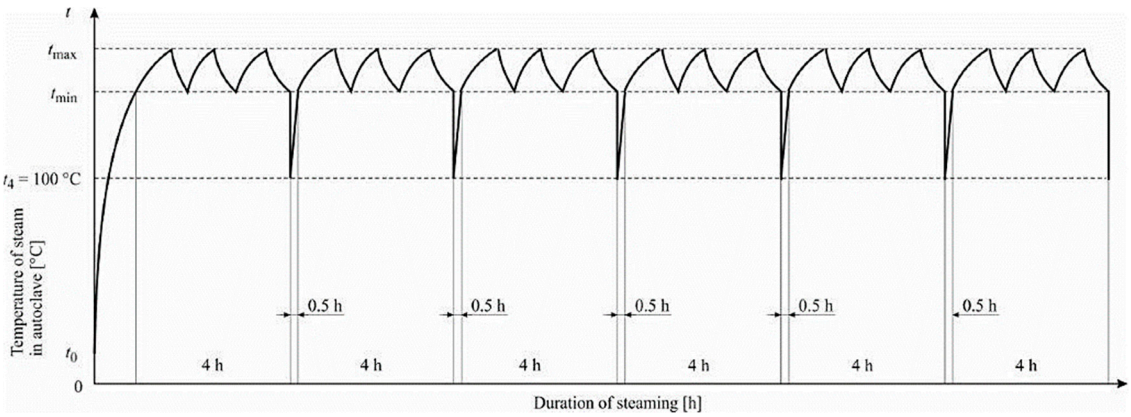


Figure 1. Diagram of wood color homogenization by steaming in a pressure autoclave.

The temperatures of the saturated moist air in Mode I, or of saturated water steam in Modes II and III, are shown in Table 1. Temperatures t_{max} and t_{min} are the temperature intervals in which heat is supplied to the autoclave in the form of saturated water steam to implement the technological process. Temperature t_4 is the temperature of the saturated water steam in the autoclave to reduce the pressure in the autoclave to the limit of atmospheric pressure, which allows the safe opening of the pressure device and the selection of a group of steamed blanks in the specified steaming time.

Table 1. Technological conditions for the homogenization of the color of beech wood in a pressure autoclave.

Temperature of Saturated Water Steam	t_{min} [°C]	t_{max} [°C]	t_4 [°C]	Wood Color Homogenization Time					
Mode I	92	98	92	τ_1 = 4 h	$\tau_{2\,=}$ 8 h *	τ_3 = 12 h *	τ_4 = 16 h *	τ_5 = 20 h *	τ_6 = 24 h
Mode II	102	108	100						
Mode III	117	123	100						

Note: * taking a group of steamed blanks from the autoclave at planned intervals took 0.5 h. The actual steaming time compared to the planned steaming time was extended by the time of the technological breaks.

The unsteamed and steamed beech wood blanks were dried in a hot-air oven according to the [30] mode to a moisture content of 10 ± 2%, with an emphasis on preserving the wood color created by the steaming process. All the dried blanks, whether steamed or unsteamed, were machined on a FS 200 horizontal planer.

Color measurement was performed with a Color Reader CR-10 Plus colorimeter (Konica Minolta, Tokyo, Japan) with a reflection spectrum in the 400–700 nm range. A D65 light source was used and the diameter of the optical-sensing aperture was 8 mm. The color measurement was performed on the milled surfaces of each blank at three points, separately in each homogenization mode and time.

The results of the measured values, lightness L*, red color a*, yellow color b* on the coordinates of the color space CIE L*a*b*, are presented in the form of writing the average measured value $\overline{x}$ and the standard deviation s_x.

