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ORIGINAL ARTICLE

Effects of steaming treatment on the technological properties of olive wood

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Abstract

Wood modification is a process that alters the properties of wood through chemical, thermal, or physical treatments, thereby improving its performance, including durability and dimensional stability. Steaming is a hygrothermal treatment that can modify physical properties and may affect mechanical performance depending on process severity. This study investigated the effects of low-temperature steaming on olive wood (*Olea europaea* L.) by applying a constant temperature (80 °C) and varying treatment duration (12, 18, and 36 h) compared with natural seasoning (control). Color and dynamic modulus of elasticity (MOE_d) were measured on boards before and after treatment; after, specimens were tested for dimensional stability, bending properties (MOR and MOE_s), compression strength, Janka hardness, and abrasion resistance. Steaming produced significant color changes in both heartwood and sapwood, with stronger responses in sapwood. Bending properties showed non-significant increasing trends, with mean MOR increasing from 50.21 MPa (control) to 62.24–64.71 MPa and the highest mean MOE_s observed in the 12 h group (+13.45% vs. control). Compression strength was comparable to the control (56.34–57.77 MPa). Janka hardness showed a decreasing tendency (up to −21.3% in the 12 h group), while abrasion weight loss increased slightly and differed significantly among groups (0.21% in control vs. 0.24–0.29% after steaming). Overall, low-temperature steaming at 80 °C appears suitable for improving olive wood color uniformity and selected technological performance while limiting the mechanical degradation typically associated with high-temperature thermal modification.

1 Introduction

Wood is a natural material that has been used for centuries in numerous applications, including construction, furniture, and packaging (Rowell et al.2005), wood-based products (Kaplan et al. 2018), and structural elements in buildings and bridges (Wacker 2021). It has high economic relevance, and it can be easily processed (Kaplan et al. 2018; Terzopoulou and Kamperidou 2022); it is also low-priced and readily available (Jones and Sandberg 2020). However, wood is a biological material and its performance is influenced by species, growth conditions and natural variability. As a result, its use can be limited by hygroscopic behavior and dimensional instability, limited durability (i.e., low resistance) against biotic agents (fungi and insects) and abiotic factors (weathering and moisture cycling), and variability in mechanical and physical properties (Xie et al. 2013; Jones and Sandberg 2020). These limitations can be mitigated by applying different modifications to increase its practicability (Jones and Brischke 2017).

Wood modification includes chemical, biological and physical treatments that aim to improve wood performance for interior and exterior applications (Militz 2015, 2020). Among physical approaches, thermal modification generally refers to heating wood at elevated temperatures—typically about 160–240 °C—under reduced-oxygen conditions (e.g., steam, inert gas, vacuum, or hot oil), mainly to limit oxidative degradation and promote controlled chemical changes (UNI CEN/TS 15679 2008; Larnøy et al. 2005; Willems et al. 2020). These treatments commonly improve dimensional stability and reduce hygroscopicity; however, as

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treatment severity increases, they may also cause reductions in mechanical performance, largely associated with hemicellulose degradation and related structural changes (Hillis 1984; Shi et al. 2007; Kocaefe et al. 2007, 2010; Baar et al. 2021). Consequently, the balance between improved technological properties and possible strength losses depends on species and process parameters (temperature, duration, and moisture/oxygen availability) (Kocaefe et al. 2007, 2010; Willems et al. 2020). In this context, steaming treatments may include steam-assisted heat treatments at medium–high temperatures (often pressurized) and mild, low-temperature steaming used mainly as a hygrothermal conditioning process (Varga and van der Zee 2008; Todaro et al. 2012; Volkmer et al. 2014; Cetera et al. 2016; Klarić et al. 2024).

The mechanical and physical properties after steaming treatment depend on the wood species and the type of treatment (Baar et al. 2021). The hydrolysis reactions are also affected by moisture content, treatment temperature, presence and absence of oxygen, and treatment time, which change the mechanical properties (Kocaefe et al. 2007, 2010). Salmén (1984) and Kelley et al. (1987) affirm that the moisture content of wood affects its mechanical properties in several ways. According to Hillis (1984), the hygroscopicity of wood decreases more rapidly under high humidity conditions, while Rusche (1973) further emphasizes that, in addition to moisture, higher oxygen concentrations accelerate the degradation rate, weight loss, and reduction in mechanical properties. As the oxygen concentration increases, the loss of mass increases and the overall extent of modification is quite variable (Romagnoli et al. 2015). Kocaefe (2010) demonstrated that extended treatment times and higher temperatures negatively affect degradation and, consequently, mechanical properties. Currently, several treatments are available that differ in inert atmosphere and temperature curing conditions (Zanuttini et al. 2019). There are five main methods of thermal modification treatment in Europe (Militz 2002)—the Dutch PLATO Process, the Retification Process (or NOW in France), the Bois Perdure Process (France), the OHT Process (Germany), and the ThermoWood Process (Finland). These wood treatments are subjected to temperatures close to or above 200 °C for several hours in a low-oxygen atmosphere. The principal differences between these methods are the technique conditions (oxygen or nitrogen, water spray, use of oil, and/or water steaming) (Homan and Jorissen 2004).

The steaming treatment of wood is also an effective method for changing its physical and mechanical properties. Hydrothermal treatment through pre-steaming, steaming, or boiling in water is frequently utilized in the wood processing sector. It is typically used for the treatment of veneer, lumber, or board prior to or following kiln-drying. Steaming wood involves heating the wood using steam without the process of drying. The advantage of steam lies in its capacity to wet the wood surface through the condensate and its exceptional ability to infiltrate even dense bundles. According to Syrjanen (2001), the various fields of application for steamed wood include exterior cladding, window and door frames, wood paneling, garden furniture, sauna furniture, flooring and decking, etc. The changes in physical properties resulting from the treatment are manifested in enhanced dimensional stability, reduced hygroscopicity and absorbability, increased resistance to fungal attack, and a darker wood coloration. Steaming treatment, in particular, represents one of the most environmentally friendly techniques for preserving wood, as it does not entail the use of chemicals (Kocaefe et al. 2007, 2010). Instead, the color changes occurred on wood during steaming process are based mainly on chemical reactions of the cell wall component (lignin, holocellulose and extractives) (Varga and van der Zee 2008; Endo et al. 2016). Certainly, the degree of color change is greatly affected by exposure duration, temperature, and moisture level, but the variations are also linked to the wood species (Mayer et al. 2006; Todaro et al. 2012). However, as suggested by Niemz et al. (2023), with temperatures between 80 and 95 °C is possible to homogenize color getting also a reduction of the absorption isotherm. Steaming times range from short exposures under high temperature/pressurized conditions (typically above 100 °C) to several hours under milder temperatures, including below 100 °C (Rowell et al. 2002). Wood can change its properties, behaving as a linear elastic solid, a viscous fluid, or a viscoelastic material, depending on the heating time, the temperature, and the concentration of other components (Militz 2002). Given the numerous parameters influencing degradation, it is challenging to determine a definitive mechanism that accounts for the changes in mechanical properties during steam treatment. The general effects of thermal and hygrothermal treatments on hygroscopicity, dimensional stability, color and mechanical performance are widely discussed in comprehensive books and review articles, which describe the underlying chemical changes and the typical trade-offs between improved stability/durability and reduced strength at higher temperatures (Hill 2007; Esteves and Pereira 2009; Navi and Sandberg 2012). These sources provide a framework for interpreting species- and schedule-dependent outcomes and for situating mild steaming within the broader family of thermal treatment processes.

Several studies have investigated the effects of steaming treatments on wood performance (Jämsä and Viitaniemi 2001; Unsal and Ayrilmis 2005; Shi et al. 2007; Korkut and Hiziroglu 2009; Kocaefe et al. 2010; Pelit et al. 2018). Overall, the literature suggests that changes in physical and mechanical properties depend strongly on species, initial moisture content, and temperature and duration of

treatment. In medium–high temperature schedules (commonly above 120 °C), reductions in strength and stiffness are frequently reported, consistent with thermal degradation of wood polymers.

Despite the extensive research conducted on thermal modification, comparatively less attention has been given to steaming treatments at temperatures below 100 °C, particularly in the context of hardwoods. Low-temperature steaming is potentially interesting for applications that aim to improve appearance and dimensional behavior while limiting mechanical degradation typically associated with higher temperatures. In addition to changes in physical and mechanical behavior, steaming is widely used to modify wood appearance. Wood color may vary substantially within the same species and, in many cases, the contrast between heartwood and sapwood is particularly marked. For species showing pronounced heartwood-sapwood differences, steam treatment is often applied to darken sapwood, thereby reducing color mismatch between heartwood and sapwood and improving overall visual uniformity (Klarić et al. 2024). As color changes are influenced by species, initial color, and process conditions, the modification of color under low-temperature steaming requires specific investigation alongside the investigation of related properties.

