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Effects of an innovative densification process on mechanical and physical properties of beech and Norway spruce veneers

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Abstract

Increased wood density is obtained by compressing the wood porous structure under suitable moisture and temperature conditions to improve its physical, mechanical and color properties. A recently proposed wood densification method based on partial removal of lignin and hemicellulose in hot water solution of sodium hydroxide and sodium sulphite has shown promising results on solid wood. However, its applicability and effect on thin wood veneers have not been tested yet. In this study, the timing of the method has been adapted to estimate the densification treatment intensity dependence of wood properties (wood density and modulus of elasticity) and color change of softwood (Norway spruce) and hardwood (beech) veneers. Compared to control, density and rigidity increased, with improved wood properties peaking after only 90 s of treatment intensity. Furthermore, the color became darker after treatment compared to control, with no significant color difference between treatment intensities. In conclusion, densification of veneers, according to the presented adapted method, provides a significant improvement of veneers physical and mechanical properties, and produces color changes perceptible by the human eye. Our results can be further implemented and adapted to application in industrial plants, calling for new application of densified veneers.

Keywords: Wood densification, MOE, Wood color, Veneers, Wood density

Introduction

The improvement of physical and mechanical properties of low-density wood has been pursued since the beginning of last century when hydrothermal and thermal treatments, and impregnation or densification processes were designed [1, 2]. Among these processes, densification is obtained by compressing wood in transverse direction causing cell lumina to obliterate and wood density to increase [3]. The increased wood density should then translate into increased wood mechanical performances [4–9]. Densification by compression can be preceded by heating wood at high temperatures [10], or softening it with hot steam [2, 11, 12] or by chemical treatments or impregnation with resins [13–15]. Wood densification is mainly applied to low-density and low commercial value wood, to replace performing [2], and often environmentally threatened wood species [16]. Recently, Song et al. [17] described the results of an innovative wood densification process. The new procedure relies on the different stability of cellulose, hemicellulose and lignin against a water solution of sodium hydroxide (NaOH) and sodium sulphite (Na_2SO_3). After a chemical bath in the water solution, wood is then compressed to reduce its volume up to 80%, increasing its density and greatly improving its mechanical properties compared to the non-treated wood. The increased values of bending strength, compression and tension parallel to the grain and hardness are impressive [17]. Moreover, after being placed in an environment with a relative humidity of 95% for 128 h, densified wood did not swell [17]. Wooden elements with such improved physical and mechanical characteristics

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could be used in many applications commonly precluded to wood-based products [10, 18], including outdoor applications.

While applied on solid wood, densification has also been experimented to improve veneers properties [11, 19, 20]. Song et al.'s [17] simple and effective strategy would transform veneers directly into a high-performance material with a more than tenfold increase in strength, toughness and ballistic resistance and with greater dimensional stability. This strategy was shown to be universally effective for various species of wood, with processed wood having a specific strength higher than that of most structural metals and alloys, making it a low-cost, high-performance, lightweight alternative [17]. Moreover, in veneers esthetic quality assessment, the color of wood, its modification and its stability over time should be considered [1, 21, 22]. Densified veneers could be applied on a flat support such as wood-based panels or used in the manufacturing of engineered composites such as sandwich panels, taking advantage of the added strength and stiffness from the densified veneer layer(s) [2, 12]. In this study, the solid wood densification process recently proposed by [17] was adapted to be applied on wooden veneers. Densification of veneers is easier compared to solid wood due to the reduced thickness of the samples that allows rapid impregnation by the softening water solution. Since the effectiveness of the densification treatment depends not only on treatment parameters, but also on the wood species and its own anatomical characteristics [1], beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) veneers were used to represent a hardwood and a softwood species. The specific aim of this paper on densified veneers is to quantify changes in veneer density, modulus of elasticity and color in relation to treatment intensity (i.e., treatment time duration). The relative ease of the veneer densification treatment is an important factor when looking at its applicability on an industrial level. Following the obtained results, implementation of the veneer densification process within the wood supply chain could therefore be beneficial as densified veneers could be used as a raw material in the production of panels with improved technological properties.

Materials and methods

Veneer specimens

Veneers were sourced at a local commercial company from commonly traded material. This is reflected in beech veneers being cut along the tangential plane at 0.6 mm thickness (beech veneers are rarely obtained from radial sections), while Norway spruce veneers were cut along the radial plane and were 0.8 mm thick. Samples of 16×4 mm were prepared to evaluate wood mechanical properties and density. A total of 270 samples (120 for beech and 150 Norway spruce) were prepared for density measurement and mechanical testing, including 30 samples for treatment intensity plus a control group (Fig. 1). Color was measured on 60 mm × 60 mm samples, 40 from beech and 50 from Norway spruce veneers. To color test the veneers, within each species, samples were divided into groups of 10 units according to treatment intensity.

Veneer samples preparation, grouping and densification process

The densification treatment used in this study was developed starting from the method developed by Song et al. [17]. Veneer densification was obtained in four consecutive steps: (i) boiling in a sodium hydroxide and sodium sulphite water solution; (ii) rinsing in deionized water; (iii) oven-drying and (iv) densification (Fig. 1). The softening solution was obtained combining in a 1:1 ratio a 2.5 M sodium hydroxide and a 0.4 M sodium sulfite solution as for Song et al. [17]. Treatment intensity of step (i) was defined by the samples immersion time (in seconds) in the softening solution and different times were assigned to each group of 30 samples. Three groups of beech samples were immersed in the softening solution for 60, 90 and 300 s, respectively. The four groups of Norway spruce samples were immersed in the softening solution for 60, 90, 300 and 480 s (Fig. 1). Higher intensities treatment for beech (300 s) and Norway spruce (480 s) samples were made proportional to treatment time used for 44-mm-thick wood blocks [17]. After the immersion in the softening solution, the specimens were bathed in boiling deionized water for 300 s. Samples were then oven-dried at 103 ± 2 °C to prepare them for the final phase of the treatment. While in the oven, samples where kept flat by setting a metal grid on top of them to prevent their deformation (i.e., cupping). Oven-dried samples were sorted out in groups of five and set side by side on a hydraulic press equipped with 100 °C hot plates and compressed perpendicular to the grain under a pressure of about 5 MPa for 300 s. An infrared thermometer was used to ensure that the average temperature during the pressing phase of the densification process was kept at approximately 100 °C.