$$x = \overline{x} \pm s_x \tag{1}$$

The color dispersion of the sapwood and wood colors of false heartwood in the color space CIE L*a*b* was determined through the standard deviations s_L, s_a, s_b determined from the measured values of the coordinates of the color space according to the equation ΔE_{sx}* in the form:

$$\Delta E_{sx}{}^{*} = \sqrt{(s_L)^2 + (s_a)^2 + (s_b)^2} \tag{2}$$

The differences between the average color values of the coordinates of the color space of the false heartwood L^*_{hw}, a^*_{hw}, b^*_{hw} and sapwood L^*_{sw}, a^*_{sw}, b^*_{sw} in the individual phases of the steaming process were evaluated through the color difference ΔE_1* in the form:

$$\Delta E_1^* = \sqrt{\left(L^*_{hw} - L^*_{sw}\right)^2 + (a^*_{hw} - a^*_{sw})^2 + \left(b^*_{hw} - b^*_{sw}\right)^2} \tag{3}$$

The differences between the average color values of the unsteamed $\overline{L_1}$, $\overline{a_1}$, $\overline{b_1}$ and steamed wood $\overline{L_2}$, $\overline{a_2}$, $\overline{b_2}$ in the sapwood zone and the false heartwood zone were evaluated through the total color difference ΔE*:

$$\Delta E^* = \sqrt{(\overline{L_1} - \overline{L_2})^2 + (\overline{a_1} - \overline{a_2})^2 + \left(\overline{b_1} - \overline{b_2}\right)^2} \tag{4}$$

3. Results and Discussion

The light white–gray color of the sapwood beech wood and the brown–red color of the wood of the false heartwood will change over the course of 24 h steaming with saturated moist air at a temperature of $t_I = 95 \pm 3$ °C, changing to a pale brown color. The color of sapwood beech wood and wood with a false heartwood changes over 24 h of steaming with saturated steam at temperatures $t_{II} = 105 \pm 3$ °C and $t_{III} = 120 \pm 3$ °C, changing to brown–gray color shades. The colors of beech wood before steaming and after steaming are shown in Figure 2.



Figure 2. Color of sapwood and heartwood before steaming and after 24 h during the steaming process in individual modes.

The course of the changes in the color of sapwood and false heartwood at individual coordinates of the color space depending on the steaming process with saturated moist air at a temperature of $t_I = 95 \pm 3$ °C and saturated water steam at temperature of $t_{II} = 105 \pm 3$ °C and temperature $t_{III} = 120 \pm 3$ °C is shown in Figures 3–5.

From the changes in the color space, it follows that the biggest changes are in the lightness coordinate L*. At all the temperatures of the steaming process, the lightness of the sapwood decreased from the value $L_0^* = 78.5$ at the steaming temperature $t_I \approx 90$ °C to the value $L_{I\text{-}24}^* \approx 71.0$ at the steaming temperature $t_{II} \approx 105$ °C to the value $L_{II\text{-}24}^* = 60.5$ and at the vaporization temperature $t_{III} \approx 120$ °C to $L_{III\text{-}24}^* = 47.5$. The darkening of the sapwood beech in the steaming process is caused by hemicellulose hydrolysis processes, their partial breakdown and an increase in the lignin content of the steamed wood [20,21,31,32].

The lightness of the wood of false heartwood L* varied in the opposite direction during steaming. While during the steaming of false core wood with saturated moist air at temperature $t_I \approx 95$ °C, the lightness of the wood increased from the value $L_0^* = 63.8$ to the value $L_{I\text{-}24}^* = 65.5$, the wood became lighter, so by steaming false heartwood beech with saturated water with steam at a temperature of $t_{II} \approx 105$ °C, the lightness value did not change, it oscillated around the value of $L_0^* = 63.8 \pm 2.6$, and at a steaming temperature of $t_{III} \approx 120$ °C, it decreased from the value of $L_0^* = 63.8$ to the value of $L_{III\text{-}24}^* = 49.0$, which was manifested by the darkening of the wood.

The lightening of the wood of the false heartwood in the first $\tau = 12$ h of steaming at temperature $t_I \approx 95$ °C points to the instability of the chromophore system of the wood of the false heartwood created by the enzymatic processes of peroxidase and polyphenoloxidase, which are responsible for the oxidation of phenolic compounds and the characteristic coloration of the wood of the false heartwood [15,33,34].