Among the various woods of economic interest, olive wood, characterized by high density and impressive hardness, has attracted increasing attention in recent years, as its mechanical properties make it suitable for parquet flooring, furniture, and other indoor products. Moreover, olive tree cultivation is one of the most widespread industries throughout the Mediterranean and the world. Therefore, from its periodic pruning, it is possible to obtain sawn timber that is useful for subsequent processing and transformation. The average production of olive pruning wood residues is about 1.7 tons/ha; about 10,950,000 hectares of olive groves are used worldwide, of which about 1,100,000 hectares are used for olive growing in Italy (Lo Giudice et al. 2021; Uzudumulu and Ates 2025). Considering the enormous potential of the utilization of such wood and considering that all previous studies mentioned tested the effects of steaming at medium-high temperatures (ranging from 120 to 220 °C), the present study evaluates steaming treatment of olive wood at 80 °C for 12, 18, and 36 h, compared with natural seasoning. It is hypothesized that the three steaming durations applied at 80 °C may reduce some limiting factors of olive wood by decreasing equilibrium moisture content and, consequently, improving dimensional stability. It is also hypothesized that mild steaming may promote color changes between sapwood and heartwood, thereby improving overall visual uniformity. The study quantifies color changes, separately for heartwood and sapwood, and measures MOE_d on boards before and after steaming. After treatment, specimens were tested for dimensional stability, bending properties, compression strength, static hardness, and abrasion resistance to provide an integrated assessment of the potential of low-temperature steaming for olive wood.

Table 1 Physical properties of *Olea europaea* wood

Property	Unit of measure	Mean	SD	*N*
Radial shrinkage	%	2.6	0.3	30
Tangential shrinkage	%	6.3	1.4	30
Axial shrinkage	%	1.1	0.7	30
Volumetric shrinkage	%	11.7	1.4	30
Density at 12% moisture content	kg/m^3	1020	61	30

2 Materials and methods

2.1 Wood sampling and steaming treatment

The wood material was collected from a local olive orchard (*Olea europaea* L.) after fruit harvesting operations in the municipality of Molochio, in the 'Plain of Gioia Tauro' (Southern Italy). During pruning operations, branches with a diameter of less than 20 cm were excluded. The carefully selected logs were transported to a sawmill (Cataldo et al. 2025), where 48 boards were chosen for steaming treatment. Each board measured 90 × 25 × 3.3 cm and was divided into the following four groups: natural seasoning, 12-hour cycle (code A), 18-hour cycle (code B), and 36-hour cycle (code C). Natural seasoning of wood material was achieved outdoors in the open air, but under cover to avoid the rain, in a space beside the laboratory for six months (from February 2023 to July 2023), in Reggio Calabria (Southern Italy). The stack, containing 48 parallel boards, separated by sticks and elevated 40 cm from the floor, was prepared with S-SW orientation. Each group consists of 12 sawn boards. Table 1 describes some physical characteristics of the olive wood measured at the laboratory of Wood Technology of the AGRARIA Department of Reggio Calabria.

2.2 Laboratory test

The sawn boards were divided into three groups (A, B, C) and each group was subjected to steam under saturated conditions and a maximum pressure of approximately 80 °C and 47 kPa for 12 h, 18 h, and 36 h, respectively. The steamer plant was a purpose-made cylindric pressure chamber, having a volume of 1.8 m^3. The autoclave was realized with a basin of boiling water and equipped with air and wood temperature thermocouple and a pressure gauge. The values were monitored and constantly downloaded on a PC, and then analyzed.

Dynamic modulus of elasticity (MOE_d) and color measurements were conducted on the sawn boards before and after steaming. After steaming, specimens were obtained from the boards to determine different properties: dimensional stability, bending strength, compression strength, Janka hardness, and surface abrasion tests.

Once the specimens were prepared, they were conditioned in a climatic chamber (Memmert 750 Eco, GmbH, Germany; temperature control setting accuracy 0.1 °C and humidity control setting accuracy 0.5%RH) at 20 °C (±2) and 65% (±5) relative humidity (RH) to reach an equilibrium moisture content (EMC) of 12%. The air-dried density of each sample was determined in accordance with the ISO 13061-2 2014, and moisture content was determined using the oven drying method (ISO 13061-1 2014). The tests were carried out in the laboratory of Wood Technology of the AGRARIA Department of Reggio Calabria. The distribution of tests is shown in Table 2. For each test, specimens were extracted from all boards within each group to ensure a uniform distribution of sampling positions and to minimize within-group variability. For color measurements ($n=8$) and abrasion resistance ($n=10$), where the required number of specimens was lower than the number of available boards (12), specimens were selected using a systematic sampling approach with a random start, ensuring an even distribution across the board set and no more than one specimen per board. In addition, specimens were taken from a standardized position along each selected board to reduce within-board variability (Mammoliti et al. 2024).

2.3 Color measurement

Color measurements of all boards were recorded on the surface of the wood samples before and after steam treatment using a SAMA tools colorimeter (accuracy 0.08 ΔEab). The sensor head had a diameter of 4 mm. Measurements were performed with a standard observer of 8° and a D65 illuminant. The reflectance percentage was converted to the CIELAB color system, where L describes the brightness; a and b describe the chromaticity coordinates on the green–red and blue–yellow axis, respectively. Tests were performed on both sapwood and heartwood. A measuring tape was placed diagonally across the board. The first measurement was taken on the sapwood, at approximately 10 cm. The second measurement was taken on the heartwood, at about half length. From the laboratory values, the difference in brightness (ΔL) and chromaticity coordinates (Δa and Δb), as well as the total color difference (ΔE), were calculated using the following formulas (Eqs. 1; 2; 3; 4):

$$\Delta L = l_2 - l_1 \tag{1}$$

$$\Delta a = a_2 - a_1 \tag{2}$$

$$\Delta b = b_2 - b_1 \tag{3}$$

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

where l_1, a_1, and b_1 = measurements before treatment; l_2, a_2, and b_2 = measurements after treatment.

2.4 Determination of dimensional stability of steamed wood

The dimensional stability test was conducted to compare how steamed and naturally seasoned olive wood responded to different temperature–humidity cycles under controlled climatic conditions. The mass and dimensions of all specimens were recorded before being placed in the climatic chamber (day 0). A 28-day (4-week) protocol was then applied in a climatic chamber, using three different conditions: 20 °C (±2) and 65% (±5) RH, 40 °C (±2) and 85% (±5) RH, and 10 °C (±2) and 90% (±5) RH. The three climatic cycles were conducted using separate sets of specimens, and for each condition, mass and dimensions were measured weekly (7, 14, 21, and 28 days). Dimensions were measured in the three anatomical directions (radial, tangential, and longitudinal) using a digital comparator (Mitutoyo ID-C ABSOLUTE Digimatic; accuracy 0.02 mm), and specimen volume was calculated from the measured dimensions

Table 2 Distribution of specimens

	Color measurements	Dimensional stability	MOE_d	Bending strength	Compressive strength	Janka hardness	Abrasion resistance
Natural seasoning	8	120	12	14	35	20	10
Group A	8	120	12	14	35	20	10
Group B	8	120	12	14	35	20	10
Group C	8	120	12	14	35	20	10
Total number of specimens	32	480	48	56	140	80	40

(Mammoliti et al. 2024). Weight was determined using an analytical balance (Nimbus NBL 223e; accuracy 0.001 g). The average dimensions of the specimens were 31.01 mm (±1.28), 31.53 mm (±1.44), and 48.65 mm (±1.26) for the radial, tangential, and longitudinal directions, respectively. The average weight was 44.48 gr (±2.82).

2.5 Determination of dynamic modulus of elasticity (MOE_d) with microsecond timer

The MOE_d was determined parallel to the grain. The boards were subjected to a single-path stress wave test using a Microsecond Timer (accuracy ± 3 µs) (Fakopp Enterprise, Agfalva, Hungary). This instrument consists of needles connected to accelerometers, which act as mediators and are inserted into the wood surface to ensure good contact with the board. A hammer is used to tap the starting sensor to generate a stress wave in the board in the longitudinal direction (Papandrea et al. 2022). The two sensors detect the start and stop signal, and the transmission time of the wave is displayed on an LCD screen with a resolution of ± 1 µs. The sensors were positioned at 85 cm from each other at an angle of 45°. The test was repeated several times for each pair of sensors to obtain the average value of at least three readings. In addition, the moisture content of each sawn board was determined using a digital moisture meter with two electrodes (Schaller, WLW). Measurements were performed on wood from a 90 × 25 × 3.3 cm sawn board. The tests were carried out before and after the steaming treatment.