Three-point bending test

Before mechanical testing, a visual inspection of the samples was carried out to exclude warped samples. After visual inspection, 18 out of 120 beech samples were excluded from mechanical testing due to permanent geometrical deformation. To avoid differences between groups size in Anova test, 6 samples were removed also from the control for a total of 24 removed beech samples.
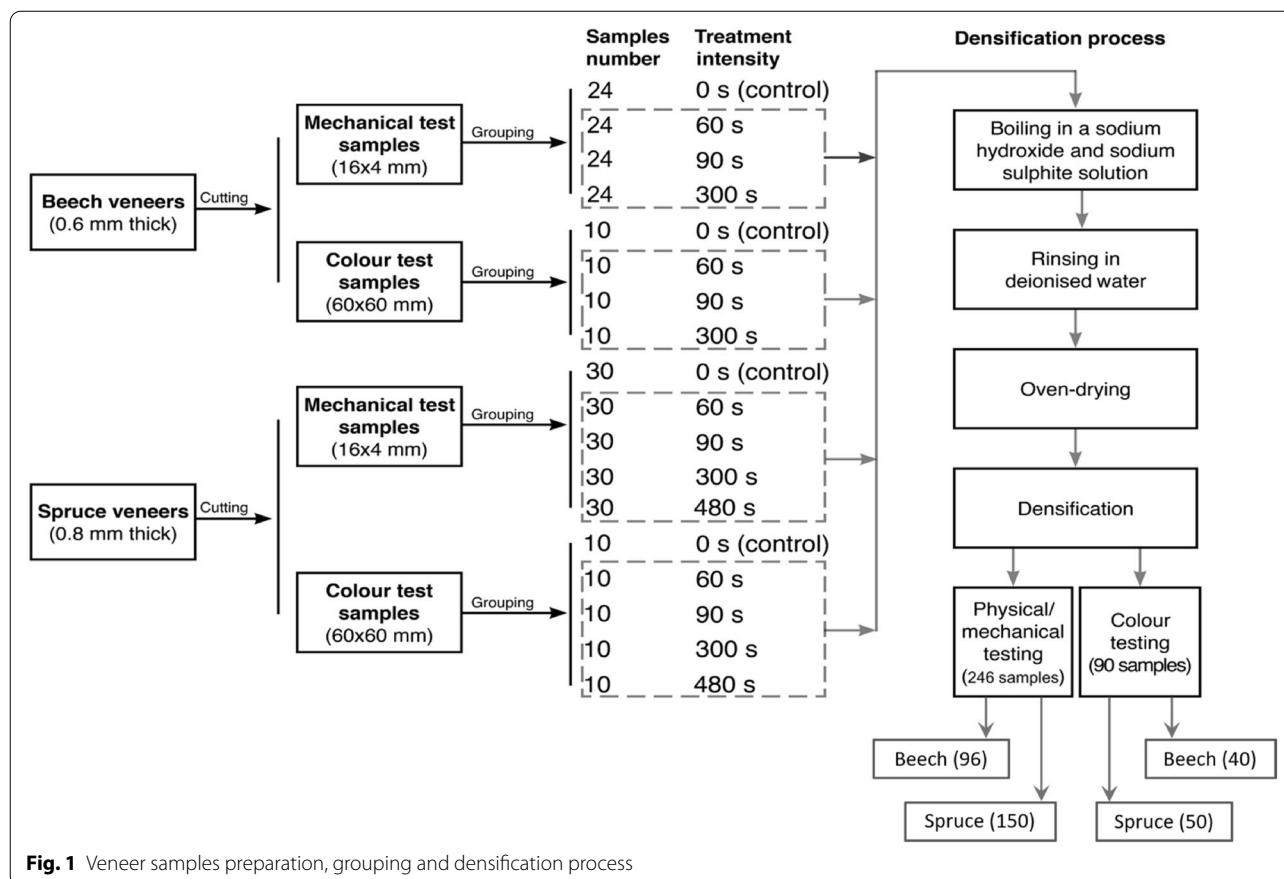
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Fig. 1 Veneer samples preparation, grouping and densification process

The modulus of elasticity (MOE) of the specimens was measured with a thermo-mechanical analyzer (Mettler Toledo TMA/SDTA 840) equipped for a 3-point bending test, with each test lasting for 300 s. During each mechanical test, the specimens were subjected to an alternating force of 0.1/0.5 N with a 6/6 s cycle. The MOE was calculated using the following formula:

$$\text{MOE} = \frac{1}{4\text{b}}\left(\frac{\text{L}^3}{\text{h}^3}\right)\frac{\Delta\text{F}}{\Delta\text{f}}$$

where *b* is the sample width (mm), *L* is the distance between two supports (mm), *h* is the sample thickness (mm), ΔF is the difference between the highest and lowest applied force (N) and Δf is the deformation of the sample (mm).

The small samples of veneers were tested in three points bending using a TMA device because this technique is largely used for preliminary tests on small sample to predict the possible end performance not only of the wood–adhesive system tested [23, 24], but also of the wood without adhesive [25]. The results obtained allow to choose between different treatments and to proceed with the standardized tests only on the samples showing the best results, thus avoiding a waste of time and material.

Veneer density measurement

Veneer density values were calculated as the ratio between oven-dry mass and oven-dry volume as commonly done with wood samples [11]. Oven-dry mass was measured with a laboratory scale balance (0.0001 g). A digital caliper (0.01 mm) was used to measure the dimensions of samples. The sample volume was then calculated according to the generic rectangular prism volume formula.

Color measurement

Color measurements were taken by a handheld colorimeter (Eoptis CLM-194) using a D65 light source and an observed angle of 10 degrees. Three parameters were measured: lightness (L^*), and the red/green (a^*) and yellow/blue (b^*) color coordinates. A mean value for each of the variables was calculated out of five measures on the samples surface, four at the corners and one in the center. The average values for L^*, a^* and b^* for each treatment intensity were then used to calculate ΔL^*, Δa^*, Δb^*. The following formulas were used to compute color difference (ΔE), color saturation (C^*) and hue angle ($h°$):

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$$\Delta E = \sqrt{\left[\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right]}$$

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h^\circ = \arctan\left(\frac{b^*}{a^*}\right)$$

The overall color changes of the densified samples compared to the control samples were evaluated using the International Commission on Illumination (CIE) *L*C*h** (CIELCh) color space system [26].

