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Microwave Treatments and Their Effects on Selected Properties of Portuguese *Pinus pinaster* Aiton. and *Eucalyptus globulus* Labill. Wood

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Abstract: The most widespread wood species in the Portuguese forest and the most widely utilized are maritime pine (*Pinus pinaster*) and eucalyptus (*Eucalyptus globulus* Labill). In the case of eucalyptus, except for the pulping sector, it might have limited usage due to drying issues and low permeability. Microwave (MW) treatment is a technology that has been used to improve wood species' permeability. Therefore, the present paper aimed to evaluate the MW treatment of both Portuguese wood species and to investigate the effects of different MW treatments on wood's density, water uptake capability, modulus of rupture (MOR), and modulus of elasticity (MOE). Using small clear wood specimens, two MW powers were used, 700 and 1200 W, and the samples were submitted to successive MW cycles of 2 min till they reached the required dryness. The results showed that each wood species had a different behavior during the MW drying in terms of drying rate, supply, and consumption of energy. In general, with the increase in MW power, the densities of both species decreased and the water uptake increased, as a possible indicator that a certain level of microstructural damage might have occurred. Regarding the mechanical properties of MW-treated maritime pine and eucalyptus wood specimens, under the harshest conditions (MW power of 1200 W), MOR and MOE were reduced compared with the wood sample without MW treatment.

Keywords: microwave drying; *Pinus pinaster*; *Eucalyptus globulus*; modulus of rupture; modulus of elasticity

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1. Introduction

Wood is one of the most commonly used materials in construction since it is abundant, sustainable, and presents a great strength-to-weight ratio compared with other materials such as concrete and steel [1]. In Portugal, many wood species have been tested for either construction or non-construction applications (e.g., pulp industry) [2–9], but maritime pine (*Pinus pinaster* Aiton.) and eucalyptus (*Eucalyptus globulus* Labill.) are two of the most common wood species in Portuguese forests [10] and are still the most used in the construction, furniture, and pulping sectors [11]. However, the usage of eucalyptus in construction and furniture is limited by the drying defects that it might present and its low permeability [12–14], which is an issue with its treatment for greater biological durability, for example [9].

Microwave (MW) treatment or drying is an approach to the wood modification field that has become more popular to increase wood's permeability [15–20], mainly in certain refractory species, such as eucalyptus [18,21,22]. It has higher heating rates compared with other methods, a volumetric and instantaneous heating approach, and a more homogenous distribution of the heat [23]. MW are electromagnetic waves whose commercial and industrial most common frequencies are 0.922 (0.915) and 2.45 GHz. The MW frequency is related to the depth of penetration inside the wood element. A frequency of 2.45 GHz is recommended for wood samples with thicknesses up to 90 mm [24].

Microwave irradiation occurs within the limits of the microwave resonator device. Within that space, microwaves are reflected from the metal case, resulting in a spatial field that is both locally and temporally changeable. When the wood is placed in this field, the water in it is affected [25]. Thus, understanding how the water molecules are present inside the wood is crucial when discussing the drying process. Thybring et al. [26] explains that water can be present in wood in two forms: (1) within cell walls, which are commonly named “cell wall water” or “bound water” since they closely interact with the cell wall components and are more difficult to remove, and (2) in the macro-void structure, which is referred to as “capillary water” or “free water” and interacts with wood through surface forces and does not significantly influence the physical and mechanical properties of the wood elements.

Because of the highly polar nature of water molecules, they can absorb MW energy and convert it to heat [27,28]. The water molecule’s angular geometry produces a hydrogen and oxygen atom–based dipole at the angle’s bisector. When exposed to an electric field, the dipole will alter its orientation. The positive end of the dipole experiences a torque in the positive field direction, whereas the negative pole aligns with the positive field direction. In an effort to align with the direction of the external electrical field, the molecule will oscillate if the field is made to alternate [27].

Depending on the MW power, energy, and frequency and continuous exposure to the MW electromagnetic field, vibrations of water molecules raise the interior temperature of the wood, creating steam pressure that can quickly reach 600 kPa [24,29–31]. This increasing steam pressure damages the wood cell tissue to varied degrees [24]. Brittle ray cells, pit membranes in cell walls, and tyloses in arteries are examples of microstructures that are prone to rupturing [32]. Changes in microstructure may lead to variations in porosity and the distribution of pore sizes, creating new pathways for the easier movement of liquid [15,27,33,34]. Therefore, these modifications to wood’s microstructure have impacts on end-product properties such as permeability [32,35] and the absorption and retention of preservation chemicals. Because of the same mechanism, the mechanical properties of MW-treated samples might change to different degrees [18,24,36–39].

When it comes to the technological potential of wood species, their potential uses, performance, and the general quality of the final product, specific properties stand out, for example, density, which has a high correlation with other properties [40,41]. Another crucial step before timber enters the construction sector is the wood treatment for greater durability [42], which is related to the ease of impregnating wood elements with a preservative agent.

In terms of mechanical properties, two fundamental properties utilized in the design of wood and timber elements, with a variety of structural applications, are the modulus of rupture (MOR) and modulus of elasticity (MOE) [43]. After MW treatment, wood elements might have their MOR and MOE modified, either by reducing or not [39].

Under MW-applied energy of 430 MJ/m^3 and initial moisture content (IMC) superior to 30%, Hermoso et al. [37] identified a reduction of about 19 and 23%, respectively, in MOR and MOE of MW-treated small clear wood specimens of Spanish *Eucalyptus globulus* containing only heartwood compared with no MW-treated ones. On the other hand, Kol et al. [34] did not find significant reductions in MOR and MOE of Oriental spruce (*Picea orientalis* Link.) sapwood in small clear specimens after MW treatment using MW powers of 925 and 1850 and applied energies of 1156 and 1542 MJ/m^3.

Applying an MW energy of 990 MJ/m^3, Torgovnikov et al. [44] found that the MOR and MOE of structural-size Sydney blue gum (*Eucalyptus saligna*) samples with IMC ranging from 78 to 108% were reduced by 56 and 39%, respectively, compared with wood samples without MW treatment. In addition, studying the impacts of an applied energy of 320 MJ/m^3 in Red Stringybark (*Eucalyptus macrorhyncha*) samples with an IMC of 70.5% [39] did not identify statistically significant reductions in both MOR and MOE values of MW-treated samples compared with reference ones.