With the density and speed of the wave available, it was possible to derive the MOE_d (Eq. 5).

$$MOE_d = v^2 * D \tag{5}$$

where v = wave transmission velocity (m/s); D = density (kg/m^3).

2.6 Determination of the static modulus of elasticity and the modulus of rupture

The static modulus of elasticity (MOE_s) and the bending strength or MOR were determined perpendicular to the grain. A four-point bending test was performed using a 300 kN universal testing machine (METRO COM, Italy – 10402030 model), in accordance with the EN 408:2010 + A1 (2012). Data were recorded using the dedicated METRO COM software. The length of the specimen was 21 times its width. The supports were placed at a distance equal to 18 times the width, and the two load points were placed at a distance from each support equal to 6 times the width. During the tests, the load and the bend values were registered. The specimens had a square cross-section with a side of 3.3 cm. The length, parallel to the grain, was 69.3 cm. The distance between the two loading points was 19.8 cm, while the distance between the two supports was 59.4 cm. The feed rate of the crosshead was 5.9 mm/min.

2.7 Determination of compression strength and static hardness—Janka

In the same laboratory, a compressive strength test was performed following the ISO 13061-17 2022. The specimens had a square cross-section with a side length of 3.3 cm. The length, parallel to the grain, was 5 cm. The maximum load is reached in no less than 1 min and no more than 5 min after the start of loading; a feed speed of 6 mm/min was set. During the tests, the values of the load and the bend were registered. The compressive strength was measured using Eq. 6, as follows:

$$C = \frac{F_{max}}{A} \tag{6}$$

where C = compressive strength parallel to the grain (N/mm^2); F_{max} = maximum load (N); A = cross-sectional area (mm^2).

The Janka hardness test was performed in accordance with the ISO 13061-12 2017. For this method, a hemispherical ball with a radius of 5.64 mm was utilized as the penetrating agent. The ball was inserted into the sample to a depth of 2.82 mm, and the maximum force exerted during the test was recorded. The Janka hardness was calculated using Eq. 7, as follows:

$$H_W = K * F \tag{7}$$

where H_W = surface hardness at moisture content W (kN); K = coefficient equal to 4/3 in the case of the penetration of the plunger to a depth of 2.82 mm; F = maximum load during the penetration of the plunger into the test sample to the specified depth (kN). A feed speed of 6 mm/min was set. The test specimens have a square cross-section of 50 × 50 × 3.3 mm. The test was carried out on the tangential section of the test specimen.

2.8 Determination of abrasion resistance

Abrasion resistance was determined according to the Taber test (5135 Abraser v2.001), using the sandpaper method, following UNI EN 15185:2011. A 240-grit sandpaper and

a load of 10 (±0.1) N (EN 1534 2020) was used for each of the two grinding wheels. The specimens were square (10 cm side) with rounded corners and had a thickness of 2.5 cm. Each wood sample was weighed before (W_1) subjecting it to the abrasion test using the ADAM Nimbus analytical balance. The samples were fixed to the Taber Abraser and the abrasion test was conducted by setting the wheel to rotate at 72 cycles per minute. After 500 revolutions, the weight loss (W_2) due to abrasion was recorded. The weight loss (W_L) due to abrasion was calculated as a percentage for each sample according to Eq. 8, as follows:

$$W_L = \frac{W_1 - W_2}{W_1} 100 \quad (8)$$

where W_L = weight loss (%); W_1 = weight of test specimen before abrasion (g); W_2 = weight of test specimen after abrasion (g). Figure 1 shows the different tests conducted.

2.9 Data analysis

The statistical analysis examined which dependent variables were statistically different in relation to the duration of the steaming treatment. A multivariate analysis was carried out, considering the duration of steaming treatment as the independent variable; then, a post hoc test was performed, applying a 95% confidence interval. SPSS software version 20.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analysis of the data.

3 Results and discussion

The following paragraphs present the results obtained from the various types of laboratory tests. Because there is a lack of studies on low-temperature steaming (< 100 °C), comparisons were limited to the closest available literature selected by treatment severity (temperature–time range). This aspect may represent a limitation of the study; however, the

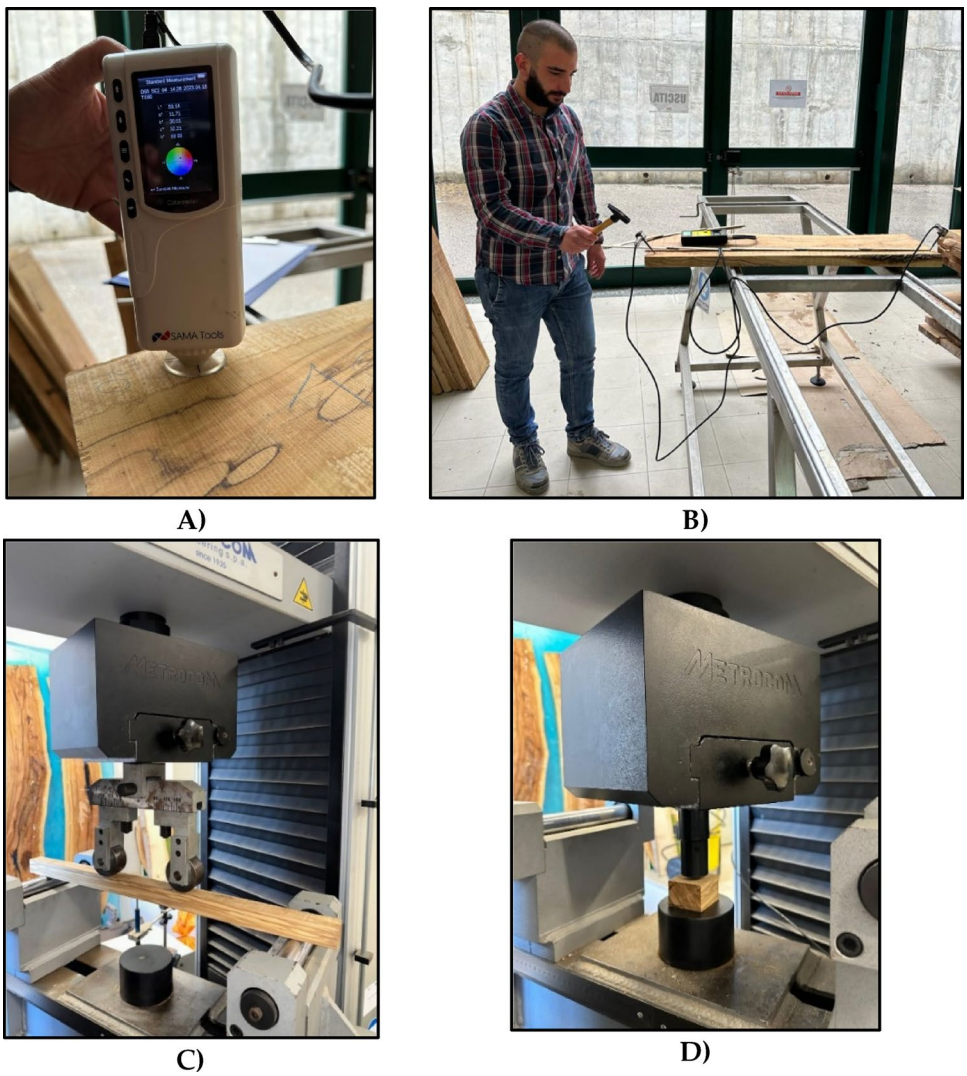


Fig. 1 Tests conducted: **A** Color measurements, **B** MOE_d, **C** Bending strength, **D** static hardness – Janka

authors aim to draw the scientific community's attention to the effects of low-temperature steaming on hardwood species, such as olive wood.

3.1 Color measurements

During the visual analysis with the colorimeter, it was found that the sapwood was more affected than the heartwood. The sapwood showed a greater browning (ΔL) than the heartwood. The greatest darkening of sapwood occurred in the group C cycle, with a loss of 13.60 units. This was followed by the group A, the group B, and natural seasoning wood, with a loss of 11.75, 6.74, and 1.69 units, respectively. Heartwood also suffered more darkening with the group C cycle (−7.88 units). This was followed by the group A cycle (−6.15 units), the group B cycle (−5.52 units), and natural seasoning wood (−1.74 units). An increase in Δa was observed in heartwood for all groups, whereas in sapwood Δa showed a more variable response (including a decrease in Group A). For heartwood, an increase in Δb is observed. In contrast, for sapwood, a loss of Δb is observed in the treatment cycles; however, an increase is observed for the natural seasoning cycle. Finally, the total color change (ΔE) of heartwood occurs in the group B cycle (9.70 units), followed by the group C cycle (9.29 units) and the group A cycle (8.31 units). The largest total color change (ΔE) in sapwood occurs for the group C cycle (15.75 units) and the group A cycle (13.56 units). This is followed by the group B cycle (9.44 units) and the natural seasoning cycle (3.64 units). Table 3 illustrates how the various color parameters change according to the duration of the steaming treatment.