Statistical analysis

A one-way analysis of variance (ANOVA) was applied to study the influence of the treatment intensity on the sample properties. Fisher–Snedecor (F) test and Shapiro–Wilk test were applied to the data to ensure that the ANOVA requirements were met. In case of ANOVA being significant, Tukey's test was used to compare the means of every treatment to the means of every other treatment for mechanical properties, veneer density and color. All statistical tests were considered significant with *P* value lower than 0.05, analyses were performed in R (Version 1.0.153; [27]). The color differences (ΔE) were

evaluated according to the chart reported by [28], where a ΔE value greater than 2 was considered to be noticeable to an inexperienced observer.

Results and discussion
Veneer density

Densified beech [$F(3, 116) = 50.89$, $p \leq 0.05$] and Norway spruce [$F(4, 145) = 63.62$, $p \leq 0.05$] veneers showed a higher density than the untreated samples (Fig. 2, Table 1). For beech samples (density before treatment: 544 kg m^{-3}), the highest average density values were achieved for treatment intensity of 60 and 90 s, leading, respectively, to 729 kg m^{-3} (34% increase) and 732 kg m^{-3} (35% increase). Among Norway spruce samples (density before treatment: 423 kg m^{-3}), the group that was immersed in the softening solution for 90 s showed the highest average density value of 520 kg m^{-3} (23% increase). Prolonged immersion in the softening solution was associated with a decrease in density for Norway spruce, but still on average higher than control sample for both species (Fig. 2). While in beech prolonged treatment intensity did not significantly increased veneer density, a significantly lower density was observed in Norway spruce for longer treatment intensities. One of the key factors of the densification process used in this study is the partial removal

Fig. 2 Boxplot showing densified beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) veneer density compared to control samples density. The black dot in each box represents the average density value while empty dots represent the outliers for treatment intensity
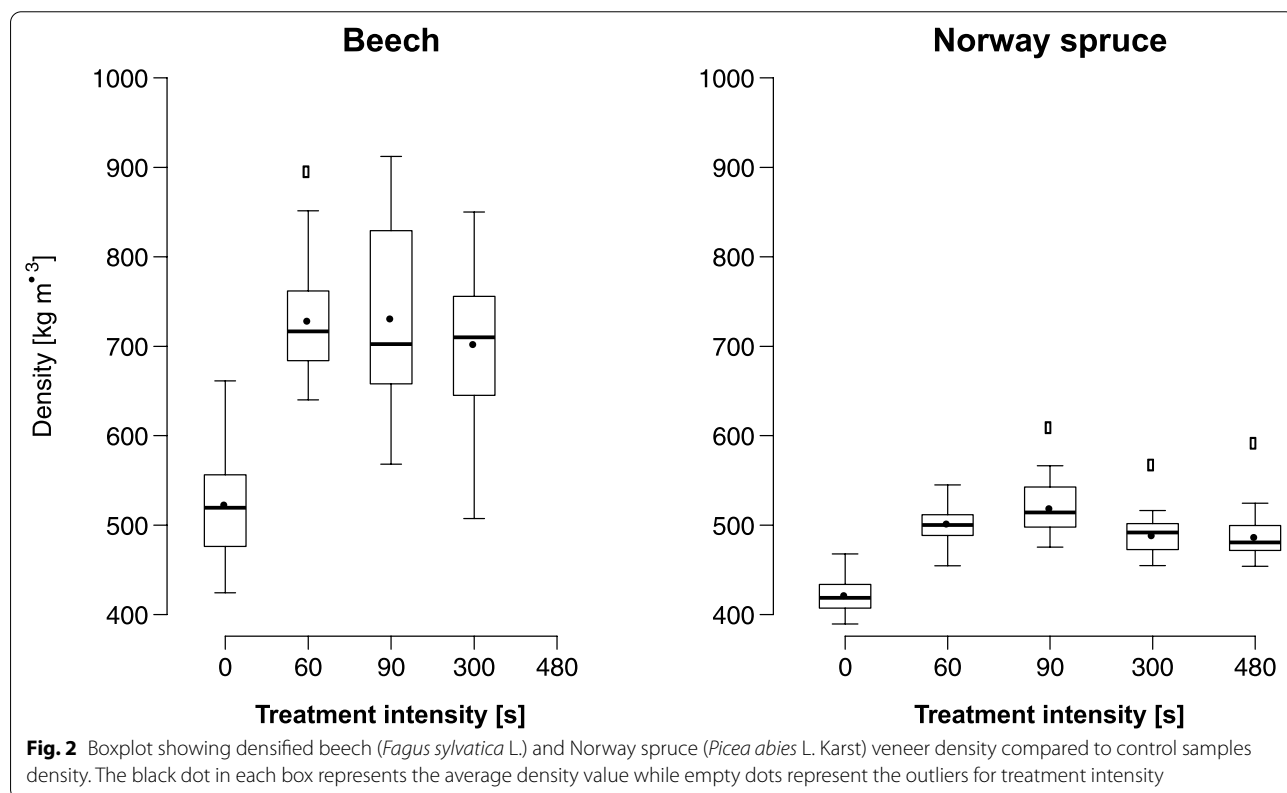
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Table 1 Tukey's test on veneer density data for beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) densified veneer samples

Species	Treatment intensity	Veneer density mean difference	95% confidence interval		P value
			Lower bound	Upper bound	
Beech	90–60 s	205.49	153.99	257.01	< 0.05
	300–60 s	208.06	156.55	259.56	< 0.05
	Control–60 s	179.44	127.93	230.94	< 0.05
	300–90 s	2.56	− 48.95	54.07	0.10
	Control–90 s	− 26.06	− 77.57	25.44	0.55
	Control–300 s	− 28.62	− 80.13	22.89	0.47
Norway spruce	60 s–control	80.07	61.99	98.15	< 0.05
	90 s–control	97.30	79.22	115.38	< 0.05
	300 s–control	66.85	48.77	84.93	< 0.05
	480 s–control	65.05	46.97	83.13	< 0.05
	90–60 s	17.23	− 0.84	35.31	0.07
	300–60 s	− 13.22	− 31.30	4.86	0.26
	480–60 s	− 15.02	− 33.10	3.06	0.15
	300–90 s	− 30.46	− 48.54	− 12.38	< 0.05
	480–90 s	− 32.25	− 50.33	− 14.18	< 0.05
	480–300 s	− 1.80	− 19.88	16.28	0.10

of hemicellulose and lignin from wood that produces mass loss in the samples [17]. Such behavior can also be observed when heat treatment is applied to wood with mass loss proportional to increasing temperature [14, 29], mainly due to the degradation of hemicellulose [30, 31]. In the analyzed samples, a decrease of veneers mass and a non-proportional decrease in veneers volume may be the main causes for the density decrease observed in Norway spruce for longer treatment intensity. Other authors reported density increase for both hardwood and softwood after densification, on average of 130% for wood blocks of five species [17], 76% for beech wood strips [12], 66 and 60% for Lignamon and steam-densified beech, respectively [32], 47% for beech veneers [33], 23% for birch wood strips [7], 42% for scots pine wood strips [10], 72% for scots pine veneers [20], 138% for Norway spruce wood strips [12] and 78% for radiata pine wood strips [34]. Given the wide variety of densification treatments, a more in-depth comparison might be useful to provide a better understanding of the true effectiveness of the treatment herein applied.