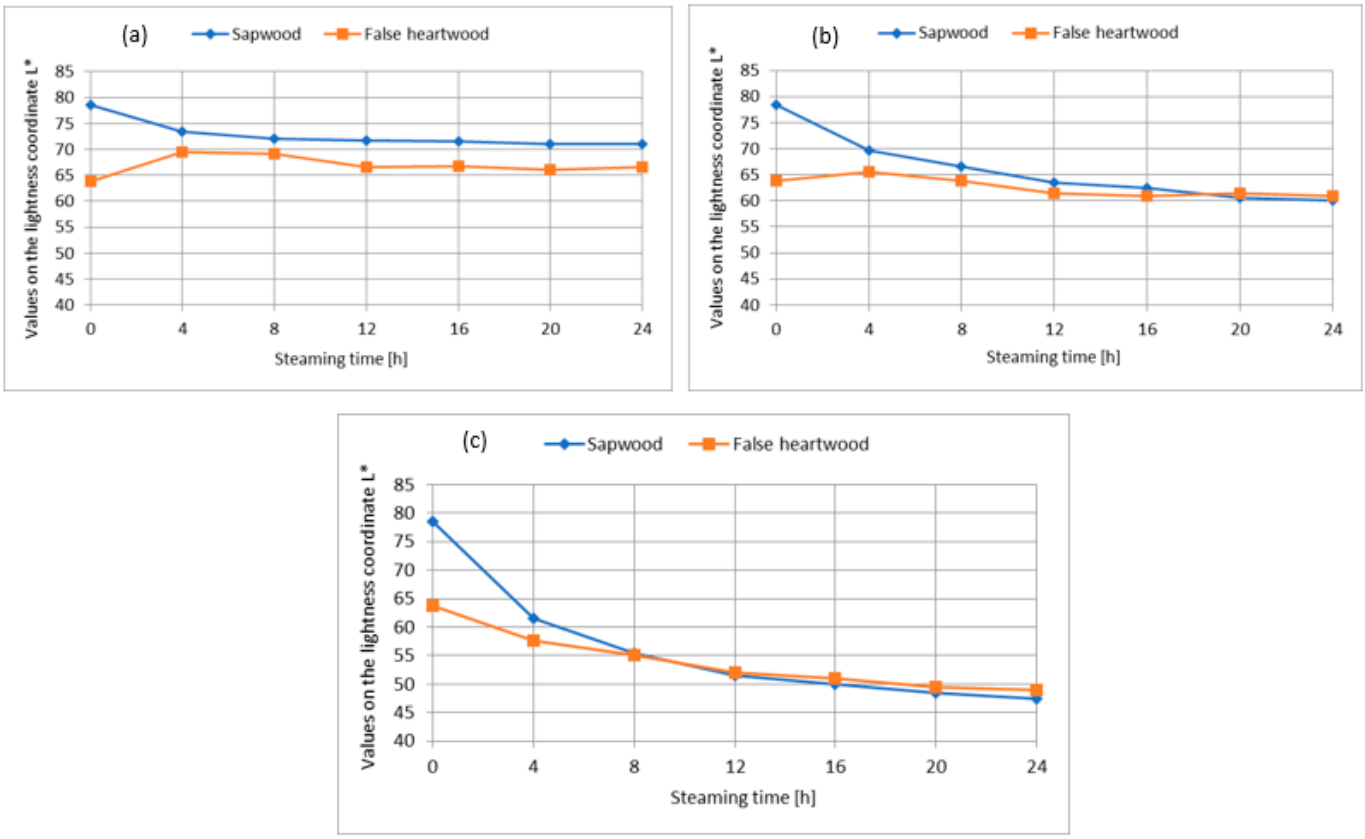


Figure 3. (**a**) Course of changes on the coordinate L* during steaming with saturated moist air with temperature t = 95 °C; (**b**) Course of changes on the coordinate L* during steaming with saturated water steam at temperature t = 105 °C; (**c**) Course of changes on the coordinate L* during steaming with saturated water steam at temperature t = 120 °C.