Bekhta and Niemz (2003) observed significant color alterations following heat treatment at 200 °C on spruce wood samples; with each treatment, the darkening increased. The greatest L reduction was observed for wood samples completely saturated with water; the loss of brightness was about 72.81% after 24 h of treatment at 200 °C, reaching a very low value (21 units) compared to 77.24 units for untreated wood. Furthermore, Bekhta and Niemz (2003) showed that a heat treatment of 4 h decreases brightness radically. In particular, the a value rises by about 38–53% in the first 2 h and then remains almost the same as after that. Conversely, the b value exhibited a substantial decline, reaching a reduction of approximately 30–45% after 24 h of treatment. During the first 2 h of treatment, the measured value increased relative to untreated wood, followed by a decline with longer durations. Within the first 4 h, the wood's color changed from yellow to blue. A notable reduction in the hue angle (h) by approximately 22–29% was recorded as the treatment duration extended from 0 to 24 h, indicating a progressive shift toward a redder hue. Additionally, the total color difference (ΔE) increased from 22 to 28% after 2 h to 43–57% after 24 h of treatment. The results suggest that using a low treatment temperature may contribute to improved color uniformity, possibly through changes in extractives and polymers. Piernik et al. (2022) found that extending the duration of the heat treatment of Scots pine leads to an increase in ΔE of approximately 20%. In addition, the longer duration leads to a decrease in ΔL of about 35%; therefore, the color of the wood becomes darker. With an extension of the heat treatment duration, an upward trend is observed for ΔE. The level of total wood color change is mainly determined by the parameter whose value changes the most, i.e., ΔL.

3.2 Dimensional stability of steamed wood

Under the 28-day conditioning at 20 °C and 65% RH, all groups showed very small negative dimensional changes in the three anatomical directions, resulting in a limited volumetric dimensional change. The volumetric change ranged from 0.16% in the air-dried control to 0.17% in the 12 h and 18 h steamed groups and 0.19% in the 36 h group, indicating that dimensional variations under these conditions were minor and comparable among treatments. In the radial

Table 3 Changes in CIELAB parameters (mean ± SD) after steaming (post–pre values)

	ΔL	Δa	Δb	ΔE
Heartwood				
Natural seasoning	−1.74 (±1.96)	2.93 (±1.65)	1.97 (±1.27)	4.39 (±1.96)
Group A	−6.15 (±4.87)	1.73 (±2.18)	−2.55 (±3.35)	8.31 (±3.88)
Group B	−5.52 (±1.94)	1.68 (±3.01)	−6.08 (±7.89)	9.70 (±6.28)
Group C	−7.88 (±3.50)	2.12 (±1.96)	−3.78 (±2.69)	9.29 (±4.14)
Sapwood				
Natural seasoning	−1.69 (±2.59)	2.15 (±1.62)	1.26 (±1.13)	3.64 (±2.40)
Group A	−11.75 (±3.88)	−2.92 (±2.76)	−4.88 (±2.57)	13.56 (±3.74)
Group B	−6.74 (±6.55)	1.89 (±4.96)	−3.81 (±2.40)	9.44 (±5.89)
Group C	−13.60 (±3.30)	4.36 (±2.59)	−5.70 (±1.97)	15.75 (±2.92)

ΔL, Δa, and Δb are the differences in the initial and final values (before and after the steaming treatment) of the L, a, and b parameters, respectively. ΔE is the total color change

direction, changes were close to zero (−0.06% to −0.04% across the steamed groups, and −0.07% in the control), while tangential changes were similarly small (approximately −0.07% to −0.10%). In contrast to the dimensional response, mass change differed more clearly among treatments: the natural seasoning specimens showed the largest weight loss (−2.13%), whereas steamed specimens exhibited smaller losses (−0.86%, −1.08%, and −0.75% for 12 h, 18 h, and 36 h, respectively). Overall, at 20 °C/65% RH the main observable difference among groups was the reduced mass loss after steaming, while dimensional changes remained minimal (Fig. 2).

Under the 28-day exposure at 40 °C and 85% RH, all groups showed positive dimensional changes in the three anatomical directions, with the most pronounced response in the radial direction. The radial change increased from +1.39% in the natural seasoned specimens to +2.44% (12 h), +3.39% (18 h), and +4.36% (36 h), indicating a markedly higher swelling of steamed specimens, particularly at the longest duration. Tangential changes followed the same pattern but with smaller variation, ranging from +1.01% (control) to +1.75% (12 h), +1.81% (18 h), and +2.75% (36 h). Longitudinal changes remained very limited, as expected, and were close to zero across all groups. In line with the dimensional response, mass increased over the cycle, from +1.37% in the natural seasoned specimens to +1.92%, +2.00%, and +2.25% for the 12 h, 18 h, and 36 h treatments, respectively. Overall, under warm and highly humid conditions, the steamed groups exhibited higher mass gain and larger swelling, with a clear increase in response with steaming duration (Fig. 3).

During the 28-day exposure at 10 °C and 90% RH, specimens also exhibited positive dimensional changes, though with variation generally lower than those observed at 40 °C/85% RH for radial and tangential directions. Radial swelling increased from +0.77% in the natural seasoned specimens to +0.86% (12 h), +0.90% (18 h), and +1.00% (36 h), showing a modest but consistent increase for steamed wood. Tangential changes ranged from +0.48% (control) to +0.55% (12 h), +0.77% (18 h), and +0.63% (36 h), with the 18 h group showing the highest tangential response. Longitudinal changes remained minimal and close to zero for all treatments. Mass gain was higher than in the 40 °C/85% RH cycle, increasing from +2.67% in the control to +2.77% (12 h), +3.34% (18 h), and +3.03% (36 h). Overall, at 10 °C/90% RH the steamed wood show slightly greater swelling and mass gain than the natural seasoned specimens, with the strongest response often observed in the intermediate duration (18 h) (Fig. 4).

Across the three climatic conditions, the dimensional response of olive wood was strongly dependent on the temperature–humidity combination. Conditioning at 20 °C/65%

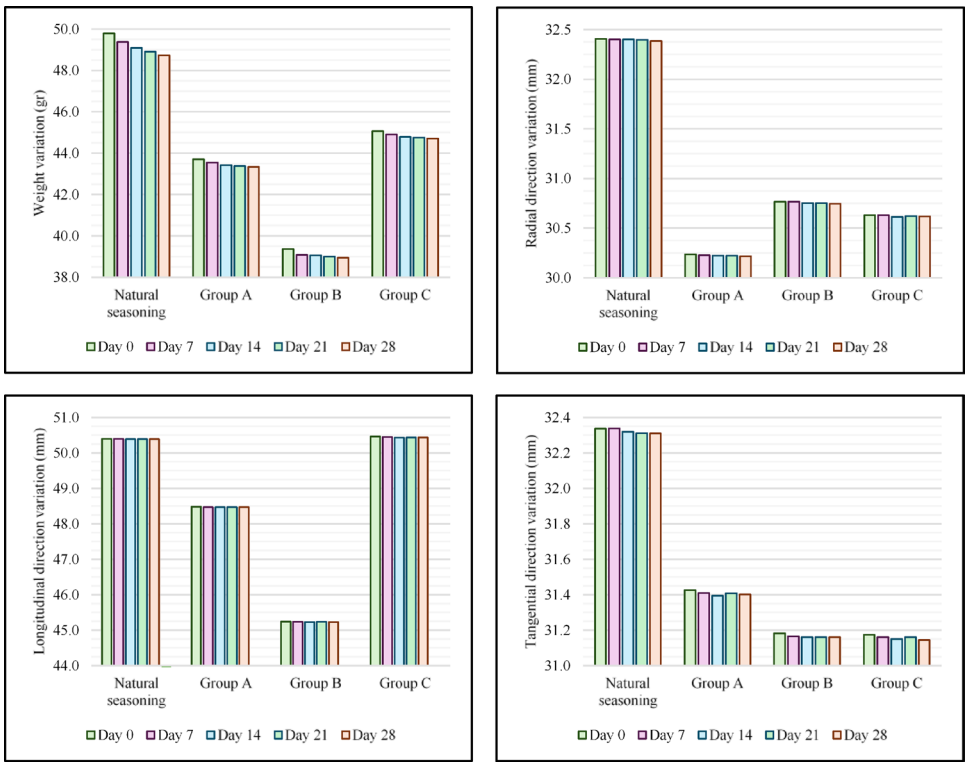


Fig. 2 Weight and dimensional variation during 28-day conditioning at 20 °C/65% RH for natural and steamed specimens