Besides the MW parameters mentioned above, studies on MW treatment also demonstrate that the MW-treated wood element is significantly influenced by other parameters, including the wood species and stem part and their initial moisture content (IMC). Hence, additional research should be done to use different test settings during MW treatment with different wood species [18]. In this context, it was observed that research works investigating the MW treatment impacts on MOR and MOE of small clear specimens of Portuguese *P. pinaster* and *E. globulus* Labill are not well established yet. Therefore, based on the benefits and recent growth of the use of MW technology for wood treatment as well as the vast availability and potential that Portuguese eucalyptus and maritime pine have, this study aimed to evaluate the MW treatment (drying) process of both Portuguese wood species in terms of consumed and supplied energy, MW treatment efficiency, and visual analysis. In addition, acknowledging the importance of density, water impregnability, and bending MOR and MOE, it was aimed to investigate the effects of MW treatment on these selected wood properties.

2. Materials and Methods

2.1. Sample Preparation

Small, clear specimens (free of knots, cracks, or other defects) of maritime pine and eucalyptus containing only heartwood from the central region of Portugal were obtained from commercial boards. The maritime pine samples were obtained from logs 30 to 33 years old and eucalyptus 20 years old.

Although early and late wood may have differences in terms of properties and permeability, since it was not within the scope of this work, there was no analysis regarding the differentiation between the early and late wood in the used wood samples. The specimens were obtained following the industrial cut in which the trunk is “sliced” into boards, and from those boards, the small clear specimens were prepared following the recommendations of [45]. A total of 36 samples of eucalyptus and 36 samples of pine measuring 20 mm $\times$ 20 mm $\times$ 320 mm (radial $\times$ tangential $\times$ longitudinal) were used. To calculate the moisture content (MC) of the wood specimens, twelve representative samples from eucalyptus and twelve from pine were randomly selected and dried to constant mass in an oven at 103 °C $\pm$ 2 °C, as done by [18] to determine their oven-dry weight. Based on this, the MC values of the wood samples during the MW treatment were calculated [46].

The wood samples submitted to the MW treatment were placed in a container of distilled water to preserve their “green” conditions so they would not lose water until the drying process began. Therefore, it is important to explain that the darker color the MW-treated sample might have had was not because of the MW treatment. The period they were immersed in water might have contributed to the change in their color. The evaluation of the color changes of MW-treated samples is not within the scope of this work, but further investigations can be done on the modifications of color changes due to MW treatments.

2.2. MW Treatment

The used specimens were divided into groups, as shown in Tables 1 and 2, for maritime pine and eucalyptus, respectively. The control groups had no MW treatment. In each MW treatment run, 4 samples were put together inside the MW oven and dried until they achieved a final moisture content of 12% on average. It was used as a 2 min MW treatment cycle, which means that the samples remained continuously in contact with the electromagnetic waves during the continuous exposure to MW energy. After each cycle of 2 min, the wood specimens were taken from the MW for 30 s to weigh them and, based on that, to determine their MC. The 30 s interval was also necessary to avoid excessive heating that could cause severe damage to the wood structure, as described by [27]. The MW treatment cycle of 2 min and the 30 s interval were chosen based on preliminary tests and data from the literature [27,47].

Table 1. MW treatment information and initial MC of maritime pine specimens.

Group	Quantity	Initial MC (%)	MW Power (W)
Control	12	11.6 (2.3) *	-
PP_1200W_2min	12	90.2 (11.6) *	1200
PP_700W_2min	12	103.4 (5.5) *	700

* Numbers in parentheses are the standard deviation.

Table 2. MW treatment information and initial MC of eucalyptus specimens.

Group	Quantity	Initial MC (%)	MW Power (W)
Control	12	12.2 (1.9) *	-
EG_1200W_2min	12	61.5 (6.4) *	1200
EG_700W_2min	12	62.6 (7.4) *	700

For each wood group of pine and eucalypt, two MW treatment schedules were used: one with an MW power of 1200 W and 2 min of MW treatment cycle time (continuous exposure time), and another with an MW power of 700 W and continuous exposure time of 2 min. * Numbers in parentheses are the standard deviation.

It is important to note that the initial MC of the pine and eucalyptus wood specimens was above the theoretical fiber saturation point (FSP), which, as explained by [15], more closely resembles real drying conditions.

The wood samples were treated in a conventional MW device with a maximum power of 1200 W, 2.45 GHz frequency, and a turntable measuring 360 mm in diameter. After finishing the MW treatment, all wood specimens were then conditioned in a room with a temperature of 20 °C ± 2 °C and 65% ± 5% relative humidity for approximately 14 days to reach the equilibrium moisture content of 12%, prior to the MOE, MOR, and water uptake tests, also referred to in this manuscript as water impregnation tests.

The energy required to heat moist wood and vaporize the water in the wood, Q_w, was calculated according to Equation (1) [48].

$$Q_w = \Delta T \times (c_1 \times m_1 + c_2 \times m_2) + \Delta m \times r \quad (1)$$

where Q_w is the energy required to heat moist wood and to vaporize the water in the wood, in kJ (kWs); ΔT is the temperature difference between the samples at room temperature before MW treatment and 100 °C; c_1 is the heat capacity of water, 4.18 kJ/kg°C; m_1 is the mass of water in the specimen, in kg; c_2 is the heat capacity of dry wood, 1.36 kJ/kg°C; m_1 is the mass of dry wood in the specimen, in kg; Δm is the mass of vaporized water, in kg; r is the heat of vaporization of water at 100 °C, 2250 kJ/kg.

The effective power density consumed to dry the wood specimens is given by Equation (2) [48].

$$P_\delta = \frac{Q_w}{V \times t} \quad (2)$$

where P_δ is the specific power density consumed to dry the wood specimens, in kW/m^3; V is the volume of wood specimen, in m^3; t is the drying time, in s.

