A Revaluation of Turkey Oak Wood (*Quercus cerris* L.) Through Combined Steaming and Thermo-vacuum Treatments

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Turkey oak is a wood species widely distributed in Southeastern Europe and in Italy, where it is mainly present in the Apennine Mountains. Compared to other oaks, Turkey oak is less valued because of its tendency to crack, its lower technological quality, and its lower durability. The aim of the present work was to improve wood quality by treating Turkey oak through combined steaming and thermal treatment under vacuum conditions. Wood was steamed at a temperature between 100 to 110 °C and thermally treated in vacuum at 160 °C using two different technologies, *i.e.*, the press vacuum plant and the Termovuoto® plant. The treated material was characterized in terms of mass loss, color change, hygroscopicity, and compression strength for both heartwood and sapwood. Results slightly differed according to the treatment or combination of treatments adopted. In general, a significant increase in dimensional stability and an improved color homogenization were obtained together with the maintenance of a good wood quality. Concerning mechanical properties, thermo-vacuum treatment increased the compression strength, while steaming had the opposite effect.

Keywords: Turkey oak; Steaming; Thermo-vacuum treatment; Color; Equilibrium moisture content; Compression strength

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INTRODUCTION

Several hydro-thermal treatment processes have been developed to improve wood characteristics through the modification of its chemical composition. The main comercial processes available on the market are: "Rectification" (France), "Le bois perdure" (France), "Thermowood" (Finland), "Plato" (The Netherlands), and "OHT-oil" (Germany) (Esteves and Pereira 2009). All these processes involve treating wood at high temperature (between 160 °C and 260 °C) in an oxygen-free environment to avoid combustion. The main differences are related to the process conditions adopted, *e.g.* the presence of a shielding gas (nitrogen or steam), open or closed system, initial wood moisture content, presence of oil, *etc*. For the same process, the treatment effects on wood depend on temperature and duration of application.

The changes in chemical composition and wood structure in the thermo processes are mainly caused by the degradation of hemicelluloses, cellulose, and lignin, which directly influences the physics and mechanics of wood (Hill 2006). The chemical changes occurring in wood determine a reduction of wood hygroscopicity and, consequently, an improvement of the dimensional stability (Sundqvist 2004) and resistance to fungal attack (Tjeerdsma *et al*. 1998)

However, the mechanical properties of wood decrease as a result of heat treatment (Kubojima *et al*. 2000; Epmeier *et al*. 2004; Unsal and Ayrilmis 2005). The improvement of some technological properties on one side, and the reduction of mechanical resistance on the other, are directly related to the mass loss, which is in turn related to the treatment intensity (temperature and time), as demonstrated with different species by Zaman *et al*. (2000) and Esteves *et al*. (2007).

Recently, a new technology called Termovuoto has been used to modify wood. Using this technology, the oxygen inside the reactor is reduced by a partial vacuum while heating is provided by forced convection (Ferrari *et al.* 2013). A description of the parameters involved in the process is reported in Allegretti *et al.* (2012). In addition, Hofmann *et al.* (2011) and Wetzig *et al.* (2012) reported significant physical, mechanical, and chemical changes for oak, beech, poplar, and ash using a similar treatment.

The effect of hydrothermal treatment on Turkey oak (*Quercus cerris* L.), a moderate-growing European hardwood species, has received relatively little study. Its natural range is from southern Europe to Southwest Asia. Turkey oak wood could represent an important resource for mountain economies, but it is affected by a series of limiting factors that preclude its penetration into the furniture market. Turkey oak wood has many of the characteristics of other oaks, but it is very prone to cracking, and it is less dimensionally stable and less durable (Giordano 1981) compared to other oaks. In addition, gluing difficulty (Lavisci *et al.* 1991) and a less appealing surface color (Tolvaj and Molnár 2006) characterize this wood. Because of such properties, this wood is mainly used as firewood.

Recently, promising evidence of possible improvements obtainable by hydrothermally treating Turkey oak wood was reported in the literature (Todaro *et al.* 2012a). Hydrothermal treatment could represent a solution to improve the properties of Turkey oak wood, allowing new final destinations, *e.g*., parquet (Todaro 2012), outdoor applications, and panels.

Turkey oak could be a valuable commercial wood, but its value is often degraded by a variety of stains, most of which are due to extractives such as tannins in the wood. These stains often can be prevented by working with wet wood and in high-temperature steaming. Lavisci *et al*. (1991) reported that the nature and concentration of extractives inside sapwood and heartwood for this kind of wood are quite different, principally in terms of the insoluble fraction.

Todaro *et al*. (2013) investigated the extractives topic on hydrothermally treated wood and found that the quantities extracted with ethanol were significantly higher than those obtained with dichloromethane. In contrast to ethanol, extraction with dichloromethane produced more extractives from the heartwood sample than from sapwood; however, the values were not influenced by the treatment applied. In terms of average values, the quantity of extractives appears to increase with the steaming treatment. Nevertheless, a decrease was observed when steam was combined with heat at the extreme temperature of 180 °C.