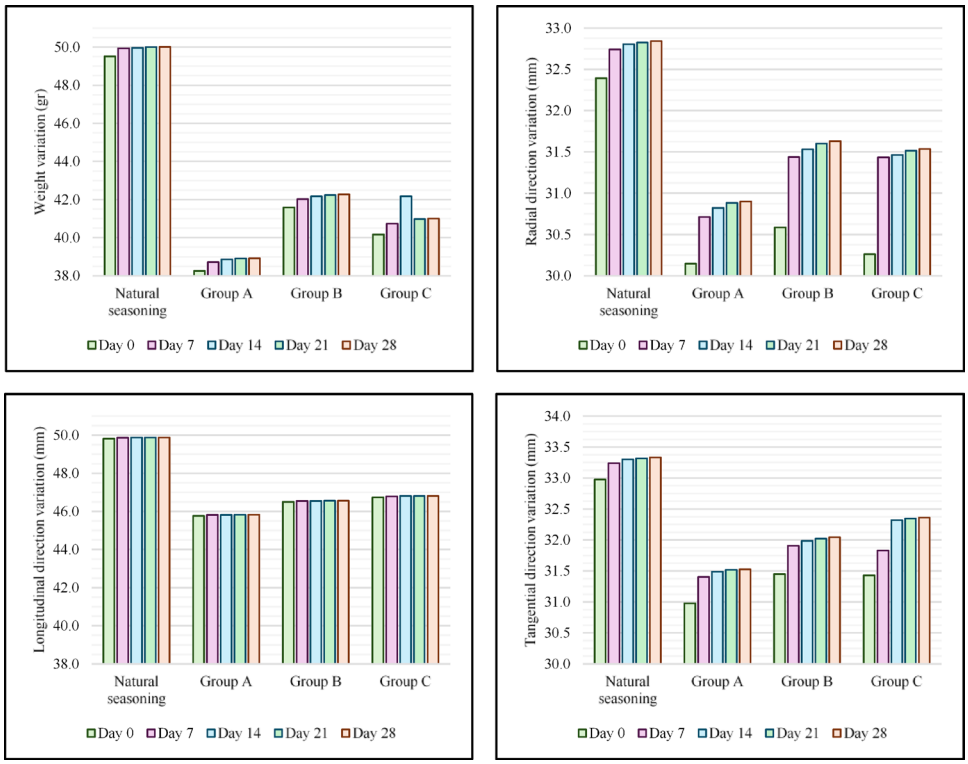


Fig. 3 Weight and dimensional variation during 28-day conditioning at 40 °C/85% RH for natural and steamed specimens

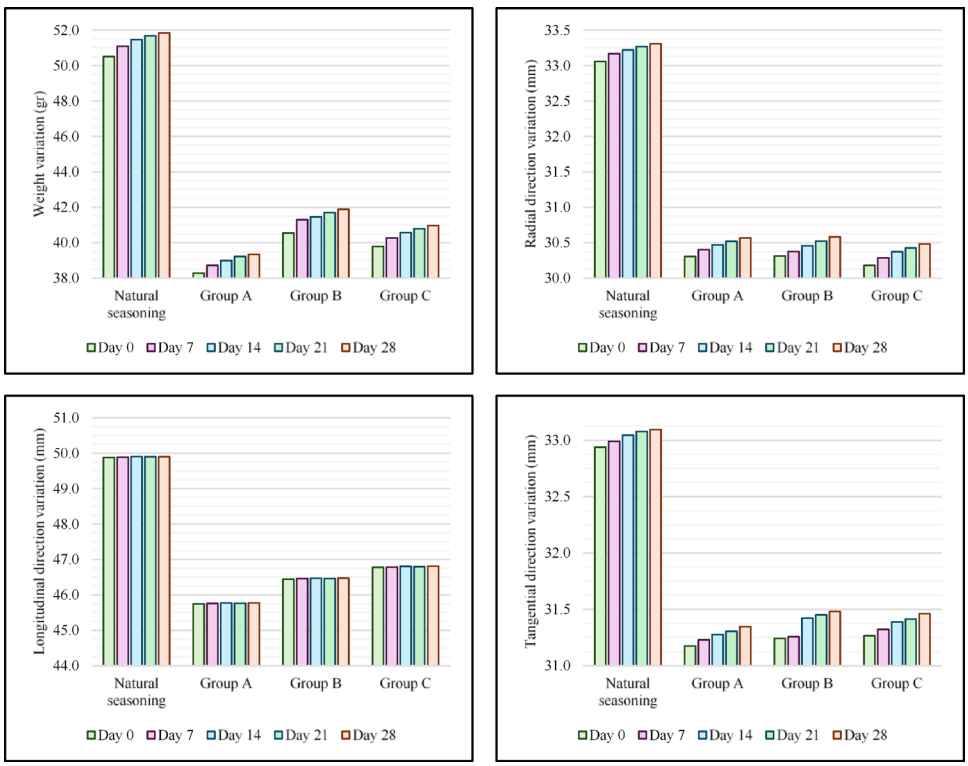


Fig. 4 Weight and dimensional variation during 28-day conditioning at 10 °C/90% RH for natural and steamed specimens

RH produced only minor negative dimensional changes, whereas both high humidity and different temperature schedules led to swelling, with markedly different variation. The warm/humid cycle (40 °C/85% RH) resulted in the largest dimensional increases—especially in the radial direction—and showed a clear tendency for greater swelling with increasing steaming duration. In contrast, the cool/humid cycle (10 °C/90% RH) produced a more moderate swelling response, with steamed specimens generally exhibiting slightly higher dimensional changes and mass gains than the natural seasoned specimens. Overall, under the present conditions, steaming mainly influenced the moisture-related response under humid environments, with little difference observed at 20 °C/65% RH.

3.3 Dynamic modulus of elasticity

By evaluating the tests performed with the microsecond timer, the measurements showed only minor variations in MOE_d after steaming, with mean changes ranging from −1.08% (control) to +4.57% (12 h), +4.39% (18 h), and +0.23% (36 h). However, the effect of treatment duration on post-treatment MOE_d was not statistically significant (univariate ANOVA within the multivariate model, $p=0.946$, Table 4). Therefore, within the variability of the measurements, low-temperature steaming at 80 °C did not produce a measurable change in MOE_d, and the small percentage differences should be interpreted as a tendency rather than a confirmed improvement. Figure 5 shows how the MOE_d changes according to the duration of the steaming treatment. MOE_{d1} is the MOE_d before steaming while MOE_{d2} is the dynamic MOE_d after steaming.

Todaro et al. (2021) reported that, for black poplar, MOE_d was higher after a thermal treatment (180 °C) than after a high thermal schedule (220 °C) under vacuum conditions. Compared to the control samples (10.39 GPa), the MOE_d increased by 9.71% (11.51 GPa) at 180 °C and then decreased by 5.91% (9.78 GPa) at 220 °C. Thus, the MOE_d appears to increase after the mild thermal treatment of wood, while it decreases at higher treatment temperatures. Cetera et al. (2016) reported that the MOE_d of the turkey oak wood samples was 16.77 GPa after a treatment of 160 °C for 3 h. In comparison with the control samples, the MOE_d decreased by 29.79% (12.92 GPa).