The theoretical specific energy consumption during the process is given by Equation (3) [48].

$$E_{cons} = \frac{P_\delta \times t}{1000} \quad (3)$$

where E_{cons} is the specific energy consumed during the MW process, in MJ/m^3.

The specific energy supplied during the process is given by Equation (4) [18].

$$E_{sup} = \frac{P \times t}{V \times 10^6} \tag{4}$$

where E_{out} is the specific energy supplied during the MW process, in MJ/m^3; P is the MW power supplied (W).

Finally, the overall MW efficiency, η, was calculated according to Equation (5).

$$\eta = \frac{E_{cons}}{E_{sup}} \tag{5}$$

The MW drying rates of the wood samples were calculated using the following Equation (6).

$$dr = \frac{MC_t - MC_{t+\Delta t}}{\Delta t} \tag{6}$$

In addition, to determine the weight percentage loss (*WPL*) of water after MW treatment, Equation (7) was used.

$$WPL = \frac{m_2 - m_1}{m_{od}} \tag{7}$$

where m_2 is the weight of the specimen before MW treatment in g; m_1 is the weight of the specimen after MW treatment, in g; m_{od} is the oven-dry weight of the specimen, in g.

The relative water loss was calculated using Equation (8). The idea is to analyze how much the *WPL* represents in relation to the initial MC of the samples.

$$Relative\ water\ loss = \frac{WPL}{Initial\ MC} \tag{8}$$

2.3. Evaluation of Water Impregnability

The samples of both wood species were impregnated with distilled water at a pressure of 600 kPa for 30 min, and the water uptake was measured using Equation (9) in order to understand the capability of MW-treated and control samples impregnated with a fluid.

$$Water\ uptake = \frac{m_{ai} - m_{bi}}{m_{od}} \tag{9}$$

where m_{ai} is the weight of the specimen after water impregnation (water uptake), in g; m_{bi} is the weight of the specimen before impregnation, in g.

2.4. Determination of Mechanical Properties

The bending modulus of rupture and modulus of elasticity of the control and MW-treated samples were determined according to ISO 13061-3 [49] and ISO 13061-4 [50], respectively. The values of MOR and MOE presented in this work were adjusted to 12% MC following the recommendations of these standards. A similar approach was used by other researchers [18,24,34,37,38].

As soon as the mechanical tests were completed, to acknowledge the MC and density of the specimens when tested, samples measuring 20 mm × 20 mm × 20 mm were taken from the undamaged part of the specimens near the point of rupture to determine their MC at the moment of the bending tests, and their MC and density were determined according to ISO 13061-1 [46] and ISO 3061-2 [51], respectively. The oven-dry density was adjusted to a 12% moisture content using the same international standard.

2.5. Statistical Analysis

The differences between MW-treated and control samples were assessed by classical analysis of variance (ANOVA) at a 5% significance level with a Tukey Test. According to the ANOVA formulation, if p-values are smaller than the significance level (p-value < 0.05), the isolated factors (density, water impregnability, MOR, and MOE) can be considered significant. To formally determine if there is a statistically significant difference between the two groups, engineers usually employ a Tukey comparison test. The letters presented in the statistical analysis results indicate that groups that do not share the same letter have a mean difference that is statistically significant. The entire statistical analysis was done using Minitab software [52].

In addition, Pearson's correlation coefficient (r) was used. It measures the degree of correlation between two quantitative variables. This approach typically uses datasets with a normal distribution and an interval or continuous scale [53]. It can range from −1 to +1, presenting a low, moderate, or strong correlation, where a 0 value means that there is no correlation. Pearson's correlation coefficient does not only measure linear relationships [54].

3. Results and Discussion

3.1. MW Treatment, Visual Modification, and Density

Table 3 shows the total MW treatment exposure time, the weight percentage loss (*WPL*), the specific energy consumed and supplied during the MW process, and the overall MW efficiency of MW-treated maritime pine specimens. The relative water loss for group PP_1200W_2min was 87.8%, and for group PP_700W_2min it was 86.9%. In addition, according to the results, the energy supplied to obtain 1% of *WPL* was 44.64 and 31.63 MJ/m^3 for PP_1200W_2min and PP_700W_2min, respectively. It is important to recall that the pine samples used in this work contained only heartwood, and [37] studying Oriental spruce containing only sapwood found that, on average, 44.37 MJ/m^3 are necessary to be supplied to the wood samples to obtain 1% of *WPL*.

Table 3. MW treatment of maritime pine samples.

Group	MW Power (W)	Total MW Exposure Time (s)	Average *WPL* (%)	E_{cons} (MJ/m^3)	E_{sup} (MJ/m^3)	η
PP_1200W_2min	1200	1520	79.8 (9.5)	1248	3563	0.35
PP_700W_2min	700	2080	89.9 (3.8)	1397	2844	0.49

Values in parentheses are the standard deviation.

The MW treatment information for eucalyptus is presented in Table 4. The relative water losses for groups EG_1200W_2min and EG_700W_2min were 81.6 and 80.2%, respectively. The values of the relative water loss for both wood species in both MW treatments are similar. For the eucalyptus samples, the energy supplied to have 1% of *WPL* was 62.00 and 42.49 MJ/m^3, respectively, for EG_1200W_2min and EG_700W_2min. Studying Spanish eucalyptus wood specimens containing only heartwood, Hermoso et al. [37] found values ranging from 36.23 to 61.18 MJ/m^3 to have 1% of *WPL*.

Table 4. MW treatment time of eucalyptus samples.

Group	MW Power (W)	Total MW Exposure Time (s)	Average WPL (%)	E_{cons} (MJ/m^3)	E_{sup} (MJ/m^3)	η
EG_1200W_2min	1200	1320	49.9 (1.2)	1197	3094	0.39
EG_700W_2min	700	1560	50.2 (1.5)	1133	2133	0.53

Values in parentheses are the standard deviation.