Concerning lignin, Bourgois and Guyonnet (1988), Zaman *et al*. (2000), and Andersons *et al*. (2009) reported that the percentage of lignin content is positively related to an increase in temperature. Moreover, Todaro *et al*. (2013) stated that this result was true for Turkey oak only when thermal treatment was associated with a previous steaming treatment. For lignin, a uniform trend between sapwood and heartwood was found. More lignin extraction occurred in samples subjected to combined treatments between more moderate steaming (100 to 120 °C) and more extreme thermal treatment (180 °C). In all samples subjected to combined treatments, the content of lignin in the heartwood was higher than that in sapwood. Moreover, both steaming and heating individually applied produced no positive or significant effect on lignin content compared to the control.

Chromatic differences inside the wood structure of Turkey oak are much more evident than in other species, with a pale and large sapwood and a dark-grey heartwood (Tolvaj and Molnár 2006), frequently accompanied by the presence of black heart (Giordano 1981). However, these chromatic differences inside the wood structure can be reduced with hydrothermal treatment, as found by Molnár *et al*. (2006) and Tolvaj and Molnár (2006).

In recent research, Todaro *et al.* (2012b) found that combined steaming and heating at low temperature modified the surface color, leading to darkening, red shifting, and homogenization. The thermal treatment seemed to have a significant effect compared to steaming only, principally on lightness and hue. Regarding the homogenization of color, severe treatments yielded noticeable results for lightness; however, for the strongest treatment (steaming at 130 °C and heating at 180 °C), a negative effect was obtained. With respect to hue, moderate treatments for both steaming and heating were preferred.

Hydrothermal treatment of Turkey oak is often a difficult task, especially for high temperature. In fact, the wood is very prone to internal or surface checks, collapse, splits, and warp occurring during the process if the heating parameters are not well chosen. The aim of this paper was to evaluate the possibility of reducing the limiting factors of Turkey oak by treating wood samples with different hydro-thermal treatments. The hypothesis was that the combination of steam (autoclave) and thermo-vacuum treatment would reduce the limitations of Turkey oak wood by increasing its value for high-quality uses.

EXPERIMENTAL

Experimental Steps

The experimental process can be described by the following steps (in chronological order) and it is schematically shown in the Fig. 1.

1. Step1 (harvest): four logs (3 m length) coming from four trees (with diameter at breast height of 40 cm) of Turkey oak were harvested in the Apennine Mountains of Italy (Basilicata Region);
2. Step 2 (steaming): two of the four logs were steamed by using the equipment described below. The steaming was performed in order to homogenize the color and relax the internal stress**.** Logs were steamed under saturated conditions; a temperature of about 110 °C and a pressure of 140 kPa were reached, and the total heating was extended to 24 h. After treatment the logs were cooled for five days in the same chambers before being cut into boards.
3. Step 3 (boards preparation): steamed and not steamed logs were cut into boards of 40 mm thickness.
4. Step 4 (seasoning): all the boards were seasoned for five months until reaching a moisture content (MC) of 20 to 25%.

5. Step 5 (matching samples): each seasoned board was cut into two parts, one to be treated and the other used as control.
6. Step 6 (boards selection): boards with defects (knots, fibre deviation, and reaction wood) were rejected. The boards without defects were instead divided into two groups of 16 boards each (8 steamed and 8 not steamed). Sixteen boards were loaded into the press-vacuum machine (PVP) and the remaining equal part in the thermo-vacuum cylinder (TVP). In both machines, developed by the Italian company *WDE Maspell srl* (see description below), the boards were dried and then thermo-vacuum treated following the same process parameters. Drying and thermo-vacuum treatment were performed in the two plants in different moments to make easy the management of the process and for energy reasons. The energy supply of the laboratory was not enough to allow the contemporary work of the two plants at high temperature.
7. Step 7 (artificial drying): wood was initially dried under vacuum conditions (20-23 kPa) and at low temperatures (starting from 55 °C up to 90 °C in eight days) to avoid internal checks, which are very frequent in Turkey oak. Only the last step of the drying, when wood MC was below 5%, was performed at 103 °C. A total of seven days was required to dry the material. At the end of the drying, the kilns were momentarily open and the boards were quickly weighed to determine the oven dried mass; then the boards were put again into the kilns to continue with the high temperature treatment.
8. Step 8 (thermo-vacuum treatment): at the beginning of the treatment the air temperature was increased until reaching the set value of 160 °C after 1.5 h; at that moment the temperature was kept constant for 3 h with a pressure of 20 to 23 kPa. At the end, a cooling phase of 3 h was conducted. The process parameters adopted during the two thermo-vacuum treatments (temperature, time and pressure) were the same.
9. Step 9 (material characterization): boards differently treated were physically and mechanically evaluated according to the specific standards.