Table 4 Multivariate analysis

Source	Dependent variable	Type III sum of squares	df	Mean square	F	Sig.
Series	MST_MOE_{d2}	251500.130	3	83833.377	0.122	0.946
	ΔE_heartwood	129.999	3	43.333	4.531	0.014
	ΔE_sapwood	554.908	3	184.969	28.655	0.000
	MOE_s	16238686.355	3	5412895.452	2.197	0.120
	MOR	84.310	3	28.103	1.917	0.159
	H	4.274	3	1.425	2.617	0.079
	WL	0.029	3	0.010	3.721	0.028

MST_MOE_{d2} dynamic modulus of elasticity post steaming, *$\Delta E_heartwood$* total color variation of heartwood, *$\Delta E_sapwood$* total color variation of sapwood, *MOE_s* static modulus of elasticity, *MOR* modulus of rupture, *H* static hardness, *WL* weight loss due to abrasion

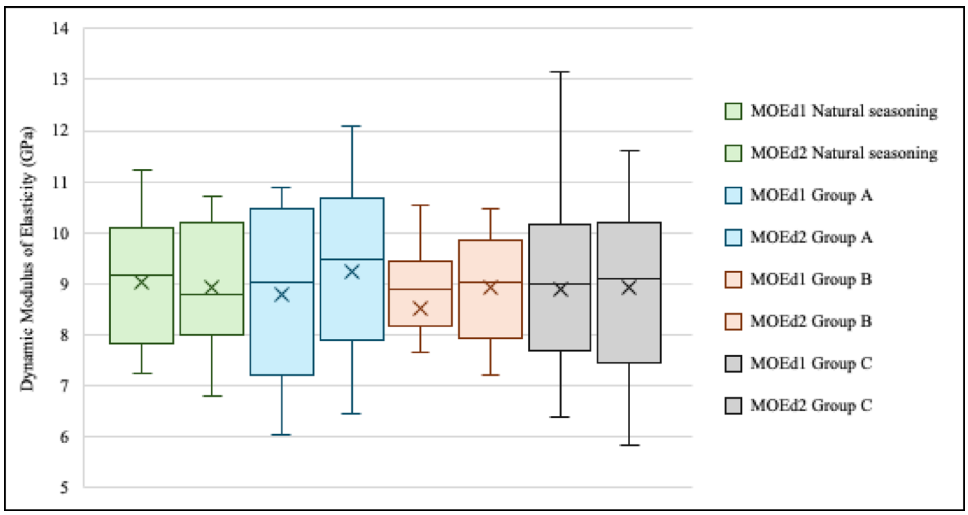


Fig. 5 Effects of steaming treatment on the dynamic modulus of elasticity

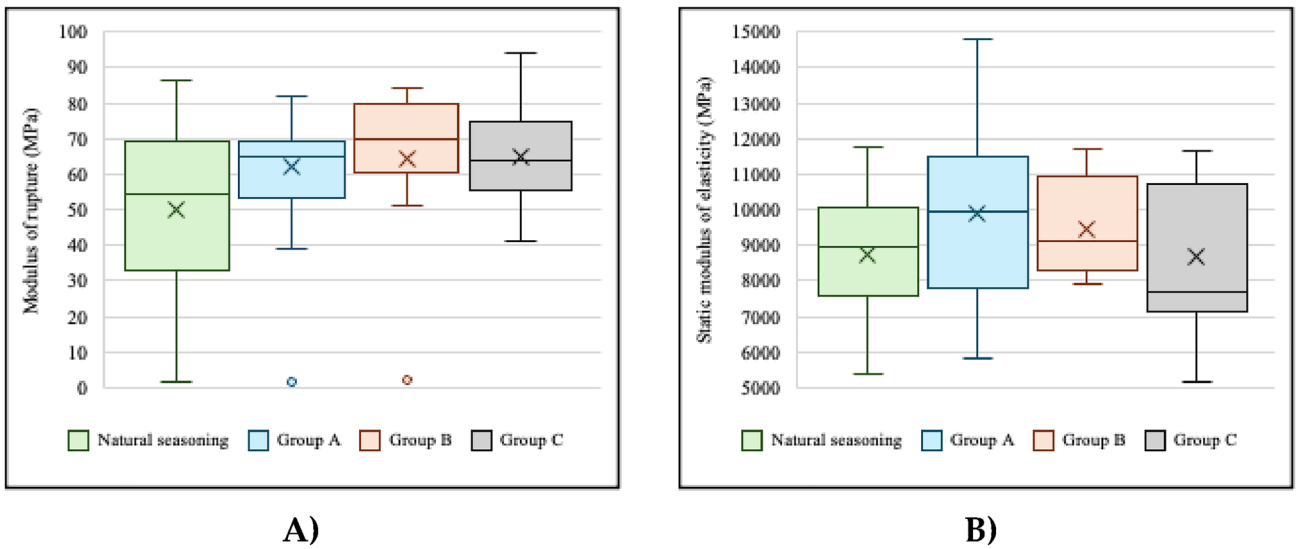


Fig. 6 Effects of steaming treatment on the MOR (**A**) and the MOE_s (**B**)

3.4 Static modulus of elasticity and modulus of rupture

Bending tests showed that steaming treatment resulted in higher mean MOR values in the steamed groups compared with control specimens, with mean MOR increasing from 50.21 MPa (natural seasoning) to 62.24 MPa (12 h), 64.57 MPa (18 h), and 64.71 MPa (36 h) (Fig. 6A). However, the overall effect of steaming duration on MOR was not statistically significant ($p=0.159$, Table 4), indicating that the observed differences should be interpreted as a trend rather than a confirmed treatment effect.

MOE_s showed mean values of 8738.23 MPa for natural seasoning, 9907.34 MPa for group A (12 h), 9456.20 MPa for group B (18 h), and 8667 MPa for group C (36 h) (Fig. 6B). Despite the slightly higher average MOE_s for the 12 h and 18 h cycles, the effect of steaming duration on MOE_s was also non-significant ($p=0.120$, Table 4). Overall, under the present conditions (80 °C steaming), bending properties exhibited moderate variability and only non-significant trends across treatment durations.

Boonstra et al. (2007) observed that a heat treatment at 165 °C applied to Scots pine samples resulted in a 10% increase in the modulus of elasticity (MOE) and a 3% reduction in the modulus of rupture (MOR) during the flexural test. In the case of radiata pine, the heat treatment at 165 °C reduced the MOR by 9% and increased the MOE by 13%. However, a further increase in temperature in the hydro thermolysis phase, up to 185 °C, caused an even more significant reduction in flexural strength, equal to 38%. When the hydro thermolysis temperature was raised to 175 °C without exposure time (0 min), a 26% increase in MOE was recorded. Subsequently, a treatment at 175 °C for 30 min, followed by an exposure to 185 °C, instead resulted in a slight reduction of 2% in MOE. Increasing the residence time during hydro thermolysis at 165 °C from 30 to 90 min caused a further 20% reduction in MOR. Although the MOE values between the 60 and 90 min treatments were similar, the 90 min treated samples showed greater variability, suggesting the presence of some structural differences. Overall, the heat treatment caused a 31% reduction in MOR, while the MOE increased by 5%. Kartal et al. (2008) found that MOR in Japanese cedar decreases with increasing duration and temperature. At a temperature of 180 °C, there is a reduction in the MOR of 1.22% at 2 h and 6.67% at 4 h. Conversely, at a temperature of 220 °C, there is a reduction of 58.28% at 2 h and of 77.60% at 4 h. Regarding MOE, they found a loss of 2.18% and 12.17%, respectively, for the 2-hour and 4-hour cycles at 180 °C. Gunduz et al. (2009) conducted a study on the heat treatment of wild pear, determining that the lowest resistance of MOR (7.5%) occurred at 160 °C for 2 h, in comparison to control samples. It was observed that the decrease in MOR values at 160 °C for 2, 4, and 6 h was 77.43 MPa, 72.56 MPa, and 65.83 MPa, respectively, compared to the control samples, which had an MOR value of 83.76 MPa. Furthermore, it was determined that the MOE at 160 °C for 2, 4, and 6 h were 7060.05 MPa, 6869.26 MPa, and 6144.14 MPa, respectively. With a different duration of heat treatment at 180 °C (2, 4 and 6 h), the MOE values were found to be 6645 MPa, 6545.86 MPa,

and 5974.97 MPa, respectively. The greatest decrease in MOR was recorded at 26% (61.92 MPa) in comparison to control samples that underwent a heat treatment of 180 °C for 6 h. Conversely, heat treatments of 2 and 4 h resulted in MOR values of 75.72 MPa and 71.27 MPa, respectively. The results of the heat treatment of wild pear wood at different temperatures (160 and 180 °C) for different times demonstrate that mechanical properties are affected by 2.5% to 27%. Kamperidou et al. (2014) conducted tests on Scots pine and found that the values of MOR and MOE decrease with the increasing duration of heat treatment at 200 °C. The average MOR value of samples treated for 4 h was 0.34% lower than the corresponding value of untreated wood samples, while samples treated for 6 and 8 h recorded MOR values that were lower by 14.6% and 25.90%, respectively. The average MOE value of samples treated for 4 h was 4.4% lower than the corresponding value of untreated samples, while the average MOE value of samples treated for 6 and 8 h showed decreases of 3.5% and 5.83%, respectively. In general, the reduction in MOE was found to be less than that of MOR. In the study conducted by Gennari et al. (2021), thermally treated wood showed a reduction in static bending strength from 61.1 to 37.6 MPa at 215 °C for a duration of 3 h. In contrast to high-temperature heat treatments, the present steaming schedule produced higher mean MOR and MOE_s values in the 12–18 h groups; however, these differences were not statistically significant and should be interpreted as trends.

