# Effect of Thermal Modification Process on Acoustic Properties Used in Musical Instrument Wood

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Spruce (*Picea orientalis*), maple (*Acer pseudoplatanus*), and mahogany (*Khaya ivorensis*) woods are commonly used wood types in making musical instruments. In this study they were subjected to thermal modification at 210 °C for 90 min. The changes in bending strength, sound velocity, acoustic radiation, acoustic impedance, and static and dynamic elasticity modulus values of wood samples after thermal modification were investigated. The results showed that spruce wood's acoustic performance decreased after thermal modification, while maple wood improved. Meanwhile, the acoustic performance of mahogany wood remained unaffected by thermal modification. Examining the alterations in mechanical properties revealed a decline in bending strength in all wood samples that underwent thermal modification. However, an increase in modulus of elasticity values was observed in spruce, whereas no change was found in mahogany and maple.

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## INTRODUCTION

Throughout the history of mankind, wooden materials have been used in many different fields, and their use in the manufacture of musical instruments dates back many years (Conard *et al.* 2009). In comparison with other materials, wood is the most used material in the production of musical instruments, both in terms of aesthetic properties and it has a high modulus of elasticity value (Bucur 2006). Although the acoustic and mechanical properties of wood are unique, the main disadvantage is that when used in humid conditions, acoustical, mechanical and dimensional futures are adversely affected (Sakai *et al.* 1990; Kabir *et al.* 1998; Obataya *et al.* 1998; Calegari *et al.* 2011; Moreno *et al.* 2011; Olivera *et al.* 2014; Yang *et al.* 2015). For this reason, researchers have attempted to improve dimensional stability of wood material by impregnating it with various chemicals (Rowell 2005; Hill 2006; Hill *et al.* 2021; Sandberg *et al.* 2021; Mai and Militz 2023; Aydogmus and Cetin 2024). However, because of increased environmental awareness in the last 25 years, the use of harmful chemicals has decreased (Schultz *et al.* 2007). As an alternative to impregnation with these chemicals, many researchers have investigated giving dimensional stability to wood through the use of high temperatures, which is called thermal modification (Stamm 1956; Burmester 1975; Sarni *et al.* 1990; Yun *et al.* 1999; Homan and Tjeerdsma 2000; Kubojima *et al.* 2000; Navi and Girardet 2000; Kamdem *et al.* 2002; Bekhta and Niemz 2003; Yildiz *et al.* 2006; Esteves *et al.* 2007, 2008;

Korkut *et al.* 2007; Esteves and Pereira 2009; Kocaefe *et al.* 2015; Kol *et al.* 2017; Nourian 2018).