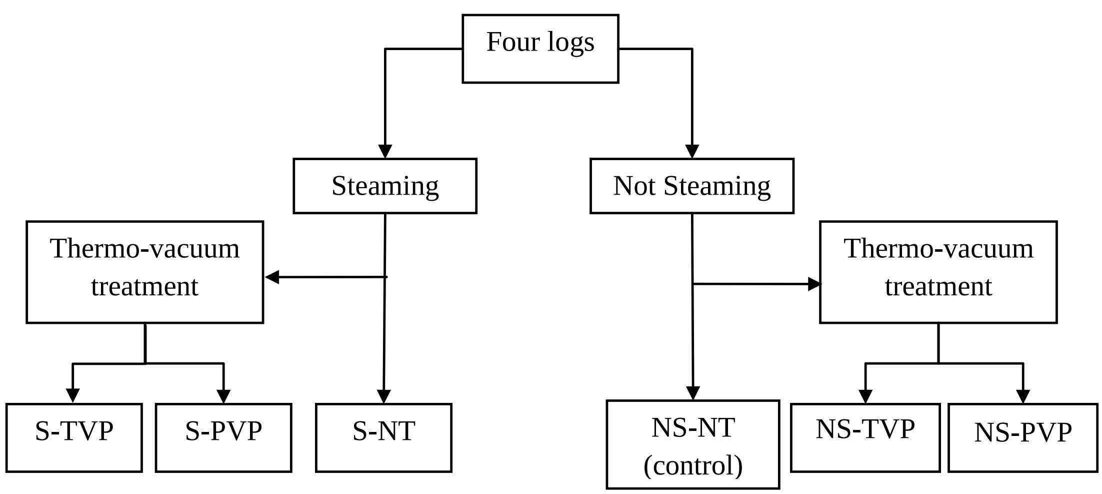

Fig. 1. Diagram of the treatment pattern. NS=not steamed; S=steamed; NT= not thermo-vacuum treated; PVP= thermo-vacuum treated with press-vacuum technology; TVP= thermo-vacuum treated with Termovuoto® technology.

Equipment

The steamer plant

The steamer was a purpose-made cylindrical pressure chamber, having a volume of 1.5 m^3. The autoclave was realized with a basin of boiling water and equipped with air and wood temperature thermocouples and a pressure gauge.

The press vacuum plant (PVP)

The machine was initially conceived as a drying-vacuum kiln, as described in Allegretti *et al.* (2003), but it was later modified to also perform thermo-vacuum treatments at high temperature (up to 250 °C). The laboratory kiln was 4 m long, 1 m wide, and could hold two board layers, which were loaded manually. Boards were placed between two metal plates containing hot oil, providing the conductive heat transfer to the material. The pressure inside the kiln could be regulated from 100 to 6 kPa. The vacuum conditions were maintained by means of a ring-type water pump equipped with a heat exchanger. The use of this plant offered the advantage of minimizing wood distortions; in fact, under the effect of pressure, the plates acted with a force upon the boards (~ 80 kN/m^2 for a pressure of 20 kPa) that made it possible to avoid potential wood deformations, which are typical for Turkey oak wood. Wood modification performed with this plant was defined as an open system because all the volatile products of the process were continuously removed from the kiln by means of the pump that regulates the set pressure.

*The Termovuoto® plant (**TVP**)*

This plant was originally a drying-vacuum plant, but it was redesigned so as to allow convenient drying and relatively high temperatures (up to 250 °C), as already reported by Allegretti *et al.* (2010 and 2012). The machine consists of a cylindrical chamber (one cubic meter of capacity) that has a double layered wall filled with hot oil. The heat inside the kiln is convectively transferred by means of a couple of efficient fans. Fan speed is proportional to the internal air pressure, ranging from 635 r min^{-1} at atmospheric pressure to a maximum speed of about 1930 rpm at a vacuum pressure of 20 kPa. The pump that maintains the vacuum is similar to the one described above. This plant can be defined as an open system.

Characterization Tests

Wood material, *i.e.*, control (not steamed and not thermo-vacuum treated), steamed and/or thermo-vacuum treated, was physically characterized to determine the effects of steaming and thermo-vacuum treatment on Turkey oak sapwood and heartwood. Wood parameters were determined according to the specific standards which are all collected in the technical specification UNI CEN/TS 15629 (2008). To minimize wood variability, all wood properties were measured and compared using matched samples cut from the same board. After seasoning, each board was sawn into two parts, one to be thermo-vacuum treated and the other to be used as reference material.

Mass loss (ML)

The mass loss (ML), due to the thermo-vacuum treatment, was determined by weighing each treated board immediately after the drying process (when the wood moisture content (MC) was 0%) and at the end of the thermo-vacuum treatment. Hence, the mass loss is given by the difference of the two previous weights over the anhydrous mass and is expressed in percent (Eq. 1).

$$ML = \frac{M_0 - M_T}{M_0} \times 100\% \qquad (1)$$

where M_0 is the weight of the board at 0% moisture content, and M_T is the weight of the board after the thermo-vacuum treatment.