Overall, eucalyptus specimens required more energy to obtain 1% of *WPL* than maritime pine ones. Under the same MW power (700 and 1200 W), to obtain 1% of *WPL*, eucalyptus specimens required 1.4 times more energy than pine. According to [29], the MW energy necessary to dry hardwoods can be up to 2.3 times higher than the one needed to dry softwoods. In addition, Wilson et al. [55] explains that hardwoods require more energy than softwood in their production, mainly in drying because hardwoods take longer drying times [56].

The vessels are unique structures found In hardwoods that direct sap upward. The size, shape, and arrangement of vessels, which are also known as pores, vary depending on the species but are generally stable within it. Simple pits and tracheids in the softwood allow the sap to travel through the ray parenchyma cells. Although the cell wall surrounds the margin of bordered pits, the sap can still travel through them to reach neighboring cells [57,58].

In terms of anatomical features, the extraction deposits that have accumulated on the pit membrane and the extent to which the bordered pit pair in the heartwood has been closed account for the majority of the permeability difference in softwood, which has simple, bordered pits that allow mass (water vapor) transfer between layers [59]. Finally, the global and directional porosities affecting mass transport are different.

For both wood species, the wood samples treated with 700 W took longer to dry than those treated with 1200 W, which shows that the higher the MW power, the faster the MW treatment process. The average total MW exposure time was reduced by 37% and 18% for pine and eucalypt, respectively, increasing the MW power from 700 to 1200 W. The findings are directly in line with previous findings of other studies, such as the ones presented by [60], who studied *Eucalyptus urophylla,* and [38], who analyzed *Pinus banksiana*.

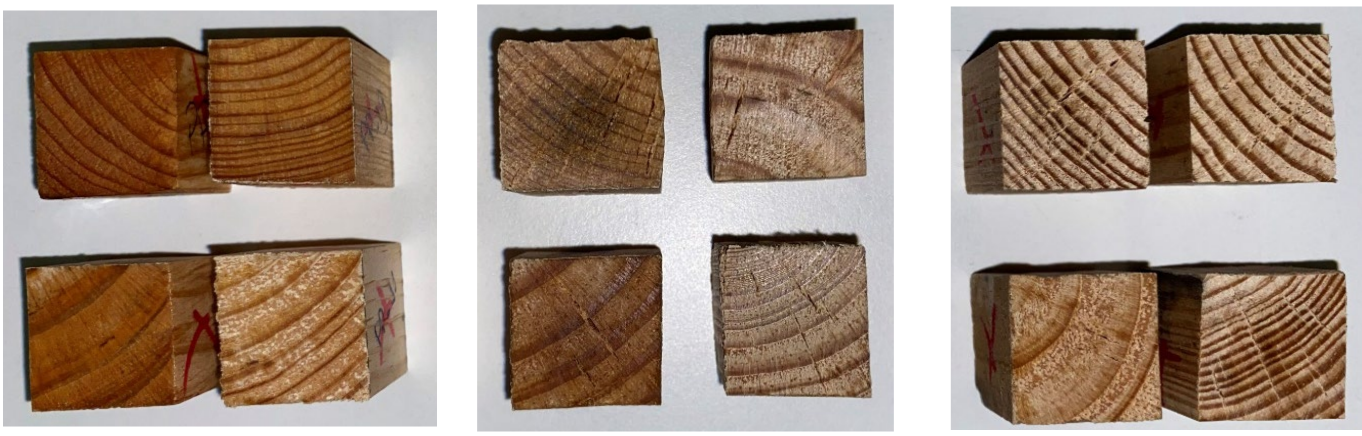
The average MW efficiency of the samples dried at 700 and 1200 W was 0.35 and 0.49 for pine and 0.39 and 0.53 for eucalyptus, respectively. According to [61], energy efficiency depends on wood species, their IMC, and MW power. Metaxase et al. and Antti et al. [28,48] also point out that the overall MW efficiency for MW ovens with industrial applications is approximately 0.50. In addition to this, as the drying process proceeds, the amount of available water to be dried decreases, affecting the absorbed power. Hence, there is a reduction in MW efficiency [62].

The measurement of the efficiency is important because part of the MW power is reflected back to the magnetrons, and another part is passed (not absorbed), either because the material loses its capability of absorbing energy as the amount of water decreases during the drying or due to the volume of wood to be dried. Torgovnikov et al. [24] points out that the water vapor, resin, and even wood particles need to be removed from the MW cavity because they may limit the proper and complete operation and efficiency of the MW device and the drying process. The vapors, for instance, can condense on the applicator's walls and absorb MW energy.

The average MW drying rates of maritime pine were 2.75%H_2O/min for PP_700W_2min and 3.57%H_2O/min for PP_1200W_2min, an increase of about 30%. Using another species of pine, *Pinus banksiana*, and increasing the MW power from 500 to 1000 W, Ouertani et al. [38] identified an increase of 33% in the drying rate. The average MW drying rates of eucalypt samples were 2.05%H_2O/min for EG_1200W_2min and 1.95%H_2O/min for EG_700W_2min. As expected, the MW drying rates of eucalyptus specimens were lower than those of maritime pine samples due to the anatomical and permeability characteristics of each wood species.