The changes in the red color coordinate a* during τ = 24 h of steaming of beech wood indicate certain differences in the color of the sapwood and the wood of the false heartwood. The sapwood, in the process of steaming at temperature $t_I \approx 90$ °C, recorded an increase in the values of the red color coordinate in the first τ = 12–16 h from the value $a_0^* = 9.2$ to the value $a_{16}^* \approx 12.1$. During the steaming of beech sapwood at the steaming temperatures $t_{II} \approx 105$ °C and $t_{III} \approx 120$ °C, the value of the red coordinate of the red color in the first hours of steaming increased by $\Delta a^* \approx 3.5$, which was visually manifested by the reddening of the wood, and consequently, the value of the red color of the steamed wood did not change.

In terms of the coordinate of the red color a* of the false heartwood, the value increased from $a_0^* = 11.5$ to the value $a_8^* = 12.4$ in the first τ = 8 h of steaming. Subsequently, the values of the red color coordinate did not change, similarly to sapwood.

The values of the yellow coordinate b* did not change during the steaming of beech wood in the temperature interval t = 95–105 °C. For sapwood, the values of the yellow color coordinate oscillated around the value $b^* \approx 19.5$, and for the heartwood, around the value $b^* \approx 19.9$. The stated finding is similar to that reported by the authors of [15] in their work. At the steaming temperature $t_{III} \approx 120$ °C, a slight decrease in the values by $\Delta b^* \approx 1.0$ was recorded for both the steamed sapwood and steamed wood with false heartwood.