Although the difference in density between control and densified Norway spruce samples, treatment intensity was not the main factor influencing density increase. Since density peak value for Norway spruce was obtained with milder treatments, there is no reason to prolong the treatment as it does not provide any further increase in veneer density.

A prominent side effect of the applied process could be related to wood surface wettability. As reported by Song et al. [17], wood wettability could be reduced since in the densified wood the fully collapsed wood cell walls are tightly intertwined along their cross-section and densely packed along their length direction [35, 36]. Bektha and Krystofiak [37] showed that the contact angles of four densified wood species at a low temperature (100 °C—4MPA for 4 min) were lower than those of non-densified wood. The authors attributed this result to the fact that dehydration of hemicelluloses, lignin and extractives does not occur at a low temperature (100 °C). In our case, the densification treatment is associate to a chemical treatment that lead to a substantial reduction of lignin/hemicellulose content in wood [17] and this could affect the wood wettability and consequently the adhesion properties of treated veneers.

Mechanical properties

Treatment intensity significantly affected the MOE for both beech [$F_{(3, 92)} = 7.223$, $p \leq 0.05$] and Norway spruce [$F_{(5, 145)} = 27.63$, $p \leq 0.05$] (Fig. 3, Table 2). However, as treatment intensity increased, the mean MOE of beech samples increased significantly, but not for the longest treatment intensity of 300 s (Fig. 3).

Beech samples left in the softening solution for 300 s showed the highest average MOE value of 10,314.95 MPa (51.30% increase compared to control samples). With increasing treatment intensity, the MOE also increased.
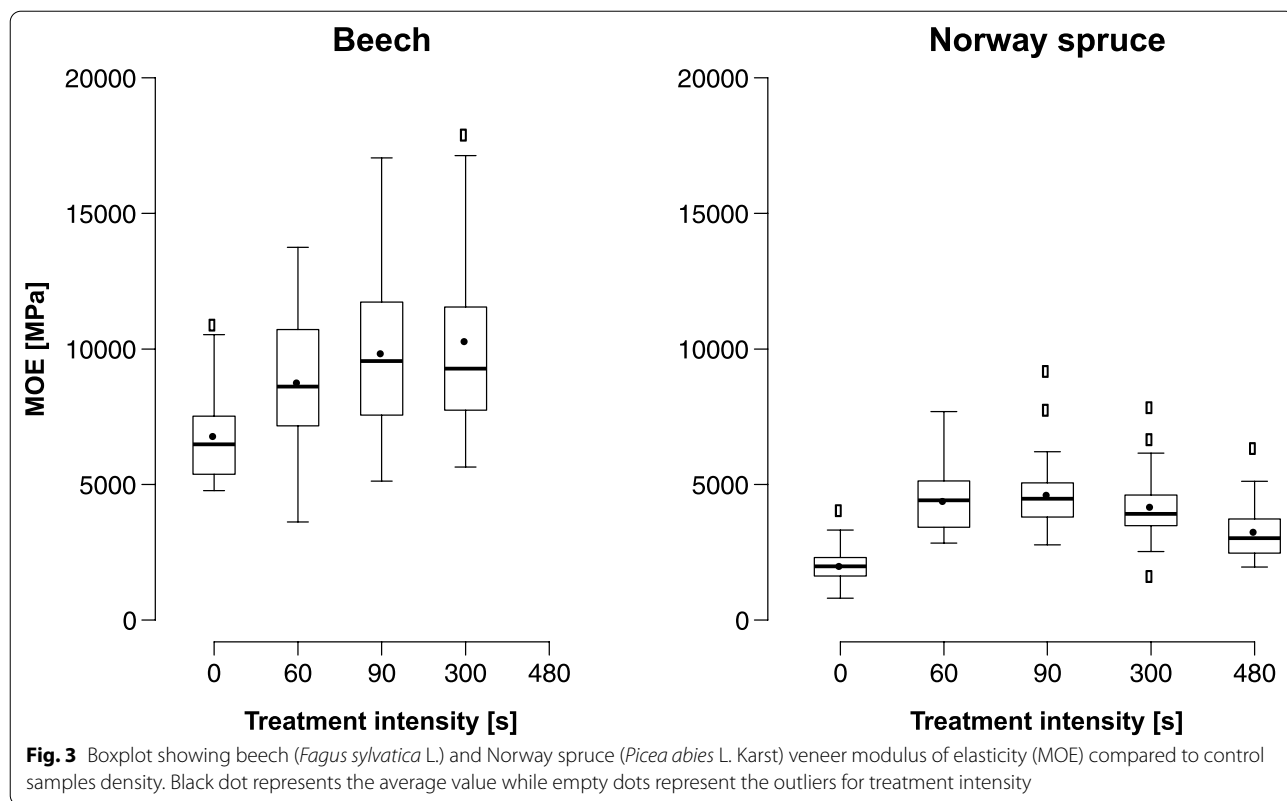
Fig. 3 Boxplot showing beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) veneer modulus of elasticity (MOE) compared to control samples density. Black dot represents the average value while empty dots represent the outliers for treatment intensity

Table 2 Tukey's test on MOE data for beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) densified veneer samples

Species	Treatment intensity	MOE mean difference	95% confidence interval		P value
			Lower bound	Upper bound	
Beech	90–60 s	1082.2783	− 1063.4571	3228.0138	0.55
	300–60 s	1525.3446	− 620.3909	3671.0800	0.25
	Control–60 s	− 1971.9088	− 4117.6442	173.8267	0.08
	300–90 s	443.0662	− 1702.6692	2588.8017	0.95
	Control–90 s	− 3054.1871	− 5199.9225	− 908.4516	<0.05
	Control–300 s	− 3497.2533	− 5642.9888	− 1351.5179	<0.05
Norway spruce	60 s–control	2391.9510	1591.4425	3192.4595	<0.05
	90 s–control	2621.5530	1821.0445	3422.0615	<0.05
	300 s–control	2175.6307	1375.1221	2976.1392	<0.05
	480 s–control	1256.6560	456.1475	2057.1645	<0.05
	90–60 s	229.6020	− 570.9065	1030.1105	0.93
	300–60 s	− 216.3203	− 1016.8289	584.1882	0.9450687
	480–60 s	− 1135.2950	− 1935.8035	− 334.7865	0.0012785
	300–90 s	− 445.9223	− 1246.4309	354.5862	0.5390946
	480–90 s	− 1364.8970	− 2165.4055	− 564.3885	0.0000559
	480–300 s	− 918.9747	− 1719.4832	− 118.4661	0.0156799

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Conversely, Norway spruce samples showed peak performances in MOE, equal to 4647.64 MPa, when samples were immersed in the softening solution for 90 s (129.39% increase compared to control samples). Norway spruce specimens treated for 300 and 480 s showed lower MOE value comparable to those obtained after 60-s treatment intensity (Fig. 3).