Equilibrium moisture content (EMC) and antiswelling efficiency (ASE)

EMC and radial-tangential swelling were measured on anatomically oriented samples with dimensions of 20 mm x 20 mm x 40 mm according to the standards set by UNI ISO 4469 (1985) and UNI ISO 3130 (1985). Fifteen samples were cut for each wood treatment, for a total of 236 samples. For the determination of EMC and ASE, the samples were initially oven dried at 103 °C and then conditioned in a climatic chamber (T = 20 °C and relative humidity (RH) = 65%) until they reached a constant weight.

The homogeneity in terms of EMC between sapwood and heartwood of the same board was evaluated through the calculation of the *index of hygroscopic homogeneity* (ID_{hyg}),

$$ID_{hyg} = \frac{EMC\ (s) - EMC\ (h)}{EMC\ (h)}\ x\ 100 \qquad (2)$$

where EMC(s) and EMC(h) are the values of EMC calculated for sapwood and heartwood, respectively.

The different average values of EMC between matching samples were processed using *Student's t-test*. Results were also analysed using a 2-factor analysis of variance (ANOVA) to evaluate the effect of the two independent variables (steaming and thermo-vacuum treatment) on the dependent variable (EMC).

Sample swelling was measured and calculated in the two anatomical directions from the state of 0% MC to the value of MC reached by the samples conditioned at 20 °C and 65% of RH. The improved dimensional stability of the treated wood was indicated as ASE65% (anti-swelling efficiency), which refers to the reduction of swelling of treated compared to untreated wood at the above mentioned climatic conditions.

Color assessment

Color was measured using a spectrophotometer (MicroFlash 200 D) with a spot probe 18 mm in diameter. Forty-five measurements were taken for each treatment type. Color coordinates referred to the three-dimensional CIE $L^*a^*b^*$ color space, where L^* indicates the lightness in a range from black (0) to white (100), while a^* and b^* define the position in the green-red and blue-yellow axes, respectively. The total color change ΔE^* was calculated with the equation reported below:

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2}\ \Delta b^{*2})^{1/2} \qquad (3)$$

The total color change ΔE^* was calculated for two different purposes: 1) to evaluate the color change, measured at the same point of a board, due to the thermo-vacuum treatment. In this case, the coordinates L^*, a^* and b^* refer to the same point and are measured at different moments (before and after the thermal treatment); 2) to evaluate the color homogeneity of wood, *i.e*., the color difference between sapwood and heartwood. In this case, the color coordinates refer to different points (one in sapwood and one in heartwood) and are measured at the same moment. Color homogeneity, induced by steaming and thermo-vacuum treatment, was similarly determined by Todaro *et al.* (2012b) and by Horváth *et al.* (2012).

Compression strength

After sawing, boards were conditioned in a climatic room at 20 °C and 65 % of RH for 45 days and then cut into samples for mechanical tests. The dimensions of samples for measuring compression strength parallel to the grain were 20 x 20 x 40 mm (tangential x radial x longitudinal). The same number of samples was randomly selected among the five treatments and the control, so that a total of 482 clear wood samples was available. For specifying the differences between sapwood and heartwood, 255 samples were obtained from the sapwood, and the other 227 samples came from the heartwood. None of the samples included the pith section. The compression strength was determined according to UNI-ISO 3787 (1985).

Quality assessment

Turkey oak is very difficult to dry and thermally treat because of its tendency to crack and collapse. In the present study, wood quality under the influence of steaming, drying and thermo-vacuum treatments was evaluated according to the standard UNI 8947 (1987). The evaluation was based on the detection and measurement of defects such as checks, collapses, and color modifications.

RESULTS AND DISCUSSION

Mass Loss (ML)

No significant differences in terms of ML were found between the two different thermo-vacuum treatments, *i.e.*, PVP and TVP (Tab.1) and not even between boards previously steamed or unsteamed. In general, the average value of ML was less than 2% for wood treated at 160 °C for 3 h. The ML found in this study for Turkey oak is similar to that reported by Ferrari *et al*. (2012) for European oak treated in thermo-vacuum conditions at the same process parameters.

Table 1. Mass loss (ML) with Standard Deviation (sd) of the Thermo-vacuum Treated Boards

	Not Steamed		Steamed	
	ML ± sd	n. of boards	ML ± sd	n. of boards
PVP	1.5±0.3	8	1.7±0.2	8
TVP	1.4±0.5	8	1.8±0.6	8

EMC and ASE

Results concerning wood EMC and dimensional stability (ASE) from matching samples are reported in Tables 2 and 3 for sapwood and heartwood, respectively. Moreover, EMC results are graphically represented in Fig. 2. In general, wood steamed or/and thermo-vacuum treated had an EMC at normal conditions (T = 20 °C and RH =

65%) lower than that of the control material and it was more dimensionally stable. This explains the negative values reported in the Tables 1 and 2 for ΔEMC and ASE. Such difference values, calculated for matching samples, were found to be significant by means of the *Student's t-test* (α=0.05). In case of sapwood, even if the values of ΔEMC reported in Tab. 2 are statistically different, the EMC for steamed and thermo-vacuum treated wood was almost the same. Greater were the variations of EMC induced by the thermo-vacuum treatment and by steaming on control wood.