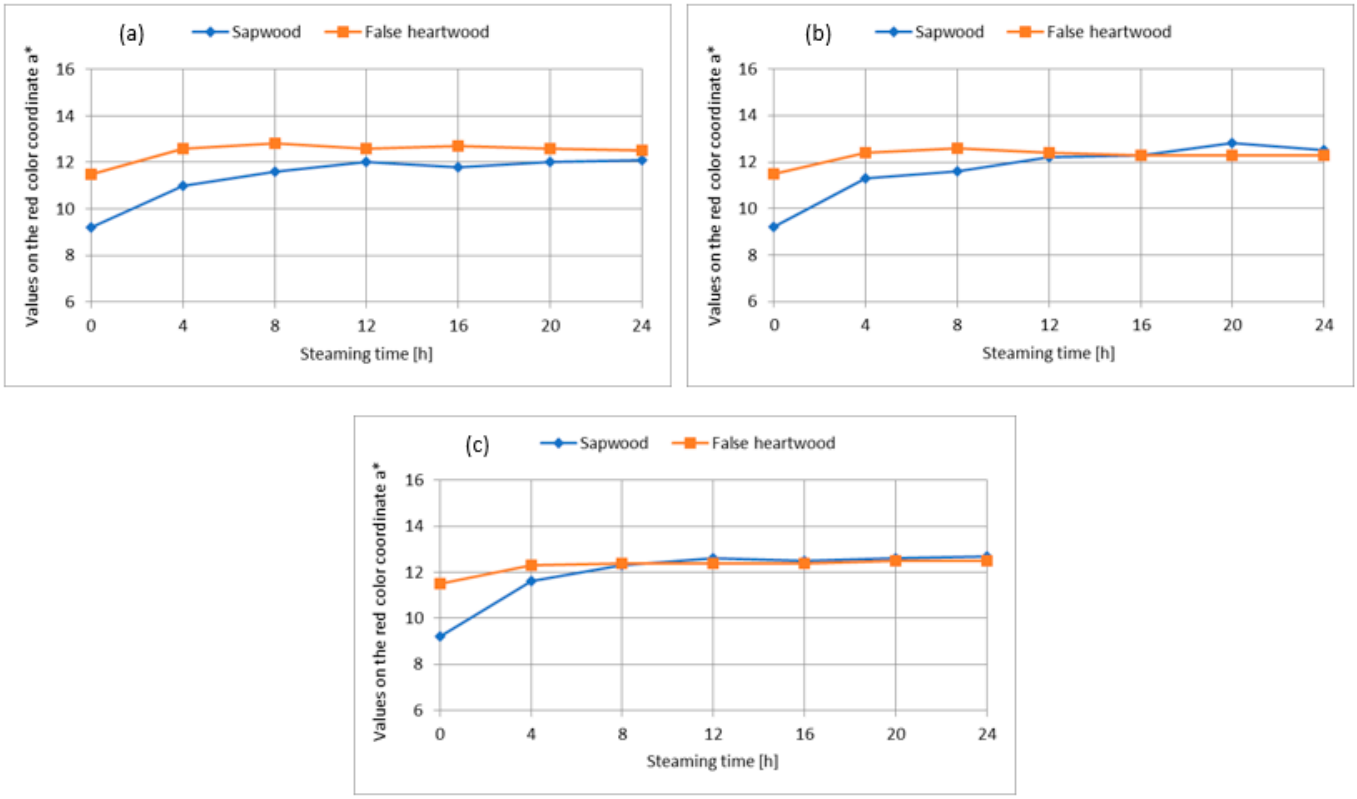


Figure 4. (**a**) Course of changes on the coordinate a* during steaming with saturated moist air with temperature t = 95 °C; (**b**) Course of changes on the coordinate a* during steaming with saturated water steam at temperature t = 105 °C; (**c**) Course of changes on the coordinate a* during steaming with saturated water steam at temperature t = 120 °C.

From the changes in the lightness coordinate L* and the chromatic coordinates of the red color a* and yellow color b* in Figures 3–5, it follows that the uniform color of the steamed sapwood and wood of false heartwood is not the same, both from the aspect of the steaming time and the achievement of a uniform color. As the steaming temperature increases, the time required for color uniformity decreases. At the same time, the darkness of the brown or brown–gray color of the steamed beech wood, despite the shortened steaming time, increases.

Table 2 shows the technological parameters of the wood steaming process in which the unification of the color of the sapwood and the false heartwood occurs, such as the steaming temperature, minimum steaming time required to achieve unification of the colors of steamed beech wood, values of the coordinates of the color space CIE L*a*b*, differences between the color of sapwood and the color of false heartwood ΔE_1*, and the dispersion of the color of sapwood and wood of false heartwood ΔE_{sx}*.

Table 2. Measured and calculated values of the color homogenization in the steaming process of sapwood and false heartwood beech.

Beech Wood		Steaming Time [h]	Values in the Color Space CIE L*a*b*			The Difference between the Color of Sapwood and False Heartwood	Dispersion of Wood Color
			L*	a*	b*	ΔE_1*	ΔE_{sx}*
Unsteamed	Sapwood	0	78.5 ± 2.5	9.2 ± 1.6	19.5 ± 1.8	14.8	3.5
	False heartwood		63.8 ± 3.6	11.5 ± 1.8	19.9 ± 1.6		4.3
Mode I t_I = 95 ± 3 °C	Sapwood	24	71.0 ± 2.1	12.1 ± 1.2	19.3 ± 1.5	5.5	2.8
	False heartwood		65.5 ± 2.8	12.5 ± 1.6	19.5 ± 1.4		3.5
Mode II t_{II} = 105 ± 3 °C	Sapwood	18	61.5 ± 1.9	12.5 ± 1.2	19.4 ± 1.4	0.4	2.6
	False heartwood		61.2 ± 2.3	12.3 ± 1.4	19.6 ± 1.4		3.0
Mode III t_{III} = 120 ± 3 °C	Sapwood	9	56.0 ± 1.8	12.3 ± 1.1	19.5 ± 1.2	0.3	2.4
	False heartwood		55.8 ± 2.1	12.4 ± 1.3	19.7 ± 1.4		2.8