Similar results are reported for viscoelastic thermal compression and other densification treatments. Compared to natural wood, poplar samples with 63%, 98% and 132% degree of densification showed an increase of MOE of 37%, 84% and 129%, respectively [5]. Surface compressed wood showed a 51.9% increase in MOE [34], and only a slight decrease after heat treatment. MOE of Lignamon and steam-densified beech increased by 86% and 51%, respectively, compared to untreated beech [31]. Finally, after thermo-mechanical densification, MOE of *Pinus eliotti* and *Eucalyptus grandis* wood blocks increased up to 85% and 33%, respectively [30].

The statistical analysis was carried out to determine whether the treatment intensity influenced the MOE. The result showed that the treatment significantly increased the MOE of both beech and Norway spruce samples, while the treatment intensity did not have a significant effect on the MOE of densified beech samples. With regards to Norway spruce veneers instead, treatment intensity influenced the MOE of densified samples (Fig. 3). The MOE of Norway spruce samples treated for 480 s was significantly lower than the MOE measured for samples that underwent a milder treatment.

This decrease observed for the properties of samples at higher treatment intensities might be caused by an excessive degradation of wood macromolecules [30]. In addition to that, the densification of veneers, being a process that involves heat and pressure, can produce fractures in cell walls, hence causing a lower increase in MOE [33]. Especially in Norway spruce samples treated for a longer when density decreased, density at 300 s and 480 s were similar but MOE, for the same two intensities, dropped significantly (Figs. 2 and 3; Table 2). This is to be expected because density and mechanical properties of wood are closely related, but this relationship can be affected by the chemical modification of wood cell walls [4–6, 8, 9, 30]. The treatment intensities yielded higher MOE when applied to Norway spruce samples, leading to a 129.39% increase from sound wood after 90 s treatment intensity, conversely for beech samples higher MOE was reached with longer and more intense treatment intensity (Fig. 3). This difference MOE response of the wood species could be due to the different veneer cutting (tangential for beech and radial for Norway spruce) [38].

Color changes

Before treatment, beech and Norway spruce veneers showed a different appearance due to tangential and radial cut, respectively. Their appearance changed further after the densification treatment (Fig. 4; Table 3). After densification, clear wavy strips appeared on beech veneers surface, especially after treatment intensity of 90 s. The presence of multiseriate rays in beech samples
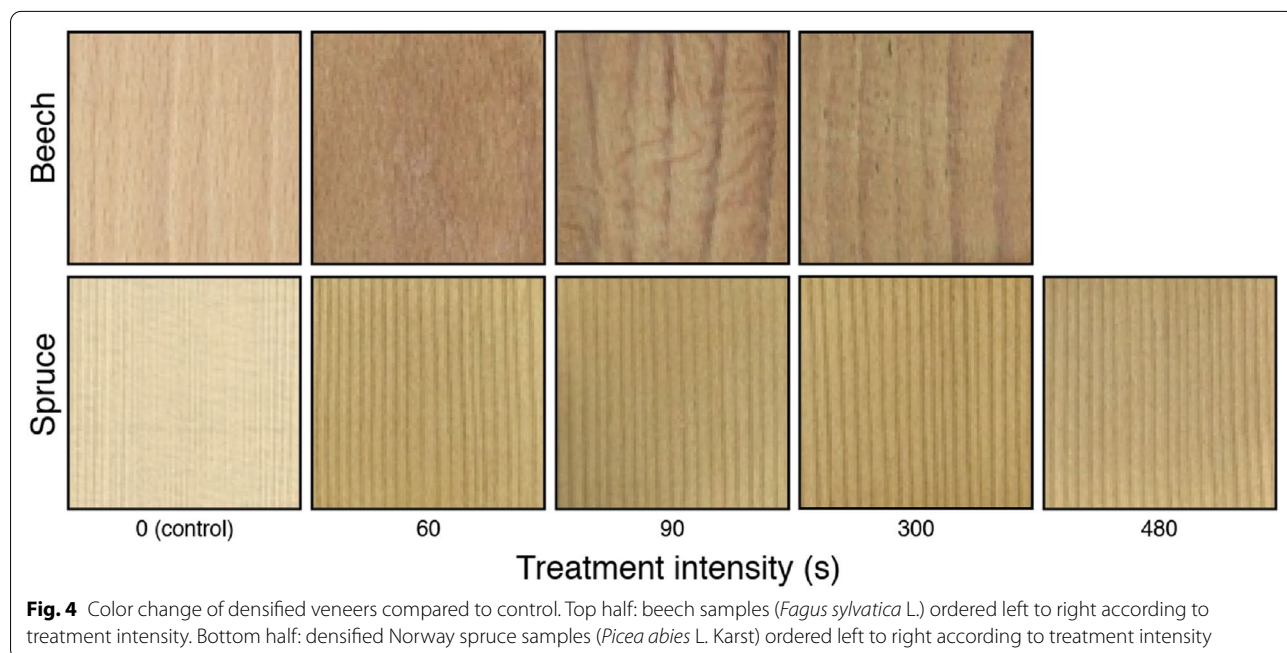

Fig. 4 Color change of densified veneers compared to control. Top half: beech samples (*Fagus sylvatica* L.) ordered left to right according to treatment intensity. Bottom half: densified Norway spruce samples (*Picea abies* L. Karst) ordered left to right according to treatment intensity

Table 3 Mean values for color parameters (and their standard deviations) of densified beech (*Fagus sylvatica* L.) and Norway spruce (*Picea Abies* L. Karst) veneer samples (*L**: lightness; *a**: red/green color coordinate; *b**: yellow/blue color coordinate; *C**: color saturation; *h°*: hue)