3.5 Compression strength and static hardness—Janka

The compressive strength parallel to the grain showed only limited variations among groups. Mean values obtained were 56.34 (±5.71) MPa for natural seasoning, 56.91 (±7.42) MPa for Group A, 57.77 (±6.92) MPa for Group B, and 54.62 (±8.02) MPa for Group C. Overall, the steamed groups were comparable to the control, with Group C showing a slightly lower average value; however, these differences were small relative to within-group variability, suggesting no clear treatment effect on compressive strength under the present conditions (Fig. 7).

Boonstra et al. (2007) discovered that the compression strength oriented parallel to the grain exhibited a marked increase after heat treatment, amounting to 28%. Romagnoli et al. (2015) reported that heat treatment at 210 °C for 2 h, negatively affected the performance of Douglas fir. Treated specimens showed a reduction in compression strength in both heartwood (7.64%) and sapwood (12.50%). Conversely, for Corsican Pine, an increase of 3.48% was observed. In a study on the properties of the heat treatment of wild pear wood, Gunduz et al. (2009) carried out the compression strength test. Compression strength decreased as treatment time increased from 2 to 6 h across different temperatures. After heat treatment at 160 °C, the compression strength was equal to 47.25 MPa, 44.72 MPa, and 44.04 MPa, respectively, for 2, 4, and 6 h. The compression strength tests effectuated at 180 °C showed values of 45.34 MPa for 2 h, 42.62 MPa for 4 h, and 41.48 MPa for

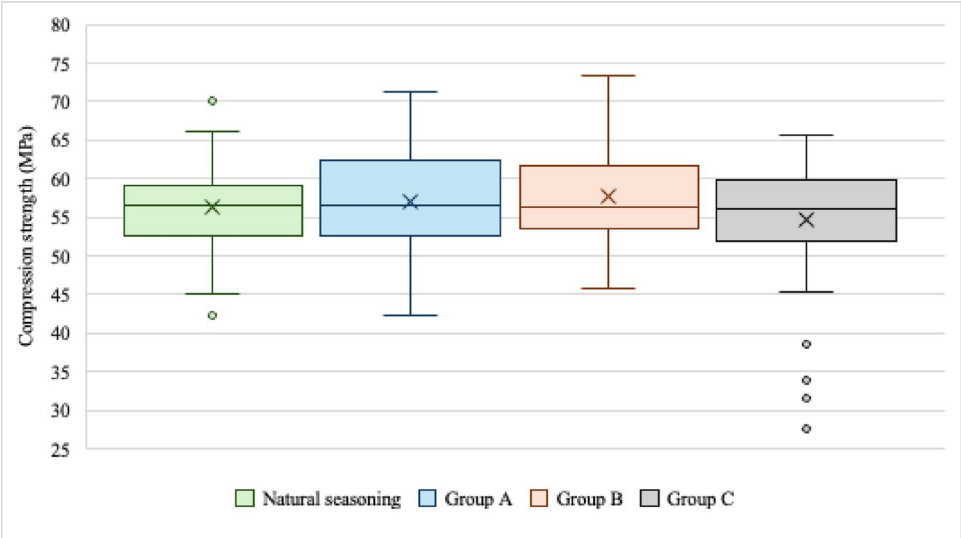


Fig. 7 Effects of steaming treatment on the compression strength

6 h. The share of compression strength reduction for 2, 4, and 6 h was 7.42%, 12.38%, and 13.71% at 160 °C and 11.16%, 16.49%, and 18.73% at 180 °C. Kamperidou et al. (2014) found that samples of all different treatment durations had slightly higher compression strength values compared to untreated wood samples. The average compression value of samples treated for 4 h was 13.76% higher than that of untreated wood, while treatment for 6 and 8 h resulted in compression strength increases of 6.09% and 4.88%, respectively. Gennari et al. (2021) found that compression strength was reduced from 36.6 MPa in untreated wood to 34.2 MPa. In addition, Piernik et al. (2022) identified a decline in performance for the species scots pine. The mean value obtained was 62.5 MPa, considering heat treatments of 1, 2, 4, 6, and 8 h, whereas in untreated wood, it was 70.2 MPa. Specifically, the value of compression strength decreased by approximately 64 MPa after 1 h of treatment to approximately 55.7 MPa after 8 h. Overall, compressive strength remained comparable to the control, suggesting no measurable effect of mild steaming on this property under the present conditions.

In this study, static hardness showed a reduction after steaming, with mean values of 6.49 (±0.90) kN for natural seasoning, 5.11 (±0.72) kN for Group A, 5.61 (±0.49) kN for Group B, and 6.15 (±1.23) kN for Group C. Compared with natural seasoning, this corresponds to decreases of approximately 21.3% (Group A), 13.6% (Group B), and 5.2% (Group C). However, the overall effect of treatment duration on static hardness was not statistically significant (ANOVA: $F=2.617$, $p=0.079$), indicating that the observed differences should be interpreted as a tendency rather than a confirmed treatment effect. Figure 8 shows the effects of steaming treatment on Janka hardness.

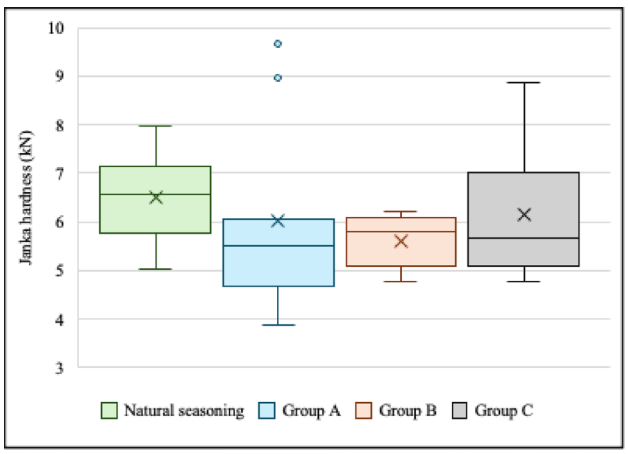


Fig. 8 Effects of steaming treatment on the static hardness

In the study conducted by Priadi and Hiziroglu (2013), it was observed that the control samples of oak exhibited the highest mean hardness value among the four species examined. The heat treatment applied to these samples ranged from 130 to 200 °C, with different times of 2 and 8 h. A similar situation occurred for mahogany and mindi samples, while a reduction was not observed for pine samples. However, the heat treatment at 200 °C for 2 h reduced the hardness of mindi, mahogany and oak. The extent of the reduction was more evident with an increase in treatment time to 8 h. For the control samples, oak had the highest hardness value, but the reduction in hardness for these samples was also greater compared to any other species considered. The hardness values after heat treatment at 200 °C for 8 h of oak samples were reduced by 42.7%, followed by mindi (20%) and mahogany (17.3%). In Kamperidou's study (2014), the hardness values of treated specimens showed a decrease as a result of the high-thermal treatment. In the first 4 h of treatment, the hardness values recorded a sharp drop; however, with increasing duration, the hardness values showed a slight increase, without reaching the resistance level of the control specimens. The average hardness value in the tangential direction of samples treated for 4 h was measured to be 25.13% lower than that of untreated wood, while treatment for 6 and 8 h resulted in lighter decreases of 24.73% and 9.34%, respectively. This trend in hardness value was similar for both the tangential and radial directions of the specimens. Salca and Hiziroglu (2014) conducted a series of experiments on black alder, red oak, southern pine and yellow poplar, applying a steaming treatment at temperatures of 120 and 190 °C for 3 and 6 h. The average hardness of red oak samples treated at 120 °C for 3 h was 18.7%, lower than before thermal treatment. However, samples exposed to 190 °C for 6 h had an average hardness of 41.7% less than that recorded before treatment. The reduction in hardness was more evident with longer exposure times. For black alder samples, a gradual decrease in hardness values was observed with increasing temperature and exposure time. The maximum reduction in hardness compared to untreated samples was approximately 4.3% at 120 °C for 6 h. At 190 °C, increasing the exposure time from 3 to 6 h reduced the hardness by 7.9%. While considering the southern pine and yellow poplar samples, few