Concerning the anti-swelling efficiency for sapwood, in radial direction the ASE values, induced by the different treatment patterns, were quite similar (from 4.9% to 5.8%), while in tangential direction the values were more variable, reaching the 15.6% for control wood treated with TVP system.

Table 2. EMC and ASE for Turkey Oak Sapwood.

Board	Steaming	Thermo-vacuum	EMC ± s.d.	ΔEMC	βR	ASE_R	βT	ASE_T
a	—	Not treated	11.39±0.05		2.07		4.41	
a	—	Treated with PVP	10.85±0.05	-4.7	1.95	-5.8	4.14	-6.0
b	+	Not treated	10.77±0.09		1.16		3.32	
b	+	Treated with PVP	10.48±0.12	-2.7	1.22	n.d.	3.63	n.d.
c	—	Not treated	11.38±0.05		1.45		3.71	
c	—	Treated with TVP	10.78±0.1	-5.3	1.37	-5.4	3.03	-15.6
d	+	Not treated	10.85±0.07		1.47		3.88	
d	+	Treated with TVP	10.43±0.08	-3.9	1.40	-4.9	3.74	-3.6

n.d.= not determined. Boards with the same letters are matching samples. All the values are express in percent.

Table 3. EMC and ASE for Turkey Oak Heartwood

Board	steaming	Thermo-vacuum	EMC± s.d	ΔEMC	β R	ASE_R	βT	ASE_T
e	—	Not treated	10.65±0.08		1.86		4.01	
e	—	Treated with PVP	9.31±0.05	-12.6	1.61	-13.4	3.54	-11.7
f	+	Not treated	8.33±0.53		1.07		2.82	
f	+	Treated with PVP	7.38±1.0	-11.4	0.73	-32.2	2.02	-28.4
g	—	Not treated	10.21±0.19		1.67		3.70	
g	—	Treated with TVP	7.83±1.16	-23.3	1.20	-28.4	2.58	-30.3
h	+	Not treated	8.33±0.53		1.29		2.81	
h	+	Treated with TVP	7.11±0.60	-14.7	0.94	-16.4	2.5	-10.5

Boards with the same letters are matching samples. All the values are express in percent.

In the case of heartwood, the EMC reduction as a consequence of steaming and thermo-vacuum treatment was higher than for sapwood, as reported in Table 3. An EMC reduction was always above 10%.

Concerning the anti-swelling efficiency, heartwood showed an ASE value in the radial and tangential direction in the interval between 11.7% and 32.2% according to the treatment pattern adopted.

Apparently, TVP technology induced a more important dimensional stability compared to PVP.

Both for sapwood and heartwood, results for EMC, coming from different treatment combinations, were analyzed by using 2-factor ANOVA, and significant effects were demonstrated for both steaming and thermo-vacuum treatments in decreasing the EMC value ($P<0.001$). Moreover, it seemed that the combined effect of steaming and thermo-vacuum influenced wood hygroscopicity, but more replications would be required to establish the significance of such influences.

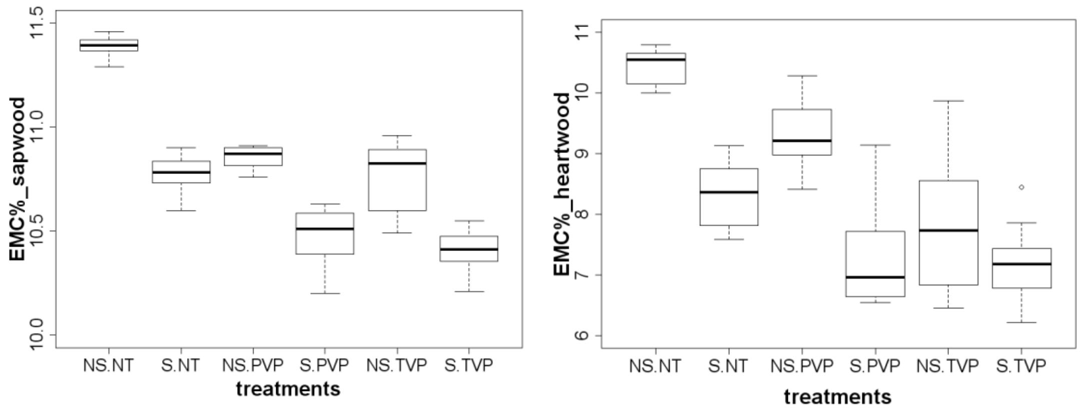

Fig. 2. EMC for sapwood (left) and heartwood (right). NS = not steamed; S = steamed; NT = not thermo-vacuum treated; PVP = thermo-vacuum treated with press-vacuum plant; TVP = thermo-vacuum treated with Termovuoto® plant

Sapwood and heartwood of the control material had different values of EMC, *i.e*., 11.4% and 10.4%, respectively. Such differences were evidence of wood heterogeneity, which was further accrued by combined steaming and thermo-vacuum treatment. These effects are shown in Fig. 3 and were also observed by Todaro *et al*. (2012a). Low values of ID_{hyg} (close to zero) correspond to high levels of wood homogeneity.