Thermal modification is a physical modification process that causes permanent changes in the chemical structure of polymers in the cell wall of wood by exposure to high temperatures to provide dimensional stability (Rusche 1973; Burmester 1975). The main reason for the dimensional stability induced in wood by heat treatment is due to changes in the chemical structure that occur due to temperature (Sarni *et al.* 1990). The impact of thermal treatment on wood is closely linked to the thermal stability of its main structural components (Esteves and Pereira 2008). Among these, hemicelluloses are the most thermally sensitive and begin to degrade at temperatures below 200 °C (Tjeerdsma *et al.* 1998). This vulnerability is due to their low polymerization degree, highly branched and variable chemical structure, and amorphous nature (Kozakiewicz *et al.* 2020). Hemicellulose degradation is typically accompanied by the release of organic acids (Byrne and Nagle 1997; Weiland and Guyonnet 2003; Nuopponen *et al.* 2004). Amorphous cellulose also undergoes changes relatively quickly, displaying thermal behavior similar to hemicelluloses. The chemical alteration of polysaccharides during heat treatment results in the loss of hydroxyl groups, thereby reducing their capacity to interact with water (Esteves *et al.* 2008; Esteves and Pereira 2008). In contrast, crystalline cellulose demonstrates considerable thermal resistance and is only slightly affected at temperatures approaching 300 °C (Kim *et al.* 2001). Lignin, the most thermally stable wood component, is a complex phenolic polymer characterized by a heterogeneous structure and a variety of inter-unit linkages (Kim *et al.* 2014). Its response to heat varies with temperature: initially, lignin undergoes depolymerization, followed by acid-catalyzed cleavage of ether bonds, leading to condensation and elimination reactions (Tjeerdsma and Militz 2005a; Yildiz *et al.* 2006). Although many studies have examined changes in dimensional stability and mechanical properties after heat treatment (Stamm 1956; Sarni *et al.* 1990; Yun *et al.* 1999; Homan and Tjeerdsma 2000; Kubojima *et al.* 2000; Navi and Girardet 2000; Kamdem *et al.* 2002; Bekhta and Niemz 2003; Yildiz *et al.* 2006; Boonstra *et al.* 2007; Korkut *et al.* 2007, 2008; Korkut and Guller 2008; Esteves and Pereira 2009; Metsä-Kortelainen and Viitanen 2010; Jimenez *et al.* 2011; Lekounougou *et al.* 2011; Allegretti *et al.* 2012; Kačíková *et al.* 2013; Morrell *et al.* 2014; Kocaefe *et al.* 2015; Navickas *et al.* 2015; Kol *et al.* 2017; Kozakiewicz *et al.* 2020; Roszyk *et al.* 2020), few studies have investigated changes in the acoustic properties of heat-treated wood samples (Kubojima *et al.* 1998; Byeon *et al.* 2010; Karami *et al.* 2013; Del Menezzi *et al.* 2014; Puszynski and Warda 2014; Pfriem 2015; Zhu *et al.* 2016; Ahmed and Adamopoulos 2018; Kang *et al.* 2019; Mania and Skrodzka 2020; Zatloukal *et al.* 2021; Danihelová *et al*. 2022).

Kubojima *et al.* (1998) subjected spruce (*Picea sitchensis*) wood samples to thermal modification at different temperatures (ranging from 120 to 200 °C) and for different durations (ranging from 0.5 to 16 h). It was determined that the density of the samples decreased due to the increase in temperature and duration after thermal modification. Additionally, the dynamic elastic modulus value exhibited an increase with thermal modification up to 160 °C, while this value decreased with increasing temperature and reaction time. The findings of the study indicated that there was an improvement in the elastic modulus values along with a decrease in moisture content and an increase in crystallinity in the wood samples.

Another study was conducted to investigate the changes in sound resistance values of spruce (*Picea jezoensis*) samples after undergoing heat treatment. The findings revealed a negative correlation between crystallinity and sound resistance, indicating that as crystallinity increased, sound resistance decreased (Zhu *et al.* 2016). Zatloukal *et al.* (2021) conducted research on the change in sound velocity of spruce (*Picea abies*) wood samples after heat treatment at 180 and 200 °C. The thermal treatment performed at 180 °C demonstrated no effect on acoustic properties; however, an increase in temperature resulted in a 2% increase in sound velocity. Furthermore, an increase in tan$\delta$ value was observed following all thermal treatment temperatures. Likewise, it was determined that the density of spruce (*Picea abies*) and maple (*Acer pseudoplatanus*) wood decreased as the temperature increased after the thermal modification process (Danihelová *et al*. 2022). Following the thermal modification process, an increase in the wood's MOE, acoustic impedance, and sound velocity was observed, while a decrease in damping capacity was determined (Danihelová *et al*. 2022). A similar outcome was observed for spruce (*Picea abies*) wood samples, which exhibited an 11% increase in dynamic elasticity modulus and a 5% increase in musical constant after undergoing thermal treatment at various temperatures (Mania and Gasiorek 2020). This was in parallel with Puszynski and Warda (2014), who found that after subjecting ash wood samples to heat treatment, the dynamic elasticity modulus and sound transmission velocity values increased by an average of 7% and 16%, respectively.

In another study, the effect of heat treatment on the modal frequency and logarithmic decay coefficient of spruce (*Picea abies*) wood samples was investigated. The results indicated that there was no significant change in modal frequency values after thermal modification. However, it was stated that there was a 10% decrease in the modal frequency after heat treatment for frequency values in the 2300 and 3500 Hz range. Furthermore, the logarithmic decreament coefficient exhibited a decline following the thermal modification process (Mania and Skrodzka 2020). Another study reported that thermal treatment at 180 °C resulted in an increase in vibration performance for beech (*Fagus slyvatica*) wood samples, while no such increase was observed for spruce wood samples (Buchelt *et al.* 2023). In a another study, the sound absorption properties of tulipwood (*Liriodendron tulipifera*), paulownia (*Paulownia coreana*), red pine (*Pinus densiflora*), and birch (*Betula costata*) wood samples following heat treatment at 175 and 200 °C were examined. The results indicated that the sound absorption coefficient of the samples increased with rising temperature (Byeon *et al.* 2010).