Species	Treatment	L*	a*	b*	C*	h°
Beech	Control	73.93 (0.58)	7.30 (0.38)	23.58 (0.75)	24.69 (0.82)	1.27 (0.01)
	60 s	58.72 (1.17)	8.24 (1.17)	28.57 (1.40)	29.80 (1.28)	1.28 (0.07)
	90 s	56.69 (2.62)	9.70 (2.62)	25.90 (1.15)	27.73 (0.71)	1.21 (0.08)
	300 s	59.25 (1.72)	5.72 (1.72)	28.87 (1.40)	29.45 (1.29)	1.37 (0.03)
Norway spruce	Control	80.75 (0.60)	2.93 (0.27)	21.14 (0.52)	21.34 (0.54)	1.43 (0.01)
	60 s	65.82 (0.78)	4.11 (0.37)	34.46 (1.09)	34.71 (1.08)	1.45 (0.01)
	90 s	65.70 (1.56)	4.35 (0.61)	35.82 (1.87)	36.09 (1.93)	1.45 (0.01)
	300 s	64.09 (0.78)	4.63 (0.60)	34.50 (1.20)	34.82 (1.24)	1.43 (0.01)
	480 s	63.59 (0.91)	4.56 (0.54)	33.28 (0.92)	33.60 (0.97)	1.43 (0.01)

could have been the cause of this color inhomogeneity. Color measurement was carried out anyway, but discussion and conclusion will take it into consideration.

The densification process caused an overall greater color change in beech samples treated for 90 s and Norway spruce samples treated for 300 s (respectively, $\Delta E = 17.56$ and $\Delta E = 21.43$). Following the evaluation reported by Dirckx et al. [28], the color change in both species was clearly noticeable and very important as ΔE exceeded the 12 units threshold comparing control and treated veneers. The densification process affected the color lightness (L^*) of both beech [$F(3, 145) = 42.94$, $p \leq 0.05$] and Norway spruce [$F(3, 45) = 536.2$, $p \leq 0.05$] samples (Fig. 5; Table 4). Treatment intensity influenced the lightness of treated samples of both species. Beech samples treated for 90 s ($\Delta L^* = -17.24$) and Norway spruce samples treated for 300 and 480 s ($\Delta L^* = -16.67$; -17.17, respectively) were significantly darker than other densified samples of their respective species. Darkening of wood happens also to heat-treated wood and it is attributed to lignin polymerization reactions [39, 40], the presence of degradation products of hemicellulose [1] and temperature of treatment [41].

Some authors suggest that surface redness could be due to the extractive content of deciduous [42] and coniferous wood [43]. Previous studies have also shown that yellow tones in densified wood may be due to quinones, quinone methides, and stilbenes that are generated from lignin degradation [44]. The densification process also influenced red (a^*) and yellow tones (b^*) of the treated veneers (Table 3) and therefore a change in hue angle ($h°$) and color saturation (C^*) was observed (Fig. 5). The red–green chromatic difference Δa^* values indicates that in general beech and Norway spruce veneers became redder after treatment. The most noticeable change happened for beech samples left in the softening solution for 90 s ($\Delta a^* = 2.39$) and Norway spruce samples left in

the softening solution for 300 s ($\Delta a^* = 1.70$). The color change towards red was greater for beech samples with the exception of samples left in the softening solution for 300 s, which showed a Δa^* equal to -1.58, meaning that the color changed towards green tones. Conversely, for Norway spruce samples, with increasing treatment intensity, the samples' color became redder with a slightly lower value observed in samples treated for 480 s. The yellow–blue chromatic difference Δb^* indicates that the color of densified samples changed towards yellow tones after the densification treatment. The highest values were found for samples left in the softening solution for 300 s for beech ($\Delta b^* = 5.30$) and 90 s for Norway spruce ($\Delta b^* = 13.37$), thus the treatment had a greater influence on Norway spruce veneers. Beech samples treated for 60 and 300 s showed a fairly equal color change, while samples treated for 90 s showed a notably lower Δb^*. Norway spruce veneers treated for 60, 90 and 300 s showed a similar color change towards yellow, while the Δb^* value was lower for samples treated for 480 s.