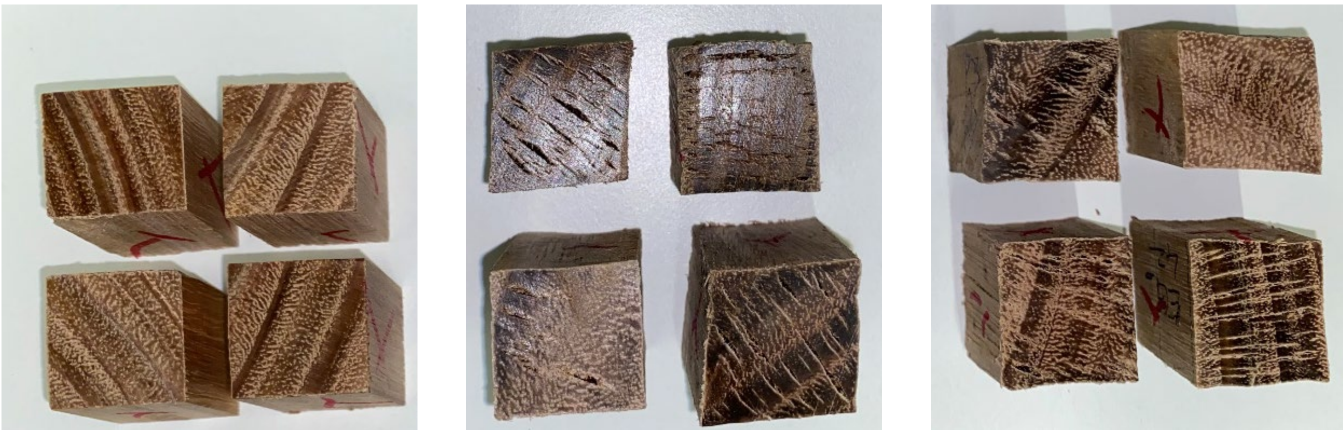
Since the generation of heat (and consequently the drying of the wood) in MW takes place through the movement of water molecules that tend to orient themselves according to the electromagnetic field generated [27], high powers supply the wood with more energy and cause water molecules to oscillate very quickly. Due to this molecular agitation, the intermolecular bonds break and reorganize, which quickly heats the wood sample through friction. Finally, the wood's internal gas pressure and temperature rise under high MW power, accelerating the drying process [38].

Figures 1 and 2 show the cross-sections of the studied wood samples, measuring 20 mm × 20 mm × 20 mm for maritime pine and eucalyptus, respectively. Even though the average drying rates of maritime pine specimens were higher than those of eucalyptus, it was noticed that there were fewer cracks in the cross-section of maritime pine specimens compared with eucalyptus, and the cross-sections of the pine samples had fewer distortions.



(a) (b) (c)

Figure 1. Cross-section of maritime pine samples of (**a**) control; (**b**) PP_700W_2min; and (**c**) PP_1200W_2min groups.



(a) (b) (c)

Figure 2. Cross-section of eucalyptus samples of (**a**) control; (**b**) EG_700W_2min; and (**c**) EG_1200W_2min groups.

Based on the visual analyses, which can be seen in the figures, the cross-sections of pine samples seem not to be severely affected even under the most intense MW treatment, 1200 W, and a cycle time of 2 min. This was probably due to pine wood's higher global and longitudinal porosity compared with eucalyptus wood.

Under both MW treatment schedules, the wood samples made of eucalyptus presented severe distortions. Both groups were drastically affected (EG_700W_2min (Figure 2b) and EG_1200W_2min (Figure 2c)) either in terms of the quantity and thickness of the cracks in the cross-section or the superficial distortions of the samples. Because of the distortions in the cross-section of the eucalypt samples, further studies reducing the MW power are necessary. The results presented here are in accordance with those from [37], which investigated small, clear specimens of *Eucalyptus globulus* from Northwest Spain.

By increasing the MW treatment intensity applied to structural-sized messmate (*Eucalyptus obliqua*) samples, Torgovnikov et al. [24] showed similar results with an increase in the cracks and fissures of the samples from control to intensive MW modification. The increase in MW power led to an increase in the damage to wood cells and, consequently, the formation of cracks in the wood. Ouertani et al. [38] stated that when high MW power is applied to moist wood, its structure is altered by steam pressure, achieving 6 bar in a few seconds [29] and temperatures reaching 160 °C in the center of the samples [31]. The combination of elevated steam pressure leaving the inside part of the wood and high temperatures ends up generating severe damage to the wood's micro- and macrostructure.

The average densities, corrected to 12% moisture content, of the control and MW-treated wood specimens of pine and eucalyptus are shown in Figures 3 and 4, respectively. Overall, as the MW power increased, the specimen's density reduction increased for pine and eucalyptus. It can be explained by the increase in the number of micro and macro cracks that were generated in the MW-treated specimens.

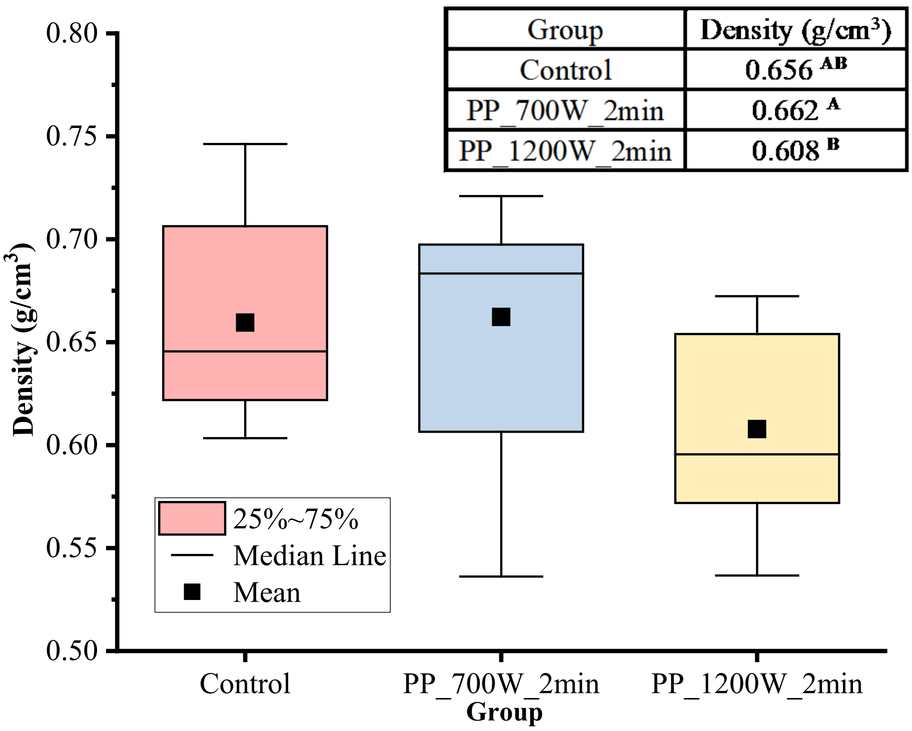


Figure 3. The average densities at 12% moisture content of maritime pine samples. Values followed by the same letter do not differ significantly at $\alpha = 0.05$.

