Effect of Cold Plasma Treatment on Contact Angle and Surface Color Properties of Untreated and Thermally Modified Scots Pine Wood

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Scots pine wood (*Pinus sylvestris*) specimens were thermally modified using the rectification method and subsequently exposed to air-plasma under atmospheric pressure for 5 and 7 min. The water contact angle and CIELAB color parameters, including lightness (L^*), red–green (a^*), and yellow–blue (b^*) coordinates, were measured. The results showed that plasma treatment decreased L^*, particularly in thermally modified wood, while inducing a slight decrease in untreated wood. The b^* value gradually increased in untreated samples, whereas thermally modified specimens exhibited pronounced increases in both a^* and b^*. Analysis of variance revealed that wood type, plasma exposure time, and their interaction had statistically significant effects on all three-color parameters. Plasma treatment markedly reduced the water contact angle in both solid pine and thermo-wood samples, demonstrating enhanced surface wettability. The strongest effect was observed in thermo wood exposed to plasma for 7 min, which exhibited the lowest contact angle and the highest level of hydrophilicity among all treatments. FTIR spectroscopy indicated a gradual reduction of hydroxyl groups and ester carbonyls in hemicellulose and an accumulation of polymerized lignin caused by thermal modification, alongside partial degradation of polar groups, surface activation, and the formation of new carbonyl functionalities.

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Keywords: Pinus sylvestris; Cold plasma; Thermal modification; Contact angle; Rectification method

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INTRODUCTION

Wood has long occupied a distinguished position in human life because of its unique characteristics, including natural aesthetics, low density, favorable machinability, and acceptable mechanical performance. Nonetheless, exposure to outdoor conditions—such as rainfall, moisture, ultraviolet radiation, and other environmental stressors—results in undesirable changes in its physical and mechanical properties. To improve durability and enhance the resistance of wood against moisture and dimensional instability, thermal modification has been widely employed. Various factors cause qualitative changes on the wood surface. Among the qualitative changes that occur on the surface are the water droplet contact angle, which indicates its hydrophilicity and hydrophobicity, as well as color changes on the wood surface resulting from the influence of different factors. Thermally modified woods generally exhibit reduced hygroscopicity and improved dimensional stability (Gonzalez-Peña *et al*. 2004). Kamperidou (2019) reported that thermal modification markedly decreases mass loss in pine wood that had been exposed to white- and brown-rot fungi. Furthermore, Ghorbani *et al*. (2020) indicated that applying thermal treatment at approximately 170 °C for one hour increases the stiffness, relative strength, and hardness of pine wood. Thermal modification has also been shown to significantly increase the water contact angle and thus reduce surface wettability (Hosseini-Fard *et al*. 2015). However, Gholamian *et al*. (2020) demonstrated that decreasing the water contact angle and enhancing surface wettability can improve coating performance and the visual quality of transparent finishes. These findings highlight that the choice of surface treatment must be aligned with the intended end-use requirements of wood—whether the objective is to enhance water repellency or to optimize coating performance.

Cold plasma technology represents a dry, clean, and environmentally friendly surface treatment method capable of modifying wood surface properties without altering its bulk structure. According to Zilla *et al*. (2015), non-thermal plasmas are preferred in wood-related studies due to the material's sensitivity to elevated temperatures. Plasma, comprised of an ionized gas containing ions, electrons, photons, and neutral species, induces excited states in atoms and molecules and facilitates various physicochemical reactions (Becker and Belkind 2003). Avramidis *et al*. (2012) further noted that plasma exposure leads to the oxidation and degradation of extractives, resulting in substantial modifications to the chemical and physical properties of wood surfaces. Altgen *et al.* (2020) investigated the wettability of beech wood surfaces after plasma treatment and monitored the reduction of plasma effects over a four-week period. Their results showed that the effects of plasma treatment gradually decreased over time; however, they did not disappear completely. In a study conducted on plasma-sprayed beech wood, Novak *et al.* (2015) concluded that hydrophobic recovery occurred after treatment, although the surface did not fully return to its original state. Žigon *et al.* (2021) reported that when a long time interval elapsed between wood treatment and adhesive bonding, some of the benefits of surface activation were lost. Nevertheless, plasma-treated samples still exhibited better performance than the untreated control samples.

Comprehensive evaluation of wood surface behavior in relation to moisture interactions and color changes is crucial for improving performance and ensuring long-term durability in outdoor applications. Water contact angle measurement serves as a reliable and quantitative indicator of surface free energy, micro-scale roughness, and the presence of functional groups. Variations in contact angle can therefore provide insight into physicochemical alterations induced by thermal or plasma treatments. Moreover, color and color stability constitute key quality attributes in decorative applications, interior architecture, and coated wood products. The CIELAB color space parameters including lightness (L^*), red–green coordinate (a^*), and yellow–blue coordinate (b^*) offer precise metrics for assessing color shifts resulting from surface modification techniques. Both thermal treatment and cold plasma can influence light absorption and scattering through alterations in the surface chemical composition, thereby modifying chromatic coordinates.

Given the importance of these surface indicators, namely water contact angle and color parameters in defining the functional performance of modified wood, detailed assessment of the effects of cold plasma and thermal treatment is essential for selecting optimal strategies for surface modification and expanding industrial applications. This relevance is particularly significant for Scots pine (*Pinus sylvestris*), one of the most widely utilized species in the wood and paper industries.