Treatment had a significant effect on C^* for both beech [$F(3, 36) = 48.47$, $p \leq 0.05$] and Norway spruce [$F(4, 45) = 240.6$, $p \leq 0.05$] veneers (Fig. 5; Table 4). When observing the Tukey's test results for each species, two separate situations were found (Fig. 5; Table 4). Among densified beech samples, specimens left in the softening solution for 90 s showed a significantly lower Chroma value (12.32% increase) than samples treated for 60 s (20.71% increase) and 300 s (19.29% increase). The random pattern on the beech veneers' surface might have mislead the measurement of the color parameters (L^*, a^*, b^*) leading to these unexpected results. Chroma values changed significantly according to treatment intensity (e.g., 57.41% increase after 480 s treatment intensity), but not uniformly. Hence, we can state that, given these results, the treatment might give more uniform results for Norway spruce veneers when samples are left in the
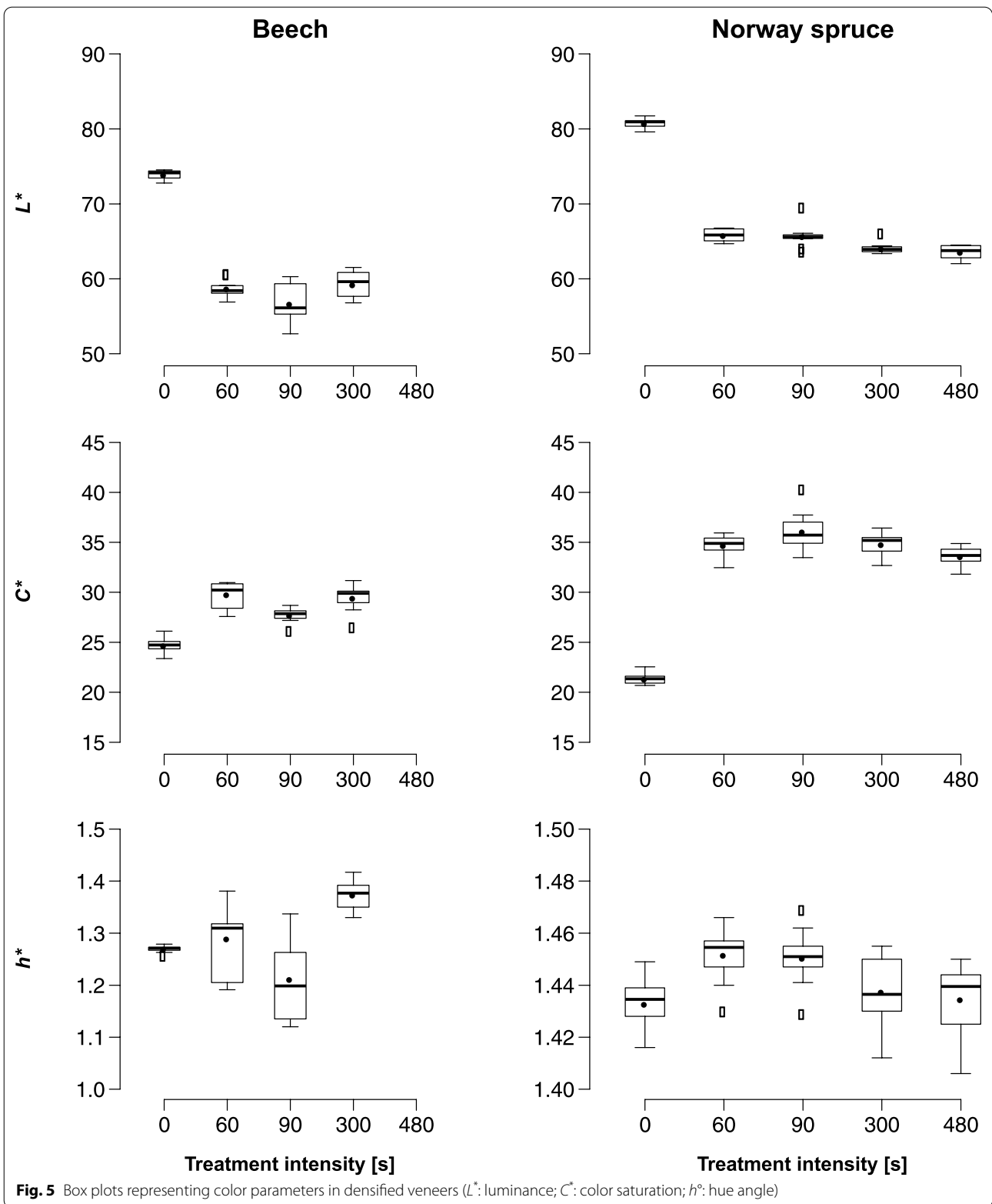
Fig. 5 Box plots representing color parameters in densified veneers (L^*: luminance; C^*: color saturation; $h°$: hue angle)

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Table 4 Tukey's test on investigated color parameters of densified beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L. Karst) veneer samples. (*a** red/green coordinates; *b** yellow/blue coordinates; *C** color saturation; *h°* hue angle; *L** lightness.*)

Species	Color parameter	Treatment intensity	Mean difference	95% confidence interval		*P* value
				Lower bound	Upper bound	
Norway spruce	*a**	60 s–control	1.1802	0.5492825	1.8111175	< 0.05
		90 s–control	1.4130	0.7820825	2.0439175	< 0.05
		300 s–control	1.6974	1.0664825	2.3283175	< 0.05
		480 s–control	1.6290	0.9980825	2.2599175	< 0.05
		90–60 s	0.2328	− 0.3981175	0.8637175	0.83
		300–60 s	0.5172	− 0.1137175	1.1481175	0.15
		480 s–60 s	0.4488	− 0.1821175	1.0797175	0.27
		300 s–90 s	0.2844	− 0.3465175	0.9153175	0.70
		480 s–90 s	0.2160	− 0.4149175	0.8469175	0.86
		480 s–300 s	− 0.0684	− 0.6993175	0.5625175	0.10
	*b**	60 s–control	13.3254	11.7943145	14.8564855	< 0.05
		90 s–control	14.6836	13.1525145	16.2146855	< 0.05
		300 s–control	13.3658	11.8347145	14.8968855	< 0.05
		480 s–control	12.1444	10.6133145	13.6754855	< 0.05
		90 s–60 s	1.3582	− 0.1728855	2.8892855	0.10
		300 s–60 s	0.0404	− 1.4906855	1.5714855	0.10
		480 s–60 s	− 1.1810	− 2.7120855	0.3500855	0.20
		300 s–90 s	− 1.3178	− 2.8488855	0.2132855	0.12
		480 s–90 s	− 2.5392	− 4.0702855	− 1.0081145	< 0.05
		480 s–300 s	− 1.2214	− 2.7524855	0.3096855	0.17
	*C**	60 s–control	13.3683	11.7921259	14.9444741	< 0.05
		90 s–control	14.7449	13.1687259	16.3210741	< 0.05
		300 s–control	13.4749	11.8987259	15.0510741	< 0.05
		480 s–control	12.2549	10.6787259	13.8310741	< 0.05
		90 s–60 s	1.3766	− 0.1995741	2.9527741	0.11
		300 s–60 s	0.1066	− 1.4695741	1.6827741	0.10
		480 s–60 s	− 1.1134	− 2.6895741	0.4627741	0.28
		300 s–90 s	− 1.2700	− 2.8461741	0.3061741	0.17
		480 s–90 s	− 2.4900	− 4.0661741	− 0.9138259	< 0.05
		480 s–300 s	− 1.2200	− 2.7961741	0.3561741	0.20

Table 4 (continued)