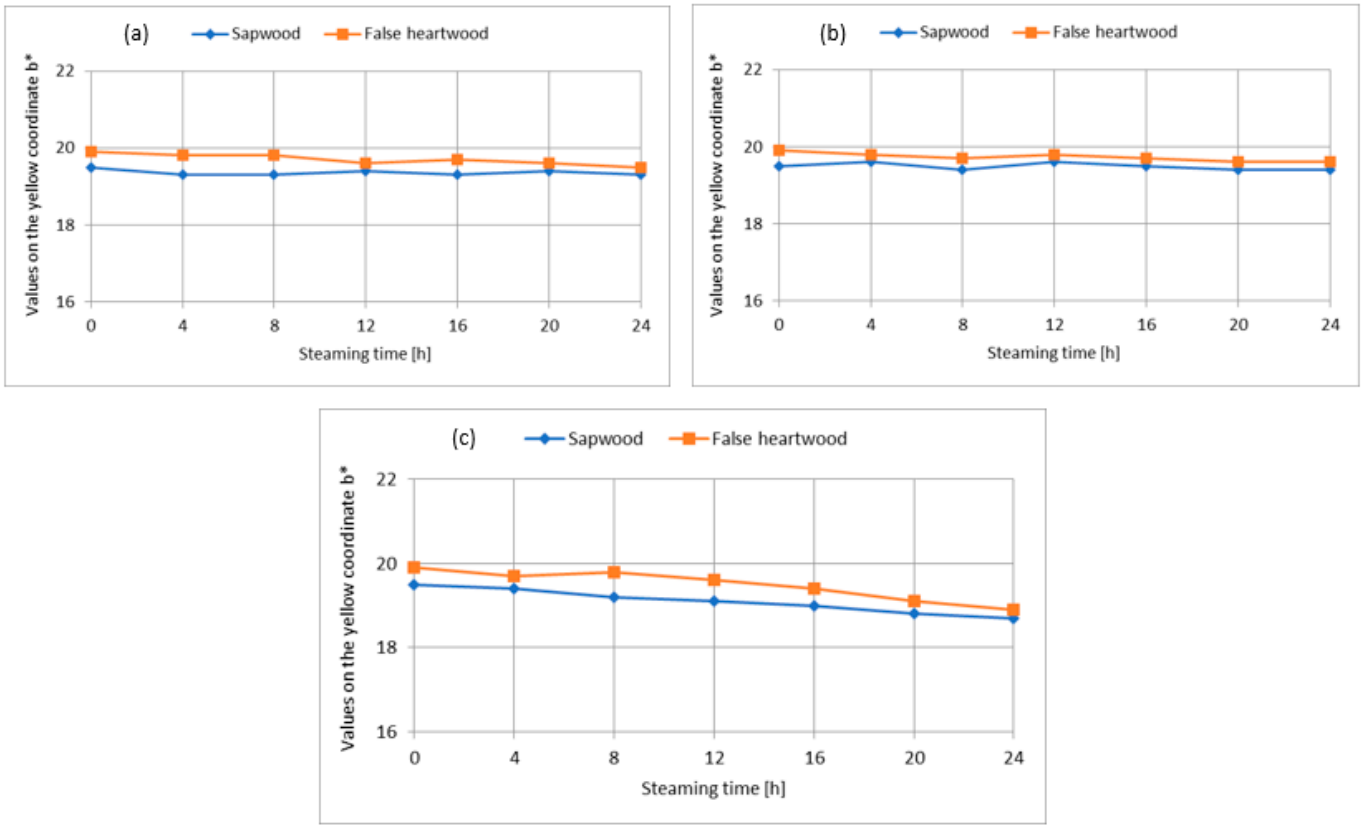


Figure 5. (**a**) Course of changes on the coordinate b* during steaming with saturated moist air with temperature t = 95 °C; (**b**) Course of changes on the coordinate b* during steaming with saturated water steam at temperature t = 105 °C; (**c**) Course of changes on the coordinate b* during steaming with saturated water steam at temperature t = 120 °C.

The process of homogenizing the color of beech wood at the individual steaming temperatures is characterized by the following findings:

(a) By steaming beech wood with saturated moist air with a temperature of t_I = 95 °C, the unification of the color of the sapwood with the false heartwood does not occur within

τ = 24 h. The sapwood darkens and takes on a pale brown color. The heartwood has lightened to a darker shade of pale brown than the sapwood. However, the significant color contrast between the sapwood zone and the heartwood zone, which is ΔE_1^* = 14.8 for unsteamed wood and reduced to ΔE_1^* = 5.5 for steamed wood at the steaming temperature t_I = 95 °C, is removed. The mentioned changes occur in beech wood by a decrease in the values on the lightness coordinate by ΔL^* = −7.5 and an increase in the values of the red color coordinate by Δa^* = +3.1. For wood with a false heartwood, the values increase, both for the lightness coordinate by ΔL^* = +2.7 and for the red color coordinate by Δa^* = +1.0.