The primary objective of this study is to investigate the effects of cold plasma and thermal treatment on the water contact angle and CIELAB color parameters (L^*, a^*, and b^*) of Scots pine wood. Additionally, this study aimed to determine the effectiveness of each treatment in enhancing water repellency, color stability, and surface appearance quality, with the broader goal of improving the functional and industrial performance of pine wood.

MATERIALS AND METHODS

Materials

Imported pine wood from Russia, free from growth defects such as knots, checks, and grain deviation, was selected. This species has distinct heartwood and visible resin canals. The density of pine wood was calculated as 0.52 g/cm³, and the equilibrium moisture content was measured at 15% also average modulus of elasticity (MOE) at 12% moisture content of this wood 8.9 GPa and the average modulus of rupture (MOR) 84 MPa were reported (Auty 2011). A total of ninety wood specimens with dimensions of 20 × 100 × 100 mm based on the six variables listed in Table 1 were prepared. The samples reached equilibrium moisture content after 3 weeks in a climate-controlled chamber at 20 ± 2 °C and 65 ± 5% relative humidity.

The specimens were then divided into two groups: the first group was subjected for plasma treatment at 5 and 7 minutes, while the second group in addition to thermal modification, was exposed to plasma spraying.

Table 1. Experimental Sample Coding for Plasma-Treated Solid and Thermowood

Wood	Plasma (min)	Code
Solid wood	0	Wood0 (control)
	5	Wood5
	7	Wood7
Thermo Wood	0	Thermo0
	5	Thermo5
	7	Thermo7

Thermal Modification Method

The thermal modification of wood using the retification process was performed. Initially, 75 wood specimens were selected, and their moisture content at room temperature using an electrical moisture meter was measured to reach an equilibrium moisture content of approximately 12%. The specimens were arranged inside a stainless-steel cylinder using the support-frame method. After the air from the cylinder was evacuated and a vacuum was applied, nitrogen gas (98% purity) and oxygen gas (2% by volume) were then injected into the cylinder to provide an oxygen-controlled environment suitable for thermal treatment. The heating process was conducted in a stepwise manner up to 200 °C. During the initial drying stage, the temperature was increased at a rate of 3 °C per minute; during the preheating stage, the rate was 2 °C per minute, and during the main heating stage, it was 1.5 °C per minute. At the end of the treatment, the specimens from the cylinder were removed and cooled to room temperature until reaching equilibrium moisture content were conditioned. This method to minimize oxidative reactions, preserve structural lignin components, and control both color and dimensional stability of the wood was chosen.

Plasma Treatment

Prior to plasma treatment, raw wood and Thermo wood specimens were polished in two stages using a sanding machine, first with coarse sandpaper (grade 100) and then with fine sandpaper (grade 180). The surfaces of the samples were cleaned from dust using air pressure from an air compressor. The samples were transferred to the laboratory for plasma treatment. The plasma process using a Gliding Arc Plasma System was conducted. In this system, the active plasma region in the space between two knife-shaped electrodes is created. The plasma is non-thermal and, due to high electron density at low temperature, the surface of materials without thermal degradation or damage can be modified. In this study, the process gas of air (Air plasma) was selected. The incoming air in the electric field between the two electrodes is ionized and converted into a flow of ions, electrons, and photons, which directly collide to the wood surface and induce physical and chemical surface modifications. Plasma spraying was performed at specified points for a fixed duration of 5 and 7 minutes, and the intended tests were carried out on the sprayed points. After plasma treatment, the contact angle and CIELab measurements were performed on the samples after one hour. Other operational parameters, including electric power, voltage, current, and the electrode-to-sample distance, in Table 2 are presented.

Table 2. Specifications of the Plasma Spraying Device

Device Name	Gliding Arc
Country of origin	Iran
Voltage	4 KV
Frequency	60 KHZ
Power	250 W
Gas used	Air
Pressure	Atmospheric

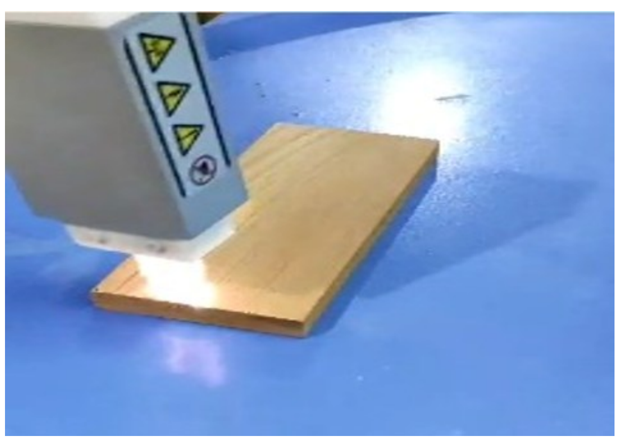

Fig. 1. Plasma spraying on wood

Contact Angle

The wettability of the surfaces was determined using the static water droplet contact angle test with distilled water. For this purpose, control specimens and plasma-treated specimens were subjected to the droplet deposition test. The contact angle formed between the water droplet and the wood surface after 5 s was recorded. For each sample, the droplet deposition and contact angle measurement were performed in five steps. The measurements were obtained with an SDC-100 device manufactured by Minder Hightech, China.

CIELab Measurement

The color of the specimens was evaluated using an X-Rite SP-64 spectrophotometer by the reflectance method and with the following specifications: Range [nm] 400 to 700, $\Delta\lambda$ = 10 nm, d/8 geometry (diffuse illumination, 8° viewing angle), and with the Color iQC software. The measurements in the three-dimensional CIELab color space were conducted. The environmental conditions during the test, including 32% relative humidity and 23 °C temperature, were maintained. The CIE Lab test was conducted on each sample with three repetitions. In this evaluation, the three main color parameters, including L^* (lightness), a^* (red–green tendency), and b^* (yellow–blue tendency), were measured and analyzed.