Within this scope, this article investigated the changes in the acoustic properties of spruce (*Picea orientalis*), maple (*Acer pseudoplatanus*), and mahogany (*Khaya ivorensis*), which are the most commonly used wood species in musical instrument making, after thermal modification. It is believed that this study will contribute to the literature by simultaneously examining the acoustic performance of both softwood, hardwood and exotic wood samples after thermal modification, particularly in terms of preferred species.

## EXPERIMENTAL

### Materials

All wood samples, spruce (*Picea orientalis)*, maple (*Acer pseudoplatanus,)* and mahogany (*Khaya ivorensis)* were kindly supplied from Kortürk Kereste Co. The test samples, 20 spruce, 20 maple, and 19 mahogany, were prepared in the dimensions of 380 x 25 x 25 mm$^3$ for thermal modification.

*Thermal modification process*

Thermal modification was completed in a reactor from Tantimber Co. in Düzce, applied TanWood thermal modification, where wood samples were subjected to steam heating in a closed system at 1.0 MPa pressure and maximum heating temperature at 210 °C for 90 min. To elaborate further on the thermal treatment stages, the samples were subjected to gradual heating over a period of four hours until they reach a temperature of 100 °C. Subsequently, at 4-hour intervals, the temperature was incrementally elevated to the range 130 to 160 and 180 °C, respectively, thereby reducing the moisture content within the sample to zero. When the final target temperature of 210 °C was reached, the process was maintained for a duration of 90 min. Thereafter, the cooling rate was augmented to approximately 12.5 °C per hour, resulting in a return to 100 °C after a total elapsed time of 8 h. After that the temperature was gradually reduced. The specimens were cooled and moisturized using condensed heat transfer. Wood samples were exposed to a total heat treatment period of 41 h.

*Mechanical properties measurements*

The bending strength and static bending elasticity modulus (MOE) values of the modified samples were determined on the LLYOD LS100 universal testing machine according to ISO 13061-3 (2014) and ISO 13061-4 (2014) standards.

*Acoustical properties measurements*

The ultrasonic sound transmission speeds (sound velocity) of the thermally modified wood samples were determined using the Slyvatest Duo (CBS-CBT, Paris, France), which measures the transmission time (time of flight, ToF) of an ultrasonic wave (µs) through two conical piezoelectric transducers (one emitter and one receiver) vibrating at 22 kHz. Medicinal gel was applied to the test specimens to ensure proper contact between the wood and the transducers. This gel improves the transmission of the ultrasonic wave at the interface, preventing interferences in the signal. The sound velocity was determined by dividing the time of sound propagation by the length of the sample was calculated through the acquisition. The sound velocity was obtained using Eq. 1,

$$v = \frac{x}{t} \tag{1}$$

where $v$ is velocity (m/sn), $t$ is the time of flight (sound transmission time, µs), and $x$ is length of specimen (m). The dynamic elasticity modulus was obtained with Eq. 2,

$$E_{dynamic} = \sqrt{\frac{v}{\gamma}} \tag{2}$$

where $E_{dynamic}$ is dynamic elasticity modulus (N/mm$^2$), $v$ is velocity (m/sn), and $\gamma$ is the relative density (kg/m$^3$) of specimen. Another value that indicates the acoustic performance of wood is the acoustic radiation value. The following Eq. 3 was used to calculate the acoustic radiation constant,

$$\text{Acoustic radiation (R)} = \sqrt{\frac{E}{\gamma}} \tag{3}$$

where $E$ is dynamic elasticity modulus (N/mm$^2$) and $\gamma$ is the relative density (kg/m$^3$) of specimen. Moreover, the sound radiation coefficient describes how much the vibration of a body is damped due to sound radiation. The following formula was used to calculate the sound radiation constant:

$$\text{Sound radiation } = \sqrt{\frac{E}{\gamma^3}} \quad (4)$$

In addition to these values, the acoustic impedance value also indicates the resistance to sound wave propagation in wood. Therefore, a low value is advantageous for instrument making. The acoustic impedance constant was obtained by Eq. 5:

$$\text{Acoustic impedance } (z) = \sqrt{E \cdot \gamma} \quad (5)$$

*Logarithmic damping (depending on distance) measurements*

The distance dependent sound damping was calculated by the pencil break method (Hsu and Breckenridge 1981). Using a four-channel MISTRAS micro-II digital acoustic emission system with R 15 AE (acoustic emission) sensor and 2/4/6 preamplifier, piezoelectric transducers, operating at frequency of 50 to 200 kHz with a threshold of 35 dB were used to pick up the AE signals from the sample surfaces. Breaking a 0.3 mm tip pencil on wood samples at 3, 10, 17, 24, and 30 cm away from the sensor, and determining the decrease in amplitude values depending on the distance. AEwinTM software was used for data acquisition and to calculate a linear/logarithmic function. The slope of this function was used as the distance dependent damping coefficient.

*FTIR analysis*

The FTIR analysis of chemically modified and unmodified wood was obtained using the KBr (potassium bromide) technique with a Shimatzu 8400s FTIR spectrometer. The spectra were collected over the 4000 to 400 $cm^{-1}$ wavenumber range, at a resolution of 4 $cm^{-1}$ (40 scans).

*Statistical analysis*

The analysis of variance (ANOVA) was used to determine the effect of thermal modification on the acoustic and mechanical properties using IBM SPSS software. The resulting F value was compared to the tabular F value at the 95% level of confidence. Once the F-tests revealed significant differences ($p < 0.05$), Tukey's *post-hoc* test was used to make comparisons and identify exactly which groups differ from each other.

## RESULTS AND DISCUSSION

### Acoustic Properties Changes

In general, wood with high specific dynamic modulus ($E/\gamma$) combined with a low acoustic impedance ($z$) is desired for piano, guitar, and violin soundboards (Wegst 2006). The changes in acoustic properties (velocity, acoustic impedance, $E/\gamma$ acoustic radiation, and dynamic elasticity modulus) of wood samples after heat treatment are shown in Table 1, Fig. 1, and Fig. 2.

A statistically significant difference ($p < 0.05$) was found for all values (sound velocity, modulus of elasticity, $E/\gamma$, and acoustic impedance) after heat treatment for spruce wood except acoustic and sound radiation value. According to the results obtained, the sound velocity, dynamic modulus of elasticity, $E/\gamma$ value, and the acoustic impedance value decreased in spruce wood after thermal modification, while the acoustic and sound radiation value did not change. Heat treatment had a reducing effect on the acoustic properties of spruce wood. In the literature, a similar decrease in dynamic modulus value was found for spruce samples after heat treatment at 210 °C for 90 min (Kačíková *et al.* 2013). Likewise, Kamdem *et al.* (2002) found that the MOE value decreased after heat treatment between 1 and 24 h at temperatures above 200 °C. In the study by Holeček *et al.* (2017), it was stated that the MOE value decreased after modification in spruce wood that was subjected to the Thermowood process for 1 h at 210 °C. Buchelt *et al.* (2023) emphasized a similar decrease in spruce wood subjected to heat treatment in a nitrogen atmosphere for 8 h at 180 °C. Zatloukal *et al.* (2021) also found a decrease in $E/\gamma$ and sound velocity after modification for spruce samples heat-treated at 180 to 200 °C for 8 h. In contrast, Navickas *et al.* (2015) exhibited a 1.5% increase in MOE following the heat treatment of spruce wood at 190 °C for 1 to 3 h. Moreover, Danihelová *et al.* (2022) found an increase in MOE, sound radiation, and sound velocity after modification of spruce heat-treated at 185 °C for 50 min. Similarly, Mania and Skrodzka (2020) stated in his study that there was a 3% increase in sound velocity for spruce (*Picea abies*) heat-treated at 180 °C for 3 h. Zhu *et al.* (2016) observed an increase in $E/\gamma$ value and sound radiation value after subjecting the spruce wood to heat treatment at 210 °C for 2 to 4 h. It is worth mentioning that Karami *et al.* (2013) emphasized that there was no difference in the $E/\gamma$ and damping values of spruce after hygrothermal modification at 150 °C.