(b) Through the process of steaming beech wood with saturated water steam at a temperature of $t_{II} \approx 105$ °C, the unification of the colors of sapwood and false heartwood occurs after 18 h of the technological process. The average values of the unified color of steamed sapwood and false heartwood in the color space are CIE L*a*b*: L* = 61.3 ± 2.2, a* = 12.4 ± 1.3 and b* = 19.5 ± 1.4. The mentioned uniform coloring of the steamed wood is achieved by the significant darkening of the sapwood and slight darkening of the wood of the false heartwood. The degree of darkening of steamed beech wood is quantified by the decrease in the values on the lightness coordinate by ΔL^* = −17.0 and the increase in the values on the red color coordinate by Δa^* = +3.3, the slight darkening of the steamed wood of the false heartwood quantifies the decrease in the value of the lightness coordinate by ΔL^* = −2.6 and the increase in the value of the red color official by Δa^* = +0.8.

The low color difference value ΔE_1^* = 0.4 expressing the difference between the color of steamed sapwood and the color of steamed false heartwood proves the elimination of the color differences between the colors of the steamed sapwood and steamed false heartwood.

The values of the color dispersion of steamed sapwood ΔEhw_{sx}^* = 2.6 and steamed wood of false heartwood ΔEhw_{sx}^* = 3.0 do not exclude the slight color variation of the wood of steamed blanks made from the zone of sapwood or the zone of false heartwood.

The color of the boundary line darkens under the stated steaming conditions, highlighting the interfaces between steamed sapwood and steamed false heartwood.

(c) Unification of the colors of the sapwood with the wood of the false heartwood by the process of steaming with saturated water steam with temperatures $t_{III} \approx 120$ °C to a dark brown–gray color occurs after 9 h of steaming. The average values of the dark brown–gray color of steamed beech wood in the color space are L* = 55.9 ± 1.9, a* = 12.3 ± 1.2, b* = 19.6 ± 1.3. The unification of the colors by the steaming process is achieved both by a decrease in the values of the coordinate of the lightness of the sapwood by ΔL^* = −22.5 and of the false heartwood by ΔL^* = −15.2, as well as by an increase in the values of the coordinate of the red color of the sapwood by Δa^* = +3.1 and wood with false heartwood by Δa^* = +0.9.

The high degree of agreement between the color of steamed sapwood and the color of steamed wood of a false heartwood is characterized by the color difference value ΔE_i^* = 0.3.

A certain color diversity of the color-homogenized beech wood blanks is attributed to the dispersion of the colors of steamed sapwood ΔEhw_{sx}^* = 2.4 and steamed false heartwood ΔEhw_{sx}^* = 2.8.

The homogenized color of steamed beech wood at a temperature of $t_{III} \approx 120$ °C is significantly darker compared to the homogenized color of steamed beech wood at a steaming temperature of $t_{II} \approx 105$ °C.

From the changes in the lightness coordinate L* and the coordinates of the red color a* and yellow color b* of the sapwood and wood of the false heartwood from the beginning of steaming to the time when color homogenization is achieved in Figures 3–5, it seems that the sapwood and the false heartwood do not share equally in the unification of the colors of the sapwood and the false heartwood during the steaming process. This stated fact is clearly documented by the size of the changes in the color of the sapwood and the wood of the false heartwood, as expressed in the form of the total color difference ΔE^* in Figure 6.