FTIR Analysis

For Fourier-transform infra-red (FTIR) spectroscopic analysis, uniform wood powder from the sample surfaces by controlled sanding was prepared (see earlier). The specimens were then transferred to the laboratory. The measurements using a Thermo FTIR device (model Avatar, USA) were also performed. In this test, infrared radiation on the powdered sample is irradiated; part of the radiation by the molecules in the wood is absorbed and part passes through the sample. The obtained spectrum the absorbance and transmittance of IR radiation at different wavelengths represents.

The absorption patterns in the FTIR spectrum revealed the chemical structure, types of bonds, and functional groups present in the material. Therefore, the range and intensity of absorbance peaks, the presence or changes in main functional groups, such as C=O, C–O, O–H bonds, and aromatic lignin bonds, can be determined. The purpose of this analysis is to study the potential changes in surface functional groups of wood as a result of plasma or retification treatments.

Statistical Analysis

Data analysis based on a factorial test in the framework of a randomized complete block design (RCBD) was performed. Statistical processing and analysis using SPSS software, version 21, was conducted. This designs the simultaneous effects of treatment duration, wood type, and their interactions on the contact angle allow them to examine. To evaluate color changes and surface quality characteristics, descriptive statistics, including mean, standard deviation, and range in the CIELab color space were used.

RESULTS AND DISCUSSION

Water Droplet Contact Angle

For each treatment under investigation, five specimens and for each specimen three replicates the contact angle was measured (Fig. 1).

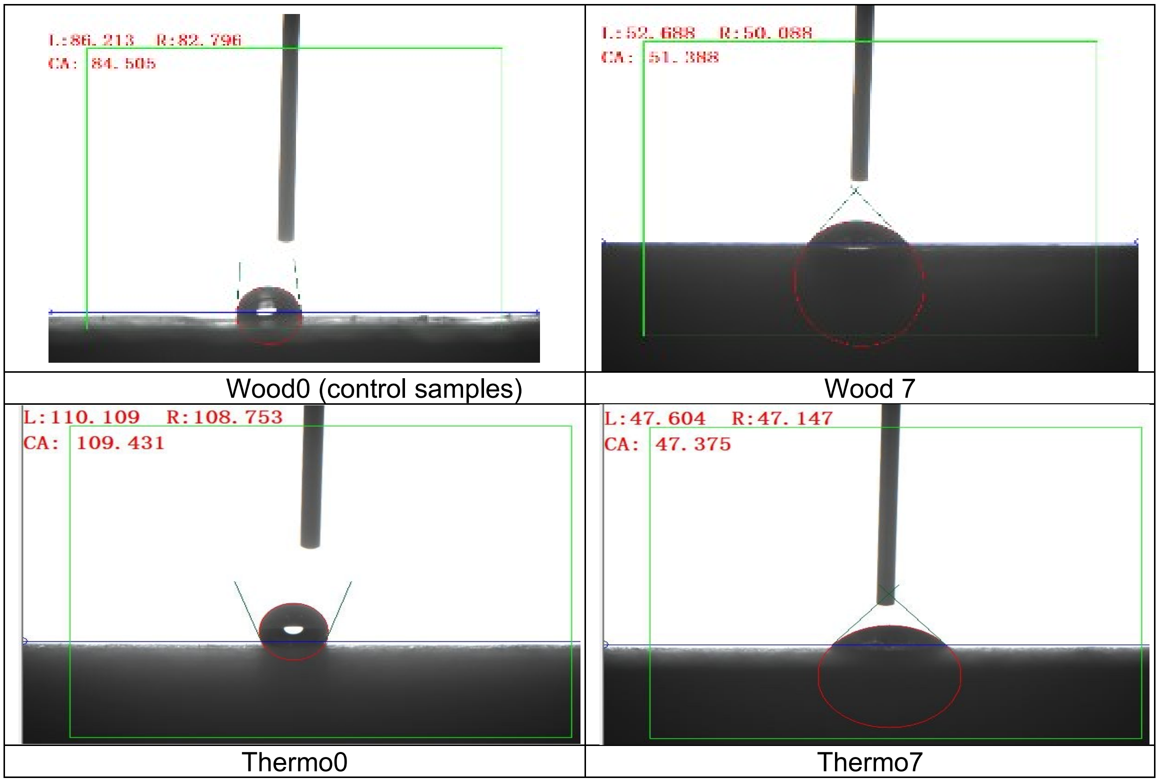

Fig. 2. Comparison of contact angles on solid wood and thermo-wood before and after plasma treatment

The results of the analysis of variance (ANOVA) indicated that the independent effects of types of wood (solid wood and thermo-wood), as well as their interactions, on the contact angle were significant (Table 3).