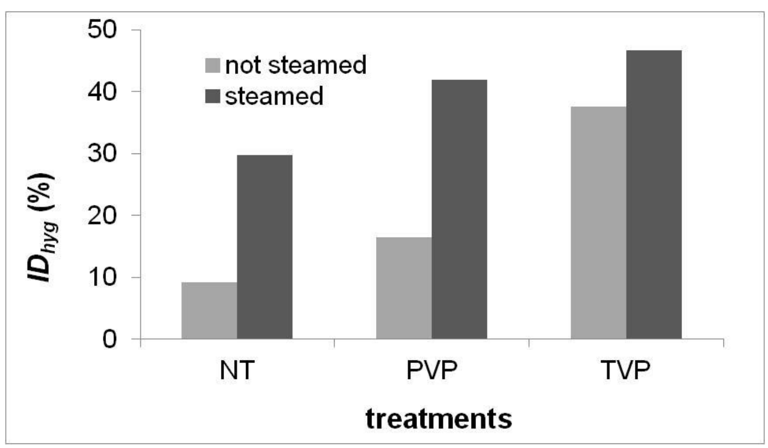

Fig. 3. Index of hygroscopic homogeneity between heartwood and sapwood for different treatments.

The increasing value of ID_{hyg}, due to the treatments applied, can be taken as evidence of different behavior for sapwood and heartwood portions, with the greater modifications occurring in heartwood. Such different behaviour was clearly related to dissimilar physical and chemical compositions between sapwood and heartwood. In fact, heartwood differs in nature and concentration of extractives compared to sapwood, as previously described. Probably, these characteristics, together with the presence of tyloses, of which Turkey oak wood is filled, contributed to emphasize heartwood modification during hydro thermal treatments. Up to now, the physical, such as permeability and diffusion coefficients, and chemical aspects, such as degradation of the main wood components, which explain the phenomena are not well known for this kind of wood and require an appropriate investigation.

Color

Steaming and thermo-vacuum treatments significantly affected ΔE^* for both sapwood and heartwood, as also reported by Tolvaj *et al.* (2006). Color data are reported in Tables 4 and 5 for sapwood and heartwood, respectively. In particular, samples not previously steamed were characterized by a ΔE^* greater than that calculated for steamed material, *e.g.*, sapwood treated by TVP had a ΔE^* of 6.68 and 14.05 for steamed and unsteamed wood, respectively. Moreover, the thermo-vacuum performed with the TVP plant resulted in a ΔE^* higher than treatment with the PVP, both for steamed and unsteamed material (Fig. 4). The difference between the two thermo-vacuum technologies was also demonstrated through the *Student's t-test* (P value< 0.05).

Table 4. Color Coordinates for Sapwood

	Steamed sapwood			Unsteamed sapwood		
	Not treated	Treated-TVP	Treated-PVP	Not treated	Treated-TVP	Treated-PVP
L*±sd	60.13±1.3	53.19±0.6	56.5±1.6	76.85±1.0	63.66±2.0	65.16±0.9
a*±sd	9.95±0.3	9.95±0.2	10.14±0.4	5.60±0.5	7.74±0.6	9.08±0.2
b*±sd	19.68±0.7	18.55±0.3	21.73±1.4	21.54±1.0	22.77±0.9	26.13±0.6
ΔE±sd		6.68±0.6	4.37±1.5		14.05±2.4	12.15±0.7
ΔL±sd		-6.64±0.6	-3.95±1.5		-13.55±2.01	-11.34±0.7

Table 5. Color Coordinates for Heartwood

	Steamed heartwood			Unsteamed heartwood		
	Not treated	Treated_TVP	Treated_PVP	Not treated	Treated_TVP	Treated_PVP
L*±sd	57.92±2.1	50.98±0.9	55.19±2.3	62.33±1.4	54.35±0.9	56.43±1.9
a*±sd	8.55±0.5	7.59±0.3	9.22±0.6	7.02±0.2	7.51±0.3	7.99±0.4
b*±sd	18.09±1.0	16.64±0.8	20.22±1.2	19.34±0.8	19.91±0.3	21.27±1.0
ΔE±sd		7.09±0.6	3.33±1.2		9.39±0.9	5.01±0.9
ΔL±sd		-6.99±0.6	-2.69±1.4		-9.30±0.9	-4.58±0.9

The product homogeneity was evaluated considering the color difference ΔE^* between sapwood and heartwood. As can be seen from Fig. 5 and for non-thermo-vacuum-treated material, steaming homogenized the wood color by significantly reducing ΔE^*, which varied from 14.8 for unsteamed material to 3.3 after steaming. The steaming of the material did not further improve its color homogeneity as a consequence of the thermo-vacuum treatment (with PVP or TVP). In the case of unsteamed material, both thermo-vacuum treatments improved the color homogeneity with a ΔE^* which varied from 14.8 to about 9 for control and thermo-vacuum treated material, respectively.