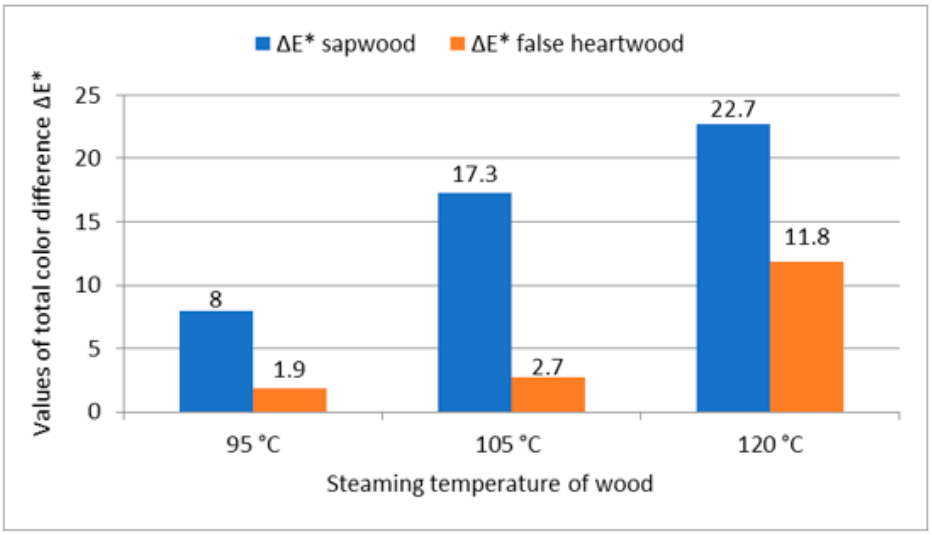


Figure 6. Magnitudes of the changes in the color of sapwood wood and false heartwood wood by the steaming process after homogenization at individual temperatures.

The changes in the color of the false heartwood caused by the steaming process are at all the steaming temperatures significantly lower than the changes in the color of the steamed sapwood. The share of the color change of false heartwood wood by the steaming process at temperatures t_I = 95 °C and t_{II} = 105 °C is approximately six times lower and at the temperature t_{III} = 120 °C it is approximately two times lower than the color change achieved by the steaming process of beech sapwood.

4. Conclusions

The results of analyses of the influence of temperature within 24 h of the steaming process of beech sapwood and false heartwood show certain different changes in the color of the sapwood and false heartwood when the uniform color of beech wood is achieved by the steaming process.

By steaming beech wood with false heartwood saturated with moist air at a temperature of t_I = 95 °C during τ = 24 h, the color of the sapwood does not unify with the color of the wood of the unsteamed false heartwood. The sapwood darkens and takes on a pale brown color. The heartwood lightens to a darker shade of pale brown than the sapwood. There is a significant color contrast between the color of the blanks from the white wood zone and the color of the blanks from the heartwood zone, which for unsteamed wood is ΔE_1^* = 14.8 and for steamed wood at the steaming temperature t_I = 95 °C, is ΔE_1^* = 5.5.

The unification of the colors of the sapwood and the wood of the false heartwood in the process of steaming with saturated water steam with a temperature of $t_{II} \approx 105$ °C occurs at 18 h. The brown color created by the evaporation process is identified by the values of the lightness coordinate L* = 61.3 ± 2.2, the red color a* = 12.4 ± 1.3 and the yellow color b* = 19.5 ± 1.4. The mentioned uniform coloring of the steamed wood is achieved by the significant darkening of the sapwood and slight darkening of the wood of the false heartwood.

Sapwood and false heartwood steamed with saturated steam at a temperature of $t_{III} \approx 120$ °C acquire a uniform dark brown–gray color in a time of $\tau \approx 9$ h steaming. The coordinates of the color homogenized steamed beech wood are L* = 55.9 ± 1.9, a* = 12.3 ± 1.2, b* = 19.6 ± 1.3. The unification of the colors through the steaming process is achieved by darkening the wood, both in the sapwood zone and in the false heartwood zone.

The unification of the colors by the steaming process is not evenly distributed in the individual modes between sapwood and heartwood. While the total color difference of sapwood to a color homogenized state is quantified by the value ΔE* = 8.0 at the steaming temperature of saturated moist air with a temperature of t_I = 95 °C and at the steaming

temperature of saturated water steam at the steaming temperature t_{III} = 120 °C by the value of ΔE* = 22.7, for wood with false heartwood at the steaming temperature t_I = 95 °C, the total color difference is only ΔE* = 1.9, and at the steaming temperature t_{III} = 120 °C, ΔE* = 11.8.

Author Contributions: Conceptualization, L.D.; methodology, L.D., M.D.; software, M.D.; formal analysis, L.D., M.D.; resources, L.D., M.D.; data curation, L.D., M.D.; writing—original draft preparation, L.D.; writing—review and editing, L.D., M.D.; visualization, M.D.; project administration, L.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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