Table 3. The Effect of Plasma Spraying on the Contact Angle for Solid Wood and Thermo-Wood in Scot Pine

Source	Sum of Squares	df	Mean Square	F-value	Significance
Corrected Model	46729.857[a]	5	9345.971	11516.822	.000
Intercept	580961.519	1	580961.519	715905.302	.000
Wood/Thermo (A)	412.511	1	412.511	508.327	.000
Plasma (B)	37457.135	2	18728.567	23078.776	.000
A*B	8860.211	2	4430.106	5459.116	.000
Error	68.167	84	.812		
Total	627759.542	90			
Corrected Total	46798.023	89			
a: R Squared = .999 (Adjusted R Squared = .998)					

Among the solid wood specimens subjected to plasma spraying, the wood samples treated for 5 min (wood5) and 7 min (wood7) compared to the control sample (wood0), a significant reduction in contact angle exhibited, indicating an increase in surface hydrophilicity. This change was caused by surface activation and the formation of polar groups because of plasma spraying. The percentage of contact angle reduction was increased with increasing plasma duration. Thermal treatment increased the contact angle and made the wood surface more hydrophobic (121°). However, applying plasma treatment to thermally treated samples for 5 and 7 minutes reduced the contact angle to 80.5° and 46.4°, respectively, indicating an increase in hydrophilicity due to the application of cold plasma the 5-min sample compared to the control approximately 25% and the 7-min sample approximately 31% reduction in contact angle (relative to the control) showed. These results suggest that plasma can as an effective method to enhance wood hydrophilicity be applied and its intensity with treatment duration increases.

Among the thermo wood, the contact angle variation ranged from 45° to 121°. After thermal modification using the retification method, the higher the contact angle, the wood surface became hydrophobic (121°). However, by applying plasma spraying on thermally treated samples for 5 min (80.5°) to 7 min (46.4°), the contact angle decreased and hydrophilicity increased. Among all treated samples, the most effective treatment in terms of contact angle was the 7-min plasma-treated thermo wood samples (46.4°), which even compared to the control (90.2°) made the wood surface became more hydrophilic. By thermal treatment, the contact angle increased and the wood surface fully hydrophobic, whereas plasma spraying on solid Scots pine and thermally treated wood the contact angle decreased, and the wood surface was made hydrophilic. In general, heat treatment significantly increased the contact angle and decreased the surface wettability, while cold plasma treatment of thermowoods had a significant effect on reducing the contact angle and increasing wettability (Fig. 2).

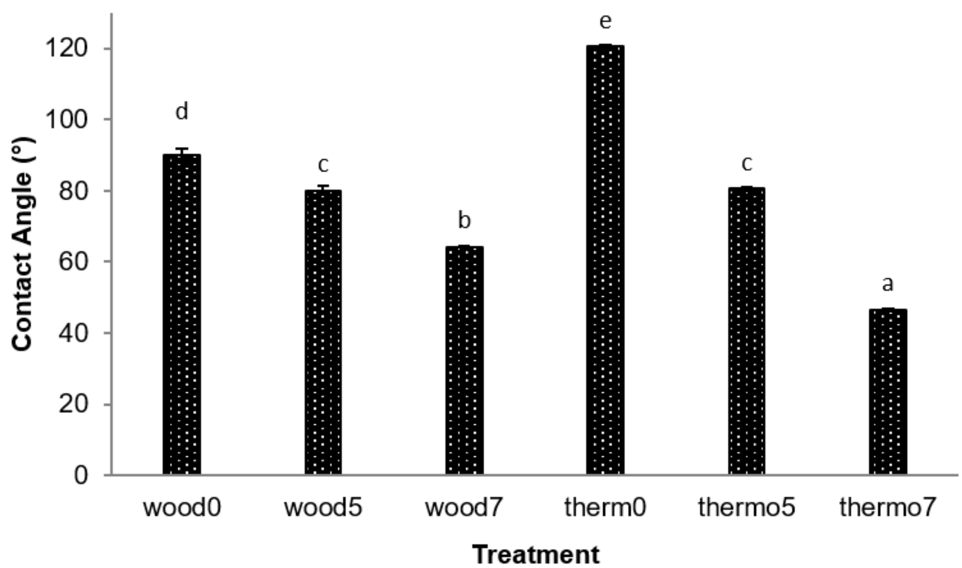

Fig. 3. Changes in contact angle of solid wood and thermo wood after plasma spray treatment

CIE *L*a*b**

The *L** parameter represents the lightness level, ranging from 100 (complete lightness) to 0 (complete darkness). The results showed that its value in control samples was approximately 82.5, representing the natural color of Scots pine wood. Application of plasma spraying on the wood surface for 5 and 7 min induced no significant change. However, after thermal modification the *L** value measured using the retification method was lower (62.9), and plasma spraying on the thermo wood surface the *L** parameter was altered. The lowest lightness value was recorded for the 7-min plasma-treated thermo wood sample (thermo7), with a lightness change (ΔL^*) of approximately 23% compared to the control observed. The highest *L** value with the highest lightness was observed in the wood7 sample, averaging 83.7.

The *L** parameter usually has the highest sensitivity to wood darkening in response to thermal reactions. In samples treated by the retification method, a significant reduction in lightness (*L**) was observed, indicating a noticeable darkening of the wood surface. This darkening was induced primarily by partial degradation of lignin structure, oxidation of aromatic bonds, caramelization of phenolic compounds, and extractives at elevated thermal treatment temperatures. Such changes lead to new chromophores and increased light absorption in the visible region. The results obtained are consistent with the findings of Barcik *et al*. (2015), as shown in Fig. 3.