Species	Color parameter	Treatment intensity	Mean difference	95% confidence interval		P value
				Lower bound	Upper bound	
	h°	60 s–control	0.0189	0.003867921	0.033932079	< 0.05
		90 s–control	0.0177	0.002667921	0.032732079	< 0.05
		300 s–control	0.0047	− 0.010332079	0.019732079	0.90
		480 s–control	0.0018	− 0.013232079	0.016832079	0.10
		90 s–60 s	− 0.0012	− 0.016232079	0.013832079	0.10
		300 s–60 s	− 0.0142	− 0.029232079	0.000832079	0.07
		480 s–60 s	− 0.0171	− 0.032132079	−0.002067921	0.02
		300 s–90 s	− 0.0130	− 0.028032079	0.002032079	0.12
		480 s–90 s	− 0.0159	− 0.030932079	− 0.000867921	0.04
		480 s–300 s	− 0.0029	− 0.017932079	0.012132079	0.98
	L*	60 s–control	− 14.9360	− 16.186056	− 13.6859439	< 0.05
		90 s–control	− 15.0588	− 16.308856	− 13.8087439	< 0.05
		300 s–control	− 16.6676	− 17.917656	− 15.4175439	< 0.05
		480 s–control	− 17.1688	− 18.418856	15.9187439	< 0.05
		90 s–60 s	− 0.1228	− 1.372856	1.1272561	0.10
		300 s–60 s	− 1.7316	− 2.981656	− 0.4815439	< 0.05
		480 s–60 s	− 2.2328	− 3.482856	− 0.9827439	< 0.05
		300 s–90 s	− 1.6088	− 2.858856	− 0.3587439	< 0.05
		480 s–90 s	− 2.1100	− 3.360056	− 0.8599439	< 0.05
		480 s–300 s	− 0.5012	− 1.751256	0.7488561	0.78
Beech	a*	60 s–control	0.9304	− 0.7820142	2.6428142	0.47
		90 s–control	2.3910	0.6785858	4.1034142	< 0.05
		300 s–control	− 1.5840	− 3.2964142	0.1284142	0.08
		90 s–60 s	1.4606	− 0.2518142	3.1730142	0.12
		300 s–60 s	− 2.5144	− 4.2268142	− 0.8019858	< 0.05
		300 s–90 s	− 3.9750	− 5.6874142	− 2.2625858	< 0.05
	b*	60 s–control	4.9954	3.5408862	6.449914	< 0.05
		90 s–control	2.3174	0.8628862	3.771914	< 0.05
		300 s–control	5.2962	3.8416862	6.750714	< 0.05
		90 s–60 s	− 2.6780	− 4.1325138	− 1.223486	< 0.05
		300 s–60 s	0.3008	− 1.1537138	1.755314	0.94
		300 s–90 s	2.9788	1.5242862	4.433314	< 0.05

Table 4 (continued)

Species	Color parameter	Treatment intensity	Mean difference	95% confidence interval		P value
				Lower bound	Upper bound	
	C*	60 s–control	5.1136	3.8357453	6.3914547	< 0.05
		90 s–control	3.0410	1.7631453	4.3188547	< 0.05
		300 s–control	4.7631	3.4852453	6.0409547	< 0.05
		90 s–60 s	− 2.0726	− 3.3504547	− 0.7947453	< 0.05
		300 s–60 s	− 0.3505	− 1.6283547	0.9273547	0.88
		300 s–90 s	1.7221	0.4442453	2.9999547	< 0.05
	h°	60 s–control	0.0196	− 0.04487028	0.084070281	0.84
		90 s–control	− 0.0584	− 0.12287028	0.006070281	0.09
		300 s–control	0.1040	0.03952972	0.168470281	< 0.05
		90 s–60 s	− 0.0780	− 0.14247028	− 0.013529719	< 0.05
		300 s–60 s	0.0844	0.01992972	0.148870281	< 0.05
		300 s–90 s	0.1624	0.09792972	0.226870281	< 0.05
	L*	60 s–control	− 15.2126	− 17.2571171	− 13.16808287	< 0.05
		90 s–control	− 17.2420	− 19.2865171	− 15.19748287	< 0.05
		300 s–control	− 14.6800	− 16.7245171	− 12.63548287	< 0.05
		90 s–60 s	− 2.0294	− 4.0739171	0.01511713	0.05
		300 s–60 s	0.5326	− 1.5119171	2.57711713	0.89
		300 s–90 s	2.5620	0.5174829	4.60651713	< 0.05

solution for no more than 300 s. Finally, C^* variation was smaller in beech samples than in Norway spruce samples and this behavior was also observed by other authors when comparing color changes in thermally treated hardwood and softwood species [22].

The densification process produced a significant variation also in the hue angle of beech [$F_{(3, 36)} = 15.76$, $p \leq 0.05$] and Norway spruce [$F_{(4, 45)} = 5.794$, $p \leq 0.05$] veneers (Fig. 5; Table 4). Upon further analysis via Tukey's test, only beech samples treated for 90 s (4.62% decrement) and 300 s (8.17% increase) showed a notable difference when compared to control specimens. In Fig. 4, we can see that beech veneers that underwent a mild and intense treatment (90 and 300 s) showed a significant difference between the respective average $h°$ values which is also confirmed by the statistical analysis (Fig. 5; Table 4). It is interesting to see how the average value for samples treated for 90 s is lower than the value for control samples, whereas the opposite happened for samples treated for 300 s. This large difference might again be due to the above-mentioned inconsistent surface color of densified

beech samples. From the data analysis herein discussed, we can say that there is no clear influence of treatment intensity on the hue angle of beech veneers. Densified Norway spruce samples were split in two distinct groups. When compared to control samples, only those treated for 60 and 90 s (1.32 and 1.22% increase, respectively) showed a significant change in hue angle. Finally, Tukey's test did not show any significant difference for Norway spruce veneers treated for 60 and 90 s, meaning that for shorter treatment intensities the time spent in the softening solution has no significant effect on $h°$ parameter.

Conclusions

Among the advantages of veneers densification, we can list greater stiffness of the veneer itself, which allows a reduced thickness of the support material to which the veneer is applied. Moreover, a more homogeneous and appealing surface color of the densified veneers increases the color value of surfaces.

Since the process applied in this study is fairly new, future studies should focus on understanding and quantifying the effects of the softening solution on

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hemicellulose and lignin, understanding the relationship occurring between extractives and surface color of densified veneers, and providing more information on the influence of treatment parameters of the densified veneers. Furthermore, additional mechanical tests, as well as the influence of wood modification on moisture affinity and on adhesion, must be done in order to achieve a better understanding of the effects of this densification method on veneers. The acquired knowledge and the relative simplicity in the preparation of the densified veneers, make this material worth exploring for possible use in flooring and other products where wear resistance and color appearance are a matter of great importance.

Abbreviations
*a**: Red/green color coordinate; *b**: Yellow/blue color coordinate; CIE: Commission International de l'Eclairage (International Commission of Illumination); *C**: Color saturation; *ΔE*: Color difference; *h*°: Hue angle; *L**: Color lightness; MOE: Modulus of elasticity; TMA: Thermo-mechanical analysis.

Authors' contributions
Conceptualization, ACe, MZ and ACr; data curation, ACe and ACr; formal analysis, MZ and ACr; investigation, ACe; methodology, MZ, TU and ACr; project administration, MZ and ACr; resources, MZ, TU and ACr; supervision, MZ and ACr; validation, MZ, TU and ACr; visualization, ACr; writing—original draft, ACe; writing—review and editing, MZ and ACr. All authors read and approved the final manuscript.

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

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

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