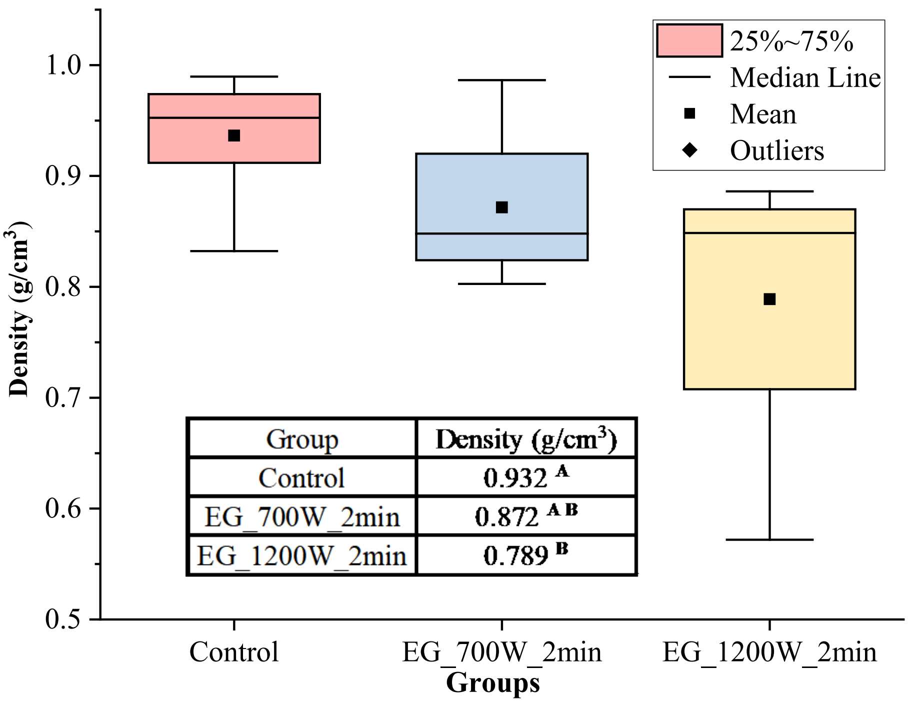


Figure 4. The results of average densities at 12% moisture content of eucalyptus samples. Values followed by the same letter do not differ significantly at $\alpha = 0.05$.

Compared with the average density at 12% MC of the control group, there was an increase of 0.85% in the density of PP_700W_2min samples and a decrease of 7.40% in the density of PP_1200W_2min samples. As shown in Figure 3, the average density at 12% MC of the pine wood samples treated with 700 W for a 2 min MW treatment cycle time was higher than that of the control group. Balboni et al. [39] faced the same situation when treating wood samples of Red Stringybark with a low level of MW treatment. As explained by [39], although not generated by MW, the checks present in the control samples may have raised just the volume of the samples. On the other hand, the checks that PP_700W_2min had did not affect density but may have permitted a reduction in drying checks.

Compared with the control group of the heartwood of eucalyptus, there were reductions of 6.51 and 15.40% for EG_700W_2min and EG_1200W_2min, respectively. The decrease in density with the increase in MW treatment was also reported by [24,39], who studied different wood species.

3.2. Water Impregnability

The water uptake of maritime pine (Table 5) and eucalyptus (Table 6) specimens was measured to better understand the modifications that different MW powers had on both species, i.e., the water impregnability allowed us to comprehend how the capability of being impregnated was modified.

Table 5. Average water uptake of maritime pine.

Group	Water Uptake (%)
Control	19.08 ^{B} (7.33)
PP_700W_2min	70.42 ^{A} (13.47)
PP_1200W_2min	68.13 ^{A} (9.47)

Values followed by the same letter do not differ significantly at α = 0.05.

Table 6. Average water uptake of eucalyptus.

Group	Water Uptake (%)
Control	14.80 ^{B} (5.98)
EG_700W_2min	30.69 ^{A} (4.58)
EG_1200W_2min	30.35 ^{A} (2.18)

Values followed by the same letter do not differ significantly at α = 0.05.

For being less refractory than eucalyptus, maritime pine significantly improved water uptake under the same MW power and treatment cycle time. Under an MW power of 1200 W and a MW cycle time of 2 min, maritime pine samples had an average improvement of around 3.6 times (compared with the control samples), while the eucalyptus samples treated with the same MW parameters had an average increase of 2.1 times (compared with the control samples). Hence, it is indicative that a harsher combination of MW power and MW cycle time would be necessary for the eucalyptus specimens to achieve the same level of water impregnation as pine samples; however, it could cause severe damage to the wood structure. Results presented by [24,63] showed that hardwood specimens with the same dimensions and initial moisture content required more MW energy than softwoods to accomplish comparable levels of MW modifications.

In addition, under the MW treatment conditions and the IMC of the samples used in this work, the increase in the MW power did not cause a significant improvement in the water uptake capability for both wood species. In fact, the average water uptake for both MW powers for pine wood species was statistically equivalent, 70.42 and 68.13%, and for eucalyptus wood specimens, 30.69 and 30.35% (Tables 5 and 6).

Although the permeability of the wood samples (control and MW-treated) was not directly measured (there are specific methodologies to measure permeability), the increase in water impregnability that the MW-treated samples had compared with the control ones might indicate that their permeability increased. Terziev et al. [64] explains that, as the pressure rises, the pressure gradients rupture the weakest portions of the wood structure, increasing the permeability of the wood to liquids and gases. For example, [15,16,24,32,33,35,60,65,66], studying different wood species, identified increases in the permeability coefficients after MW treatment.

Finally, it might indicate that they could be easier impregnated with preservative products and even polymers in order to obtain wood composite products with improved mechanical, biological, and fire resistance properties, for instance.