For maple wood, it was found that there was no statistically significant difference in the values of Young's modulus and acoustic impedance ($p > 0.05$), while there was a statistically significant difference in the other values (sound velocity, $E/\gamma$, and acoustic radiation) after heat treatment ($p < 0.05$). Analyzing the results obtained, there was an increase in the values of sound velocity, $E/\gamma$, and acoustic radiation after thermal modification, while there was a decrease in the value of acoustic impedance. Although there was a numerical increase in the dynamic elasticity modulus values after the modification process, this increase was not statistically significant ($p > 0.05$). In literature, Danihelová *et al.* (2022) reported an increase in MOE, sound , and sound radiation values after modification for maple exposed to heat treatment at 185 °C for 50 min. Similarly, Ahmed and Adamopoulos (2018) observed an increase in sound velocity for birch, poplar, and ash woods subjected to the Thermowood process in his study. Moreover, Lekounougou *et al.* (2011) found an increase in the MOE value of white birch samples after heat treatment at 215 °C. In addition, Puszynski and Warda (2014) and Roszyk *et al.* (2020) also reported an increase in MOE and sound velocity after heat treatment of ash wood at 210 °C in their studies. In contrast, a study by Kaya (2023) revealed a decline in the MOE value of maple and cypress woods following heat treatment at temperatures of 200 °C for 3 h.

An increase in the acoustic properties of wood can be attributed to the impact of heat treatment on the location of OH-bonds. Thermal treatment has been shown to reduce the amount of amorphous regions in cellulose and hemicellulose, which ultimately leads to a decrease in the adsorption of water from the atmosphere. Consequently, this results in a reduction of the equilibrium moisture content of the wood. It has been demonstrated that wood with a lower moisture content tends to exhibit higher acoustic properties (Del Menezzi *et al.* 2014).

The phenomenon of decreased modulus of elasticity following thermal modification can be attributed to the degradation of wall materials resulting from heat treatment. This degradation leads to a change in the modulus of elasticity (Holeček *et al.*

2017). Furthermore, cracks that emerge in wood samples following heat treatment may also exert an influence. Moreover, the decline in density resulting from weight loss has a negative impact on the MOE. As the modulus of elasticity diminishes due to a reduction in cell wall material, acoustic properties also decrease (Buchelt *et al.* 2023).

For mahogany wood, it was found that there was no statistically significant difference in all values (sound transmission rate, modulus of elasticity, $E/\gamma$, acoustic impedance, and acoustic radiation). It was found that the acoustic properties of the mahogany samples did not change statistically after the thermal modification process. In other words, there is no effect of the acoustic properties of mahogany after heat treatment. A review of the literature pertaining to the alteration of acoustic properties in exotic woods following heat treatment reveals several notable findings. Del Menezzi *et al.* (2014) observed that *Simarouba amara* wood exhibited no statistically significant change after being exposed to temperatures of 200 °C for a duration of 70 min. Similarly, Wu *et al.* (2016) found that *Metasequoia glyptostroboides* wood demonstrated no discernible change when subjected to temperatures of 220 °C for 30 min. Furthermore, de Jesus *et al.* (2022) reported that *Bertholletia excelsa* wood exhibited no significant alterations following thermally modified conditions at 200 °C for a duration of 1 h. These observations are consistent with the results obtained in this study, suggesting that the heat treatment process does not induce substantial changes in the acoustic properties of exotic woods.