It was also observed that the total color difference between sapwood and heartwood of control Turkey oak was greater (14.8) than that reported by Horváth *et al.*

(2012) for the same wood species (6.83). Chromatic differences in the wood structure of many timber species are principally due to the presence of external compounds, such as extractives (Todaro *et al.* 2013), which are more abundant in the heartwood than in sapwood. This evidence confirms that extractives, of which heartwood is generally richer than sapwood, play a great role in changing color by hydrothermal treatments.

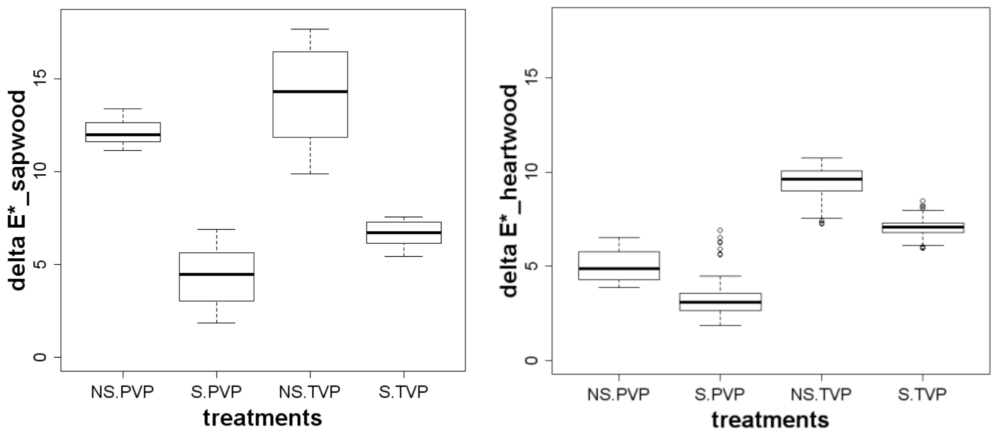

Fig. 4. ΔE* as a function of steaming and thermo-vacuum treatment. NS = not steamed; S = steamed; NT = not thermally treated; PVP = thermo-vacuum treated with press-vacuum technology; TVP = thermo-vacuum treated with Termovuoto® plant

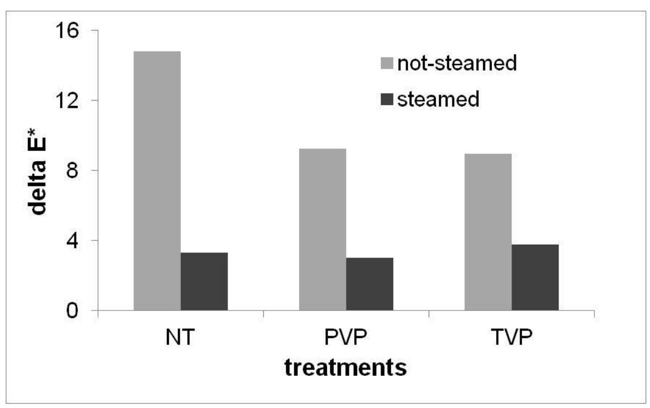

Fig. 5. Color difference (ΔE*) between sapwood and heartwood for different treatments

Darkening and a red shift of wood color show promise as a means of substituting more expensive wood species with lesser appealing ones. As reported by Sundqvist (2004), the major part of the change in colour is due to compounds emanating from hydrolysis of carbohydrates and extractives. Hydrolysis is an important reaction that occurs when wood is heat-treated and moisture is present in wood cells or under steaming conditions. The level of moisture and temperature during steaming of Turkey oak wood has been found to be the most important factor affecting color variation (Todaro *et al.* 2012b). These hypotheses were also supported by Stamm (1956) who reported that thermal degradation of wood material was greater in a closed system and under steaming heating condition. These preliminary results demonstrated that hydro-thermal treatments might be a good alternative for obtaining a more suitable surface appearance.

Compression Strength

Both for sapwood and heartwood, the compression strength parallel to the fiber was significantly increased by the thermo-vacuum treatment and decreased by the steaming process, as reported in Table 6. An increase of the compression strength because of the thermo-vacuum treatment was already described for fir and spruce by Allegretti *et al*. (2010) and for loblolly pine and water oak by Adewopo and Patterson (2011). According to some authors (Yildiz and Gümüskaya 2007), the crystallinity of cellulose, which is strongly correlated to mechanical properties, is not changed or can even be improved up to certain temperatures (even 200 °C), depending on the treatment conditions applied.

The results confirmed the strong influence of the steaming process on green wood. In any case, the effect of steaming on green Turkey oak wood is still not completely clear in this study.