3.3. Mechanical Properties

Table 7 shows the average bending strength (MOR) and stiffness (MOE) at 12% MC, their standard deviation, and the percentual changes in the mechanical properties of the maritime pine specimens. The average MOR and MOE of the control group were 89 and 12,399 MPa, respectively. Although the average MOR value of group PP_1200W_2min was smaller than the other two, it was statistically equivalent to PP_700W_2min and the control groups. Hence, it means that although the strength and stiffness values of PP_1200W_2min were statistically equivalent to the control group, there was a reduction of about 22% of MOR and 15% of MOE compared with control specimens. Studying another species of pine, *Pinus banksiana*, Ouertani et al. [38] found a reduction of around 18% and 28% in MOR and MOE, respectively, using an MW power of 1000 W.

Table 7. Results of the mechanical properties at 12% moisture content of maritime pine samples.

Group	MOR (MPa)	Change of MOR (%)	MOE (MPa)	Change of MOE (%)
Control	89.47 ^{A} (21.83)	-	12,399 ^{AB} (2840)	-
PP_700W_2min	89.72 ^{A} (23.71)	+0.28	14,719 ^{A} (3121)	+18.71
PP_1200W_2min	70.19 ^{A} (22.56)	−21.55	10,504 ^{B} (3143)	−15.28

Values followed by the same letter do not differ significantly at $\alpha = 0.05$.

Torgovnikov et al. [24] explains that three levels of modification in the wood can occur. Under a low level of MW power, the permeability may be increased. However, it might not be sufficient to produce statistically significant reductions in the strength properties, as occurred in the results [39]. In our results, although a certain level of reduction was expected in the MOR and MOE values of PP_700W_2min, no reduction was measured, which may indicate that a low level of modification was applied to the wood.

When analyzing the relationship between MOR, at 12% moisture content, and water impregnation of the maritime pine wood samples (Figure 5), the wood samples of the group PP_700W_2min had the highest water uptake, which might imply a better capability of being impregnated without having reductions in the MOR values.

The average results of MOR and MOE at 12% MC, their standard deviation, and the changes in these two properties for the eucalyptus wood specimens are presented in Table 8. As MW power increased, a decrease in both mechanical properties was observed, as reported in other works in the literature using other wood species [18,24,27,37,39]. For eucalypt MW-treated samples, the increase in MW power was inversely proportional to MOR and MOE, where the groups EG_700W_2min and EG_1200W_2min had an average

MOR loss of 23 and 26% and MOE loss of 15 and 32%, respectively. The Pearson correlation analysis demonstrated a moderate to strong correlation, $r = -0.674$ (p-value = 0.016), between the MW power and MOR of eucalyptus wood samples.

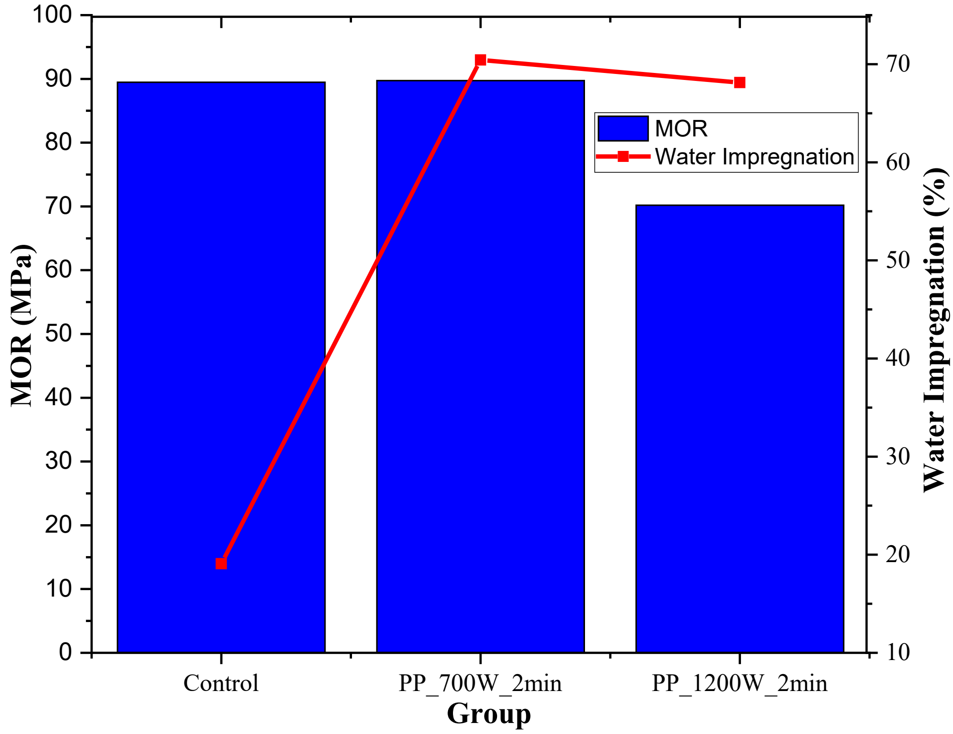


Figure 5. Relationship between MOR values and water impregnation in maritime pine samples.

Table 8. Results of the mechanical properties at 12% moisture content of eucalyptus samples.

Group	MOR (MPa)	Change of MOR (%)	MOE (MPa)	Change of MOE (%)
Control	113.60 ^{A} (10.26)	-	17,690 ^{A} (2421)	-
EG_700W_2min	87.83 ^{B} (23.17)	−22.68	14,993 ^{B} (2915)	−15.25
EG_1200W_2min	84.30 ^{B} (21.80)	−25.79	12,045 ^{B} (3524)	−31.91

Values followed by the same letter do not differ significantly at $\alpha = 0.05$.

Torgovnikov et al. [44] identified reductions of 60% for MOR and 43% for MOE in wood samples of Australian *Eucalyptus globulus* treated under high MW intensity. Studying heartwood specimens of *Eucalyptus globulus* from the Northwest of Spain, Hermoso et al. [37] identified reductions of about 23 and 19% in MOR and MOE, respectively, under an MW power treatment of 500 W.

Besides the severe distortions and damage identified in the eucalyptus wood specimens treated with 1200 W, under this MW power, the most significant reductions in the analyzed mechanical properties were seen, which is an indication of the inviability of treating eucalypts with those MW conditions. Similar results were presented by [67], studying Norway spruce (*Picea abies*) wood specimens. Under the higher MW power and exposure time combinations used by the authors, the wood samples were deeply damaged, so it was impossible to investigate the MOR and MOE values.