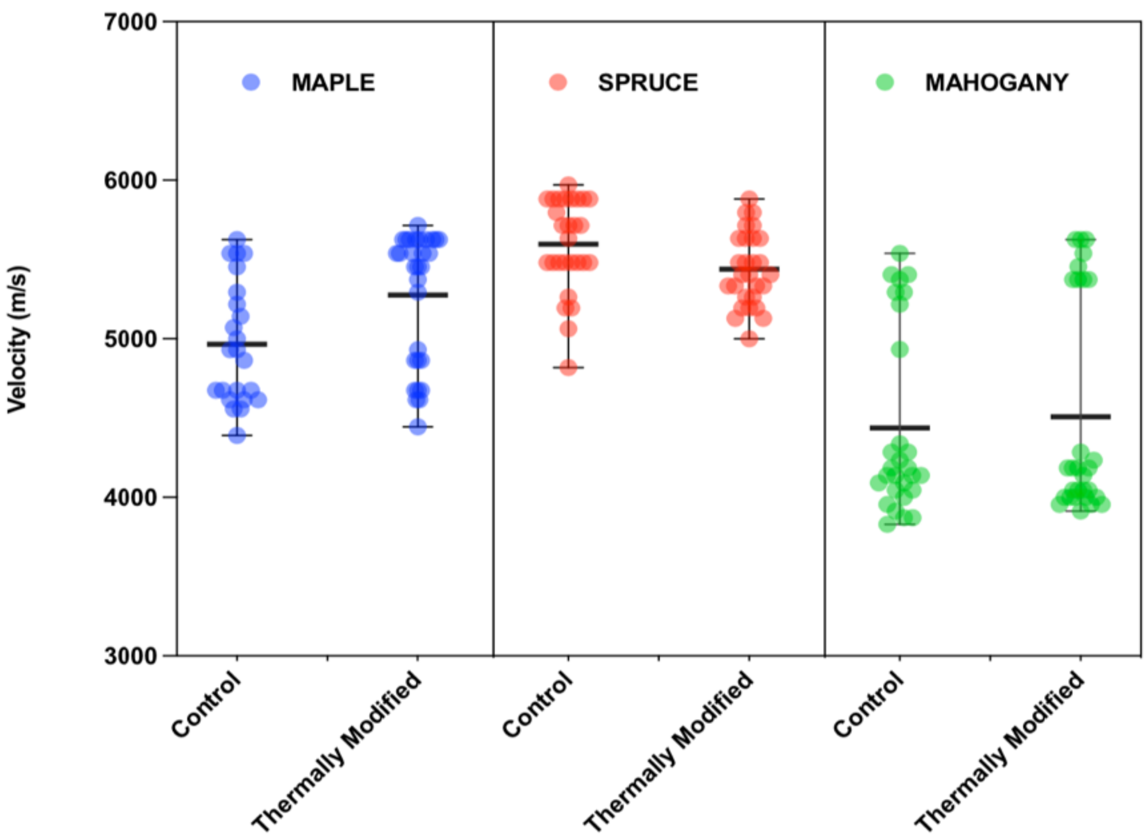


**Fig. 1.** Sound velocity of the spruce, maple, and mahogany wood for unmodified and modified with heat treatment

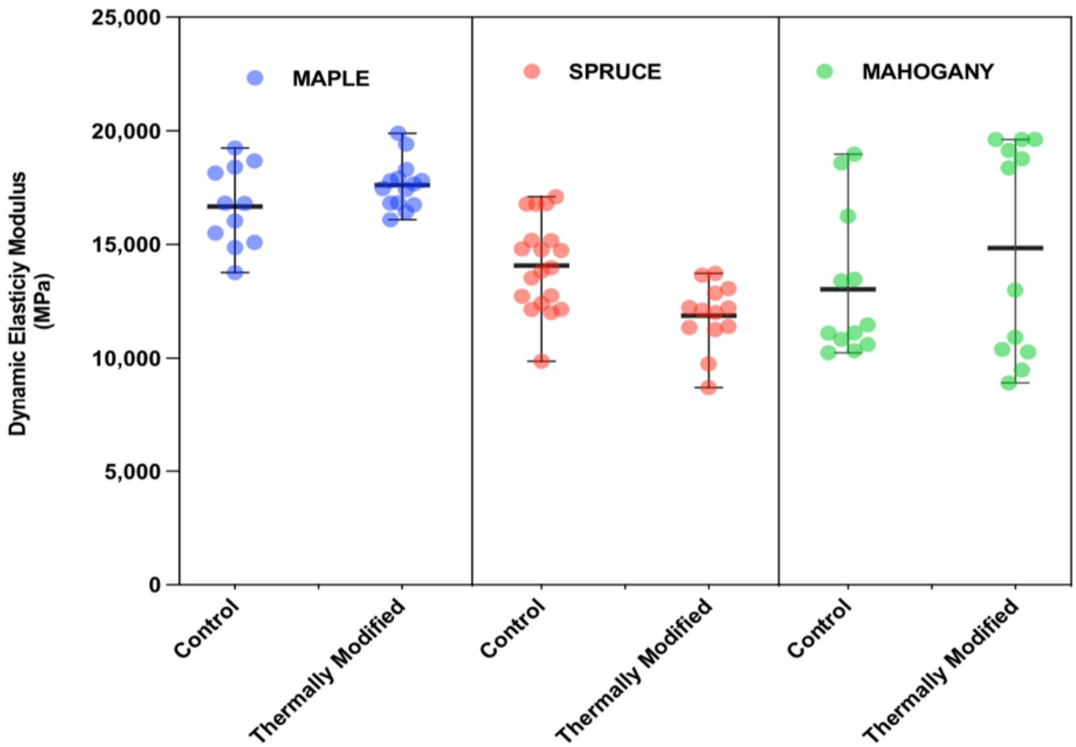


**Fig. 2.