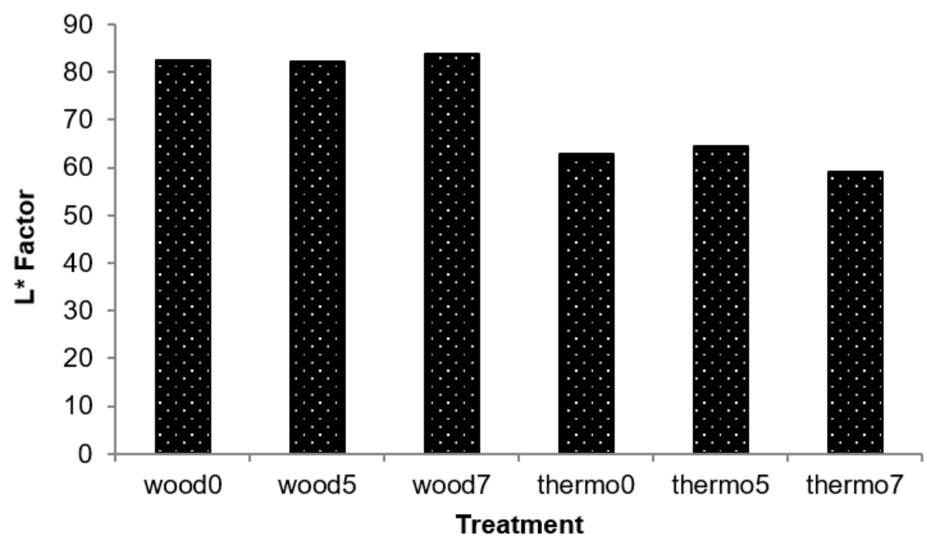

Fig. 4. Comparison of *L** values in solid wood and thermo wood after plasma spray

The results for the *a** color parameter measurements in Fig. 4 showed that this parameter in raw wood samples (wood0 to wood7) ranged from 3.2 to 3.8, whereas in thermally modified thermo-wood samples (thermo0 to thermo7) it significantly increased and ranged between 9.36 and 10.6. The *a** parameter represents the red–green axis in the CIElab color space; thus, an increase in its value indicates an increase in red intensity and, consequently, a shift of color toward the red spectrum. The noticeable increase in *a** in thermo wood samples demonstrates the effect of thermal treatment on the chemical composition of the wood surface. During the thermal modification process, partial thermal degradation of hemicelluloses and occurrence of oxidation reactions, along with the condensation of aromatic lignin structures, the formation of chromophore compounds such as quinones and phenylpropanoids. These compounds cause the increase in the red color factor (a*).

Previous studies also showed that lignin condensation reactions and certain extractives in thermo wood result in the enhancement of red color intensity (Výbohová *et al*. 2018). Based on the plasma treatment results, on raw wood surfaces no significant change in the a* parameter was induced, and only minor variations within the natural range were observed. This can be attributed to the superficial and limited nature of plasma modification, which do not induce deep color changes in the lignocellulosic matrix.

For Scots pine raw wood samples (wood0) up to plasma-treated samples for 7 min (wood7), the b* parameter (surface yellowness) slightly increased from 20.42 to 21.35 (Fig. 5).

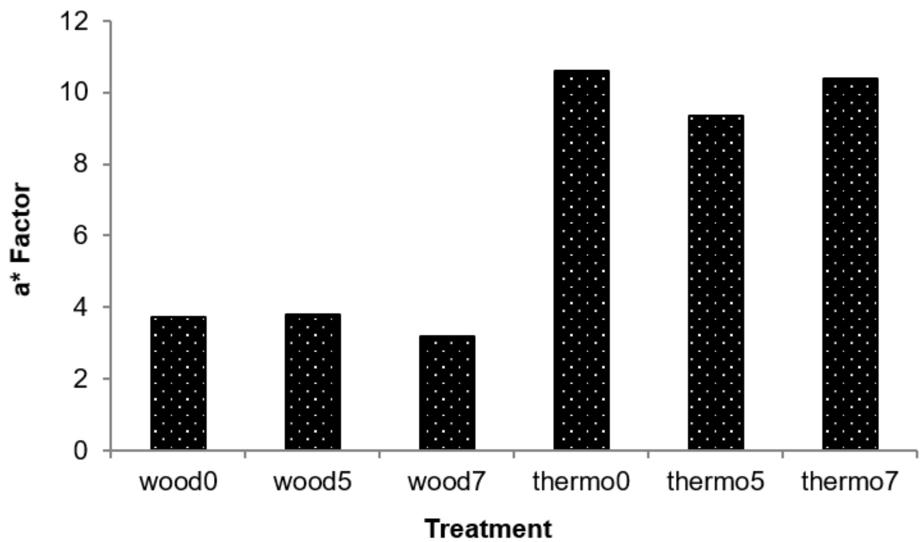

Fig. 5. Changes in redness (a^*) in solid wood and thermo-wood after spray plasma treatment

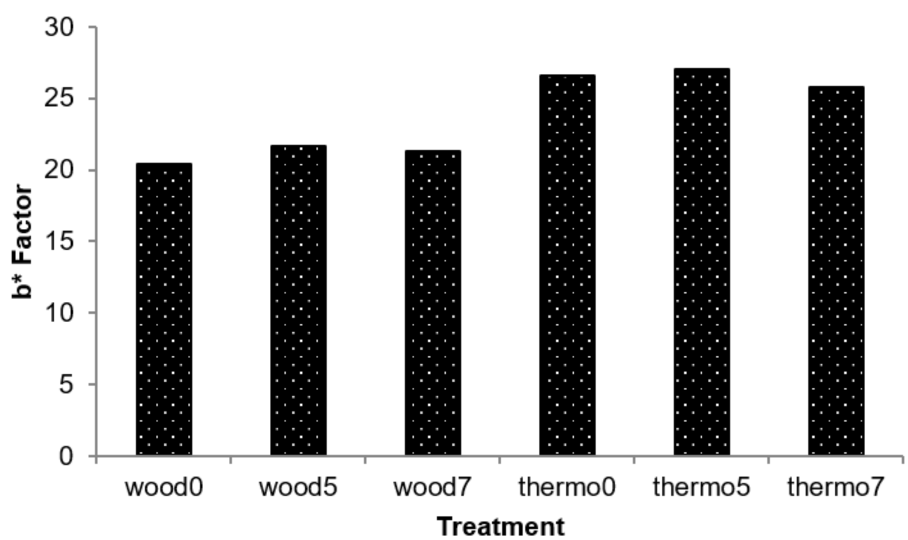

Fig. 6. Changes in yellowness (b^*) in solid wood and thermo wood after plasma spray treatment