Figure 6 shows the relationship between MOR, at 12% moisture content, and water uptake in eucalyptus wood samples.

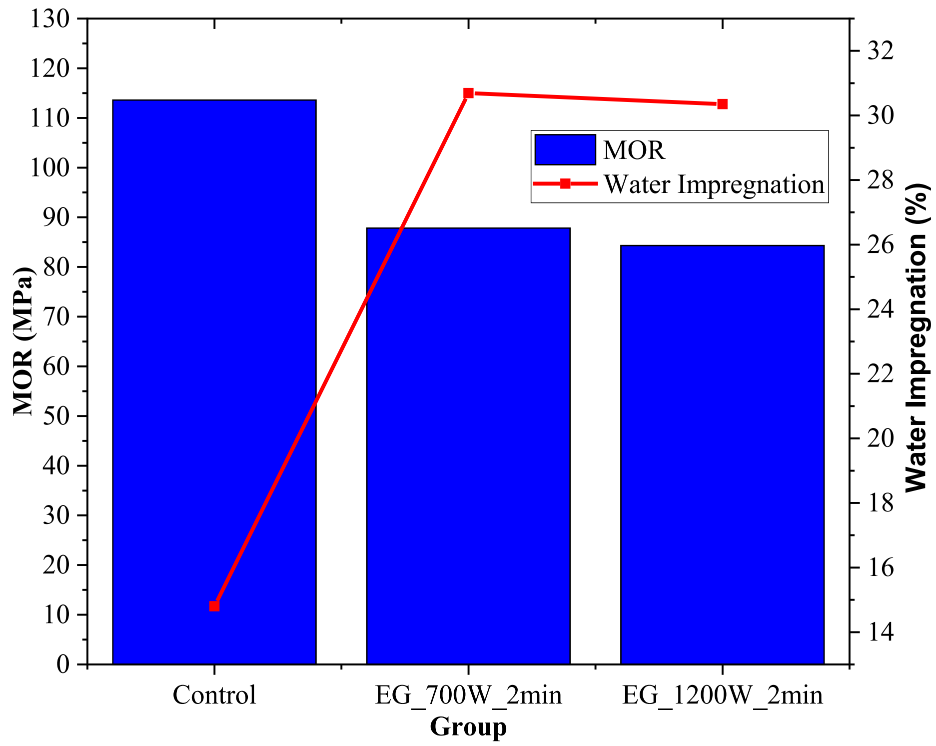


Figure 6. Relationship between MOR values and water impregnation in eucalyptus samples.

In addition to this, the strength-to-density ratio of each wood species and for each group was also evaluated by using the MOR and density values at 12%, as shown in Table 9. This is an important way to assess the effectiveness and performance of a given material.

Table 9. Strength-to-density ratio.

Group	MOR/Density (MPa/g/cm^3)
Maritime pine	
Control	136
PP_1200W_2min	115
PP_700W_2min	136
Eucalyptus	
Control	122
EG_1200W_2min	107
EG_700W_2min	101

Regarding the maritime pine groups, the control and PP_700W_2min groups had the same values for the strength-to-density ratio, 136, which is another evidence that 700 W and 2 min are reasonable options for treating the studied maritime pine wood elements. For the eucalyptus, for both treatment schedules, the strength-to-density ratios were smaller than in the control group. Despite that, both wood species and groups (control and MW-treated) had high strength-to-density ratios. For example, structural steel has a strength-to-density ratio ranging from 50 to 130, and concrete in compression has a strength-to-density ratio ranging from 13 to 50. Although timber engineering works with properties and performance on structural elements (structural timber), small clear wood properties and more detailed levels are critical for a fundamental understanding of the main issues in timber engineering [68].

When more MW energy was supplied to the wood, probably more fissures and different degrees of damage might have happened in the microstructure of the wood (and even the macrostructure). Studies carried out by [69] using SEM endorsed that increased MW energy led to an increase in damage to wood microstructure. Numerous cavities were formed in the wood due to the high MW energies used, changing its porosity, permeability, strength, and flexibility [24]. Nasswettrová et al. [70] complements this by explaining that the modifications made to the wood's cell structure by MW treatment will also depend on the total MW exposure time and wood density.

Because of that, according to the findings presented in this work, each wood species behaved differently under MW treatment, and the harsher the MW treatment conditions, the greater the number of cracks in the cross-section of the samples, the more noticeable the distortion that the samples suffered, and the greater the decrease in density and strength properties.

Hence, the choice of the most appropriate MW treatment parameters for each wood species must be made by analyzing the final end use of each one, taking into account all the studied variables: MW drying rate (faster or slower the MW treatment process), efficiency, amount of energy required to remove 1% of water, modifications in the values of density, MOR, and MOE, and improvements in water impregnability.

4. Conclusions

1. Each wood species behaved differently under the same MW power and continuous exposure time in terms of total MW drying time, average drying rate, and efficiency. The pine samples had higher drying rates compared with the eucalyptus specimens.
2. For both wood species, the higher the MW treatment power, the more expressive the distortions in the cross-section of the samples. In addition, as a consequence of the possible damage that occurred in the microstructure of the wood, a reduction in the densities of the samples was identified as the MW power increased, with the eucalyptus samples being more affected than the pine samples.
3. The MW treatment remarkably improved the water impregnability of the samples. However, in most cases, the better the improvements in water uptake, the higher the reductions in strength and stiffness.
4. Under an MW treatment power of 700 W and a 2 min cycle time, the MOR and MOE values of MW-treated maritime pine samples were statistically equivalent to the ones from the control group, and they improved the water uptake around four times.
5. For the eucalypt groups EG_1200W_2min and EG_700W_2min, the average reductions of MOR were 26 and 23% and of MOE were 32 and 15% in relation to the control samples, respectively, with an average increase of two times in the water impregnability.

Finally, the best overall results for pine wood species were obtained using a MW power of 700 W. For eucalypts, further studies are necessary, making some fine adjustments to determine the adequate MW drying parameters so that the measured permeability can be enhanced without noticing reductions in the strength properties.

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