When wood material is subjected to a hydro-thermal treatment, by heating in hot water or steam, a plasticization of wood occurs. The degradation of hemicelluloses that connect cellulose and lignin in the cell wall influences the physical and chemical properties of the wood (Esteves and Pereira 2009). The presence of water in wood during steaming certainly affects the degradation of the wood components by promoting hydrolysis and creates conditions favourable for the condensation of lignin.

The importance of the moisture content of the wood during steaming was also highlighted by Sundqvist (2004), who reported that normally noticeable changes in the lignin structure occur at a temperature of around 120 °C even if, at 100 °C in wet conditions, wood lignin may plasticize and change in structure (Stamm 1956). Because lignin is considered the main wood component responsible for the material's compression strength, its modification could be the reason for the decreased properties (Cao *et al.* 2012).

Table 6. Compression Resistance (σ_c) and Related Density (ρ) of Turkey Oak Treated at Different Conditions

State	σ_c (MPa) ± s.d.		Var σ_c %		ρ (kg/m^3)	
	sapwood	heartwood	sapwood	heartwood	sapwood	heartwood
NT_NS (control)	68.04±8.3	87.47±6.6	-	-	743±24.6	803±9.6
PVP_NS	77.66±7.1	94.05±6.5	+14.1	+7.5	784±11.9	844±20.8
TVP_NS	77.21±8.3	94.39±7.7	+13.5	+7.9	714±43.4	789±17.3
NT_S	54.84±6.4	73.07±8.9	-19.4	-16.5	657±20.9	729±4.1
PVP_S	58.76±7.0	73.97±8.7	-13.6	-15.4	637±18.2	689±12.4
TVP_S	61.32±10.6	78.6±6.7	-9.9	-10.1	724±4.1	722±7.5

Data refer to wood under normal conditions. For symbols, see Fig. 1.

Quality Assessment

Table 7 summarizes the main wood property modifications induced in wood by the hydrothermal treatment compared to the control values. The treatment indicated with TVP-S seemed to give the best results. In fact, the treatment significantly increased the dimensional stability of wood without substantially decreasing the compression strength.

For steamed wood, the results of this study were consistent with those of Giordano (1980), who reported that steaming green wood with heat vapour or in hot water reduced the internal and original tensions of wood. Moreover, boards without natural defects did not show qualitative damage at the end of the drying and thermo-vacuum treatments. No deformations, collapses, or checks were encountered. On the contrary, boards that contained defects, particularly knots, showed severe internal checks spread along a great part of the board after thermo-vacuum treatment. It is not clear if such cracks appeared during steaming or during drying; a deeper investigation is therefore necessary. Mohebby and Sanaei (2005) and Boonstra *et al.* (2006) reported frequent collapses and deformations in hardwood species treated at high temperatures in steam. For Turkey oak wood, it is important to pay attention to the quality of the original trunks. In fact, the results suggest that for Turkey oak, it may be very important to choose logs without defects to decrease problems during treatment and to increase the performance and efficiency for structural or other final applications.

Table 7. Percentage Variation of Some Wood Properties of Treated Wood Relative to Control

Treatment	ΔEMC%	Δswelling (Rad+Tang)%	Δ*L**%	Δσ%
NT-NS(1)	**10.90**(1)	**2.81**(1)	**70.17**(1)	**76.93**(1)
PVP-NS	-7.56	+0.04	-12.22	11.76
TVP-NS	-14.69	-27.19	-16.90	9.77
NT-S	-12.28	-20.69	-15.79	-17.23
PVP- S	-18.13	-32.35	-20.50	-14.83
TVP- S	-24.18	-27.73	-25.74	-8.76

Data refer to the average wood values, *i.e*. sapwood and heartwood together. *(1) Absolute value*

CONCLUSIONS

1. Concerning EMC and dimensional stability, sapwood and heartwood behaved differently when treated by steaming and thermal processes. In particular, sapwood was characterized by a lower reduction of EMC and swelling values compared to heartwood. As a consequence of this difference, from a hygroscopic point of view, the wood after treatment was less homogeneous.
2. Steaming (110 °C for 24 h) caused a greater color homogeneity between sapwood and heartwood compared to the thermo-vacuum treatment (160 °C for 3 h).
3. Both for sapwood and heartwood, the total color difference ΔE^*, induced by the thermo-vacuum treatment, was significantly influenced by the specific technology, *i.e.*, TVP caused a more noticeable darkening of the material than did PVP.
4. In general, processes performed with PVP technology had fewer major effects on wood properties (color and EMC) than processes using TVP. This could be due to an imperfect contact between the hot plates and the wood surface.
5. Thermo-vacuum treatment, performed at 160 °C, caused an increase in the compression strength, while the steaming process had the opposite effect.

6. The effects of combined steaming and thermo-vacuum treatment on wood properties require further tests, with more experimental replications necessary for statistical analysis.
7. An accurate selection of the material before treatments is suggested to avoid severe checks due to the presence of natural wood defects.
8. These preliminary studies require further investigation for a better understanding of the behavior of steamed and thermally treated Turkey oak. The optimum procedure that valorizes this wood species (also in terms of durability) should be identified.

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