In thermo wood samples, thermal treatment had a significant effect on the increase of surface yellow intensity, and the *b** values measured were significantly higher than those of untreated samples (Fig. 6). Among the thermo wood samples, the highest and lowest *b** values were recorded in 5- and 7-min plasma-treated thermally modified samples, respectively. Overall, the results indicated that plasma treatment at longer durations may cause minor degradation or reduction in the stability of the yellow color produced by the thermal process.

FTIR Analysis

The FTIR spectrum of untreated Scots pine wood reflects its fundamental lignocellulosic architecture comprising cellulose, hemicellulose, and lignin. The broad absorbance band at 3410 to 3360 cm^{-1} represents the stretching vibration of the hydroxyl (–OH) groups and indicates the extensive hydrogen-bonding network within the cell-wall polymers. The peaks at 2915 to 2920 cm^{-1} correspond to alkyl C–H stretching in $–CH_2$ and $–CH_3$ groups of polysaccharides and lignin. The strong band at 1728 to 1734 cm^{-1} is attributed to ester carbonyl (C=O) stretching of acetyl and carbonyl groups in hemicelluloses. The characteristic aromatic bands at approximately 1595 and 1510 cm^{-1} confirm the presence of guaiacyl-type lignin. In the fingerprint region, the bands at 1373 cm^{-1}, 1160–1055 cm^{-1}, and 897 cm^{-1} denote cellulose C-H bending, C–O–C/C–O polysaccharide vibrations, and the β (1→4) glycosidic linkage of cellulose (Zhang *et al*. 2020; Zeleniakiene and Žiogelis 2023).

Following thermal modification, pronounced spectral alterations were observed that signify the thermochemical reactions within the wood cell wall. The substantial decline in the 3410 cm^{-1} band indicates the reduction of free hydroxyl groups due to hemicellulose degradation and bound-water loss. The decreased intensity of the 1728 cm^{-1} band demonstrates the deacetylation and cleavage of ester carbonyl groups—particularly at carbons 2 and 3 of the galactoglucomannan backbone. The relative increase in aromatic bands at 1595 and 1510 cm^{-1} reflects lignin condensation and the formation of more crosslinked aromatic structures. The reduction of the 1373, 1160, and 1055 cm^{-1} bands confirms the decomposition of amorphous cellulose and hemicellulose regions. Likewise, the diminishing absorption at 897 cm^{-1} suggests partial disruption of β-glycosidic linkages. Collectively, these chemical transitions enhance the abundance of polar groups, improve biological resistance and dimensional stability (Candelier *et al*. 2022; Esteves and Pereira 2019).

In plasma-treated samples (7-min exposure), a distinct pattern of spectral modification is observed that characterizes the plasma-induced surface chemistry. The moderate decrease in the 3412 cm^{-1} band indicates the reduction of accessible –OH groups through dehydration and partial hemicellulose scission. In contrast, the increased band at 1732 cm^{-1} confirms the formation of newly generated carbonyl and ester groups due to surface oxidation. The aromatic lignin bands at 1639 and 1511 cm^{-1} imply their structural stability under plasma exposure and demonstrate the surface-limited nature of chemical changes. Alterations in the 1375, 1160, and 1058 cm^{-1} bands represent the partial cleavage of glycosidic bonds and the activation of reactive sites on cellulose and hemicellulose surfaces. The decline in the 897 cm^{-1} band evidence modifications in the amorphous regions of cellulose. The increased intensities in the 615 to 650 cm^{-1} regions signify the formation of phenolic and aromatic carbonyl structures produced under oxidative plasma conditions. These reactions increase the surface polarity, interfacial adhesion enhancement, and improve the overall surface performance (Jamali and Denes 2008; Tu *et al*. 2023).