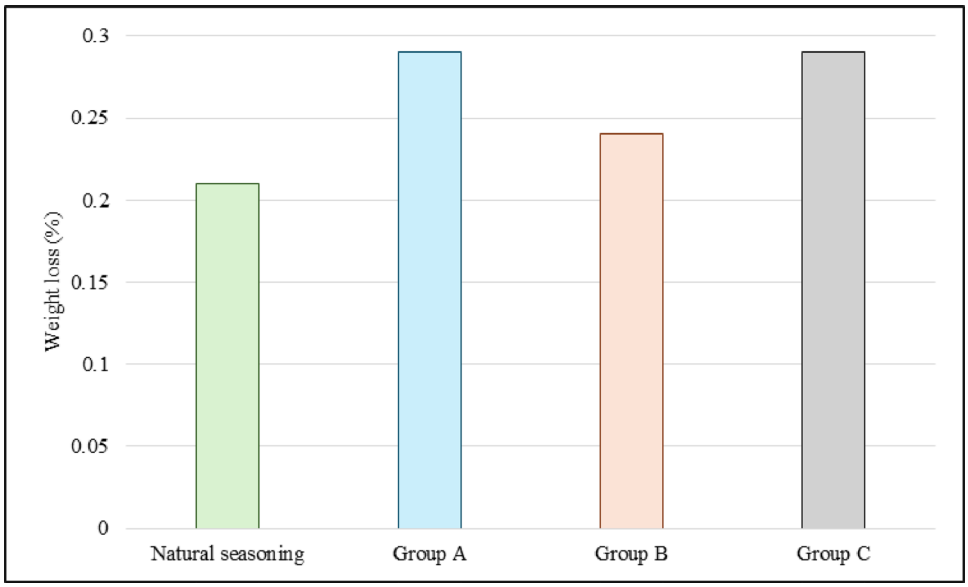


Fig. 9 Effects of steaming treatment on abrasion

significant differences were found, which may be related to their low density. Furthermore, red oak had the highest hardness values before thermal treatment but reduced more than other wood species. The results show that steam treatment at relatively low temperatures (80 °C) reduces Janka hardness compared to air-dried samples. The observed reduction (up to −21%) is lower than that reported at higher temperatures (up to −42.7%), yet it aligns with the same decreasing trend. This confirms that even low-temperature treatments can adversely affect mechanical performance.

3.6 Abrasion resistance

Abrasion-related weight loss differed significantly among groups ($p=0.028$), with values ranging from 0.21% (control) to 0.24–0.29% after steaming, and the small variation of these differences compared with high-temperature treatments reported in the literature likely reflects the milder temperature used here (Aytin et al. 2015; Kol et al. 2015). Figure 9 shows the effects of steaming treatment on abrasion.

Aytin et al. (2015) found the highest weight loss in untreated specimens (2%). For the 190 °C cycle, there was a weight loss of 1.7% and 1.8% for the 1-hour and 2-hour cycles, respectively. Finally, for the 212 °C cycle of 1 h and 2 h, they found the same weight loss, which was equal to 1.8%. Kol et al. (2015) demonstrated that after the abrasion test, heat treatment induced greater weight losses in wood materials, and higher heat treatment temperatures caused greater weight losses in the samples. It is stated that the minimum weight losses (0.3%) from abrasion in spruce wood were in the control samples, while the maximum weight losses (0.5%) were in samples treated at a treatment temperature of 212 °C. Similarly, for beech wood, the results were similar. The maximum weight losses from abrasion (0.4%) occurred in samples treated at 212 °C, and the minimum weight losses from abrasion (0.1%) were in the control samples.

3.7 Data analysis

Multivariate analysis showed that the different durations of steaming treatment significantly influenced some dependent variables (Table 4). Tukey's test showed that the color variation in heartwood and sapwood varied, as did the abrasion weight loss (Table 5). The color variation in duramen was found to be significantly affected between the 36-hour cycle and the control specimens. The change in sapwood color was found to be significantly affected by all durations of steaming treatment compared to the control; additionally, between 12 and 18 h and between 18 and 36 h, the change in sapwood color was statistically different. The abrasion weight loss was only significantly different between the control wood and the wood that had undergone a 12-hour steaming treatment.

Table 5 Tukey test

Dependent variable			Mean difference (I-J)	Std. Error	Sig.	95% confidence interval	
						Lower bound	Upper bound
*ΔE*_heartwood	**0**	**12**	−4.077	1.785	0.136	−9.074	0.921
		18	−4.875	1.785	0.057	−9.872	0.122
		36	−6.2483*	1.785	0.011	−11.246	−1.251
	12	**0**	4.077	1.785	0.136	−0.921	9.074
		18	−0.798	1.785	0.969	−5.796	4.199
		36	−2.172	1.785	0.624	−7.169	2.826
	18	**0**	4.875	1.785	0.057	−0.122	9,872
		12	0.798	1.785	0.969	−4.199	5.796
		36	−1.373	1.785	0.867	−6.371	3.624
	36	**0**	6.2483*	1.785	0.011	1.251	11.246
		12	2.172	1.785	0.624	−2.826	7.169
		18	1.373	1.785	0.867	−3.624	6.371
*ΔE*_sapwood	**0**	**12**	−10.4517*	1.467	0.000	−14.557	−6.346
		18	−5.3550*	1.467	0.008	−9.461	−1.249
		36	−12.3733*	1.467	0.000	−16.479	−8.268
	12	**0**	10.4517*	1.467	0.000	6.346	14.557
		18	5.0967*	1.467	0.012	0.991	9.202
		36	−1.9217	1.467	0.567	−6.027	2.184
	18	**0**	5.3550*	1.467	0.008	1.249	9.461
		12	−5.0967*	1.467	0.012	−9.202	−0.991
		36	−7.0183*	1.467	0.001	−11.124	−2.913
	36	**0**	12.3733*	1.467	0.000	8.268	16.479
		12	1.9217	1.467	0.567	−2.184	6.027
		18	7.0183*	1.467	0.001	2.913	11.124
WL	**0**	**12**	0.0875*	0.029	0.033	0.006	0.169
		18	0.0375	0.029	0.584	−0.044	0.119
		36	0.0765	0.029	0.072	−0.005	0.158
	12	**0**	−0.0875*	0.029	0.033	−0.169	−0.006
		18	−0.0501	0.029	0.343	−0.132	0.032
		36	−0.0110	0.029	0.981	−0.093	0.071
	18	**0**	−0.0375	0.029	0.584	−0.119	0.044
		12	0.0501	0.029	0.343	−0.032	0.132
		36	0.0390	0.029	0.552	−0.043	0.121
	36	**0**	−0.0765	0.029	0.072	−0.158	0.005
		12	0.0110	0.029	0.981	−0.071	0.093
		18	−0.0390	0.029	0.552	−0.121	0.043

ΔE_heartwood total color variation of heartwood, *ΔE_sapwood* total color variation of sapwood, *WL* weight loss due to abrasion

4 Conclusion

This work presents the results of analyses regarding the physical–mechanical properties of olive wood, which was subjected to steaming treatment at a temperature of 80 °C for durations of 12, 18, and 36 h. Steaming produced a clear modification of appearance, with significant differences in total color change for both tissues (*ΔE*_heartwood: $p=0.014$; *ΔE*_sapwood: $p<0.001$), and larger responses in sapwood than in heartwood. Abrasion-related weight loss (WL) also differed significantly among groups ($p=0.028$), although the variation of the change remained small (≈0.21–0.29%). In contrast, no statistically significant effect of steaming duration was detected for MOE_d ($p=0.946$), MOE_s ($p=0.120$), MOR ($p=0.159$), or Janka hardness ($p=0.079$), indicating that the applied mild steaming schedule primarily modified color while preserving the main mechanical properties at the tested level. Dimensional stability indicators showed only limited differences among groups and should be interpreted as trends within the present experimental variability. The results of this study have revealed that steaming treatment can add potential value to olive wood, making it more effectively usable in the production of indoor products (flooring, furniture, etc.). Moreover, the results of this study contribute to a better comprehension of the potential use of this species, which has been increasingly gaining traction in the market in recent years. Furthermore, this preliminary study of the physical and mechanical properties of

olive wood treated at 80 °C could lead to further research at different temperatures. To gain a deeper understanding of the influence of the treatment on these properties, future studies should explore the underlying mechanisms of color and hygroscopic changes through chemical analyses (e.g., FTIR, TGA/DTG, and extractives profiling), investigate anatomical/microstructural effects using microscopy (SEM/light microscopy), and assess longer-term performance through durability and ageing tests (e.g., fungal resistance, weathering/UV exposure, and abrasion) across an expanded temperature range.

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Data availability The data are available upon request to corresponding author.

Declarations

Conflict of interest The authors declare no conflicts of interest.

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