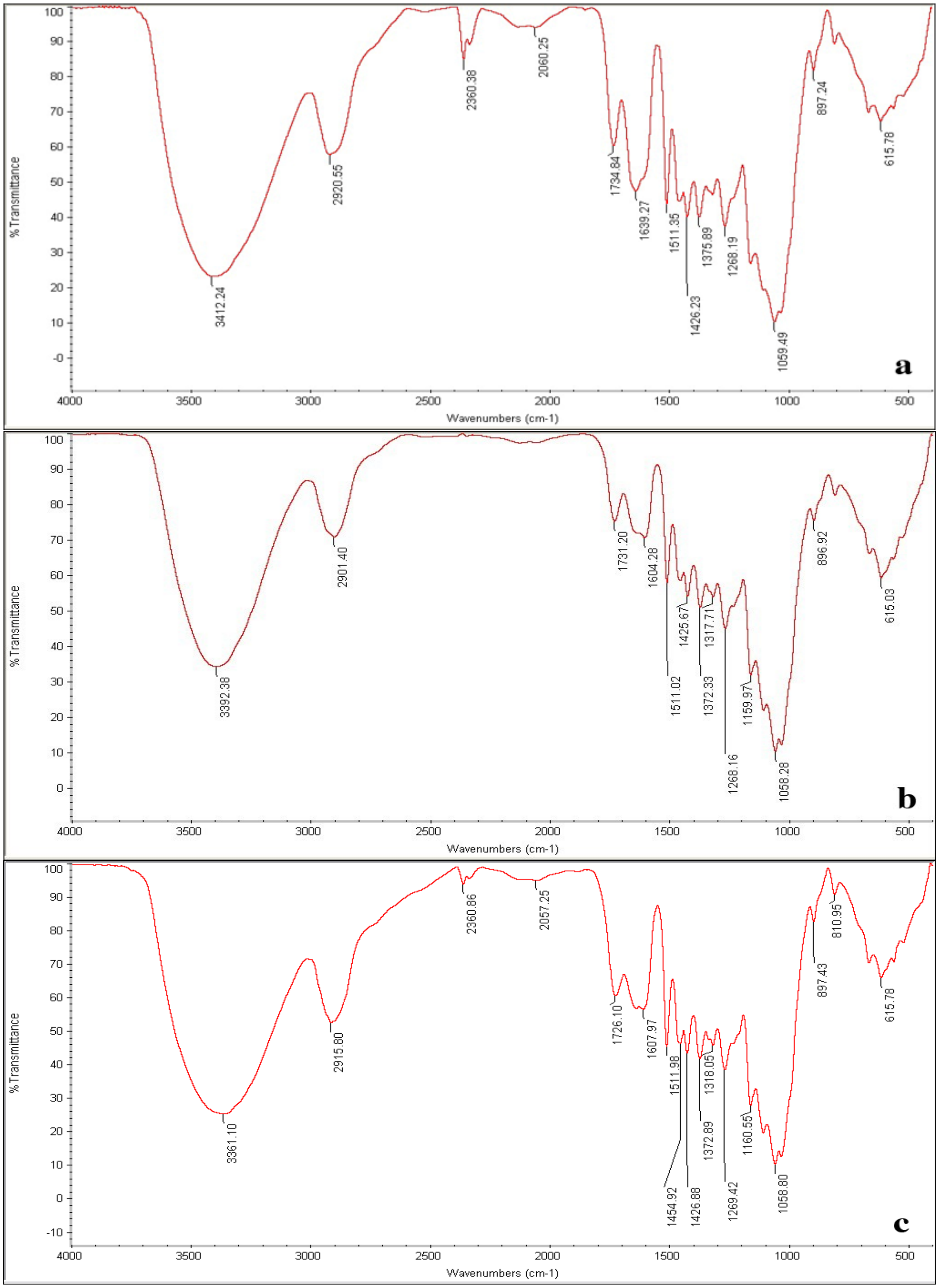

Fig. 7. FTIR spectra of raw wood and thermo-wood: a) wood0, b) thermowood0, and c) thermowood7

Overall, the thermal modification causes the gradual removal of hydroxyl and promotes the formation of ester carbonyl groups in hemicellulose and the relative enrichment of polymerized lignin structures, whereas in plasma treatment the surface activation intensifies, generates new carbonyl functionalities, and elevates surface polarity. Both treatments induce substantial structural alterations within the lignocellulosic matrix, yet plasma modification plays a more influential role in surface functionalization and enhancement of chemical reactivity. These findings agree with contemporary literature on thermal and plasma modification of wood and demonstrate the potential for improving physical, mechanical, and chemical properties through controlled modification pathways (Klébert and Unger 2022; Žigon *et al*. 2022; Košelová *et al*. 2023).

CONCLUSIONS

In this study, the effects of cold air plasma on the hydrophilicity and color characteristics of Scots pine (*Pinus sylvestris*) were investigated for exposure times of 5 and 7 minutes. The conclusions obtained from the results were summarized below:

1. Thermal treatment caused a significant decrease in the lightness parameter (L^*) and darkening of the wood surface. These effects could be attributed to partial lignin degradation, thermal conversion of phenolic compounds, and the formation of chromophoric structures, as previously reported in the literature.
2. Plasma treatment rendered both raw and treated wood hydrophilic; however, the hydrophilicity of the treated wood was greater than that of the raw solid wood.
3. Extending plasma treatment from 5 to 7 minutes intensified modifications in the contact angle and surface functional groups, indicating that the extent of plasma–surface interaction is directly dependent on exposure duration.
4. Fourier transform infrared (FTIR) spectroscopy revealed that thermal treatment resulted in gradual degradation of hemicellulose, reduction of hydroxyl and ester groups, and enrichment of aromatic lignin structures. In contrast, plasma treatment led to the formation of oxidized carbonyl groups, activation of reactive sites, and increased surface polarity. These findings indicate distinct modification mechanisms for each treatment in the lignocellulosic matrix were revealed.
5. Factorial analysis within an RCBD design showed that wood type, plasma treatment duration, and their interaction had statistically significant effects on the water contact angle. This highlights the importance of simultaneous consideration of material characteristics and surface treatment parameters when assessing wettability behavior was demonstrated.
6. The combined application of thermal and plasma treatments represents an efficient approach for wood surface engineering in coatings, adhesives, and outdoor applications, as the simultaneous control of wettability, surface energy, and color enables the design of functional surfaces tailored to industrial requirements.

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Conflict of Interest

The authors declare that there are no conflicts of interest that could have influenced the research or publication of this manuscript.

Use of Generative AI

The authors used ChatGPT (OpenAI, USA) solely for English language editing. The content, data, and scientific interpretation were fully produced and verified by the authors.

REFERENCES CITED

Altgen, D., Altgan, M., Kyyro, S., Rautkari, L., and Mai, C. (2020). "Time-dependent wettability changes on plasma-treated surfaces of unmodified and thermally modified European beech wood," *European Journal of Wood Products* 78(5). https://doi.org/10.1007/s00107-020-01505-0

Auty, D. (2011). *Modelling the Effects of Forest Management on the Wood Properties and Branch Characteristics of UK-grown Scots Pine*, PhD Dissertation, Aberdeen University, Scotland, UK.

Avramidis, G., Klarhöfer, L., Maus-Friedrichs, W., Militz, H., and Viöl, W. (2012). "Influence of air plasma treatment at atmospheric pressure on wood extractives," *Polymer Degradation and Stability* 97(3), 469-471. https://doi.org/10.1016/j.polymdegradstab.2012.01.010

Barcík, Š., Gašparík, M., and Razumov, E. Y. (2015). "Effect of temperature on the color changes of wood during thermal modification," *Cellulose Chemistry and Technology* 49(9–10), 789-798.

Becker, K. H., and Belkind, A. (2003). "Introduction to plasmas," *Vacuum Technology and Coatings* 5, 31-36.

Candelier, K., Dibdiakova, J., and Gérardin, P. (2022). "Structural evolution of lignin and polysaccharides in heat-treated softwoods evaluated by FTIR spectroscopy," *Cellulose* 29, 1123-1139.

Esteves, B., and Pereira, H. (2019). "Wood modification by heat treatment: A review," *BioResources* 14(1), 1-28. https://doi.org/10.15376/biores.14.1.1-28

Gholamian, H. (2020). "Improving the adhesion of paint coatings to wood by plasma surface treatment," *Journal of Science and Technology of Coatings* 14, 41-47.

Ghorbani, M., Nikkhah Shahmirzadi, A., and Topa, A. (2020). "Effect of compression on the practical properties of chemically and thermally modified poplar wood," *Iranian Journal of Wood and Paper Industries* 11, 185-197.

González-Peña, M., Breese, M., and Hill, C. (2004). "Hygroscopicity in heat-treated wood: Effect of extractives," in: *International Conference on Environmentally Compatible Forest Products (ICECFOP)*, 105-119.

Hosseini Fard, M. S., Khajestero, S., and Mohammadi, B. (2015). "Evaluation of the effect of thermal treatment on the contact angle and adhesion strength of water-based clear lacquer and semi-polyester on fir wood," *Iranian Journal of Wood and Paper Science Research* 30, 173-181.

Jamali, A., and Denes, F. (2008). "Water vapor plasma processing of wood: FTIR spectroscopy reveals increases in lignin-related bands and decreases in carbohydrate bands," *Journal of Wood Preservation*, Report, 1–10.

Kamperidou, V. (2019). "The biological durability of thermally- and chemically-modified black pine and poplar wood against basidiomycetes and mold action," *Forests* 10(12), 1111-1128.

Klébert, S., and Unger, E. (2022). "Can plasma surface treatment replace traditional wood modification methods?" *Coatings* 12(4), article 487. https://doi.org/10.3390/coatings12040487

Koševová, Z., Ráheľ, J., and Galmiz, O. (2021). "Plasma treatment of thermally modified and unmodified wood surfaces by diffuse coplanar surface barrier discharge," *Coatings* 11(1), article 40. https://doi.org/10.3390/coatings11010040

Novak, P., Popelka, A., Spitalsky, Z., Micusik, M., Omastova, M., Valentin, M., Sediacik, J., Janigova, L., Kleinova, A., and Slof, M. (2015). "Investigation of beech wood modified by radio-frequency discharge plasma," *Vacuum* 119(September), 88-94. https://doi.org/10.1016/j.vacuum.2015.4.38

Tu, Y., Liang, J., Yu, L., Wu, Z., Xi, X., Zhang, B., Tian, M., and Li, D. (2023). "Effects of plasma treatment on the surface characteristics and bonding performance of *Pinus massoniana* wood," *Forests* 14(7), article 1346. https://doi.org/10.3390/f14071346

Výbohová, E., Kučerová, V., Andor, T., Balážová, Ž., and Veľková, V. (2018). "The effect of heat treatment on the chemical composition of ash wood," *BioResources* 13(4), 8394-8408. https://doi.org/10.15376/biores.13.4.8394-8408

Zeleniakiene, J., and Žiogelis, R. (2023). "Chemical profiling of thermally modified wood using ATR-FTIR and chemometric modeling," *Materials* 6(4), 46-58.

Zhang, J., Kamke, F., and Gong, M. (2020). "FTIR analysis of chemical changes in thermally modified softwoods," *Wood Science and Technology* 54, 625-641.

Žigon, J., Saražin, J., Šernek, M., Kovač, J., and Dahle, S. (2021). "The effect of ageing on bonding performance of plasma treated beech wood with urea-formaldehyde adhesive," *Cellulose* (2021) 28, 2461-2478. https://doi.org/10.1007/s10570-021-03687-z

Žigon, J., Sedighi Moghaddam, M., and Wålinder, M. E. P. (2022). "Wettability and surface interactions of natural and thermally modified pine wood with water and water-based coatings: The effect of surface pretreatment type," *European Journal of Wood & Wood Products* 80, 1523-1533. https://doi.org/10.1007/s00107-022-01892-9

Zille, A., Oliveira, F. R., and Souto, A. P. (2015). "Plasma treatment in textile industry," *Plasma Processes and Polymers* 12(2), 98-131. https://doi.org/10.1002/ppap.201400052

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