** Dynamic elasticity modulus of the spruce, maple, and mahogany wood for unmodified and modified with heat treatment

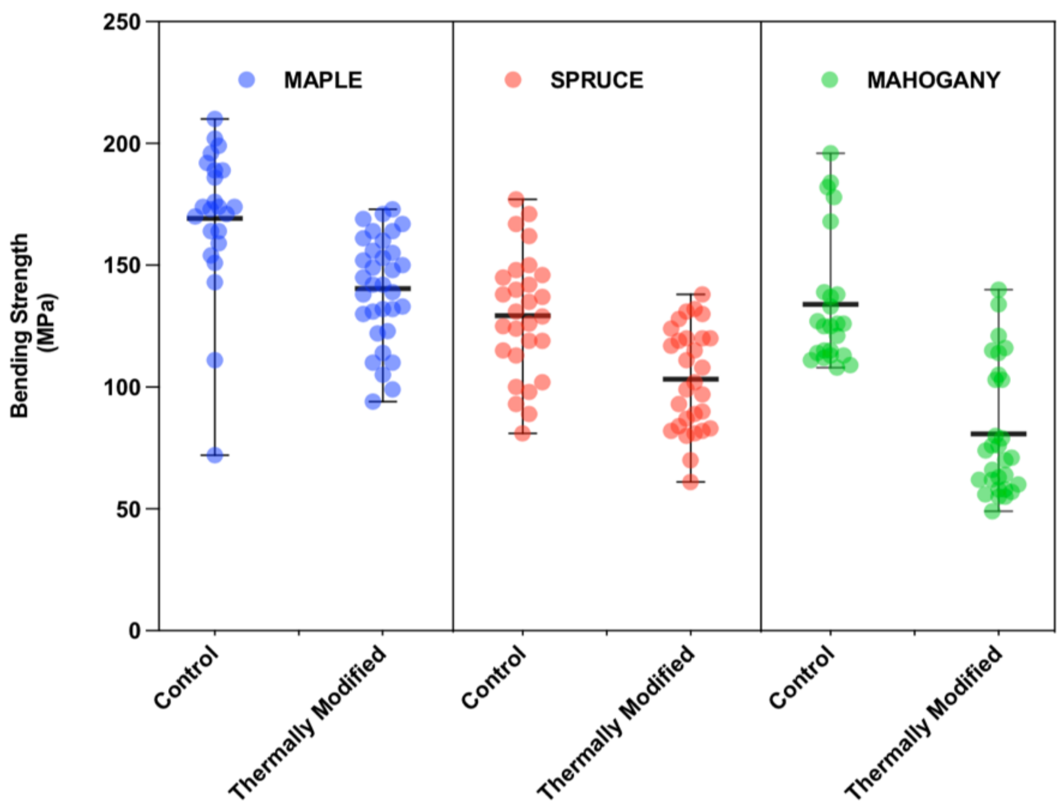


**Fig. 3.** Bending strength of the spruce, maple, and mahogany wood for unmodified and modified with heat treatment

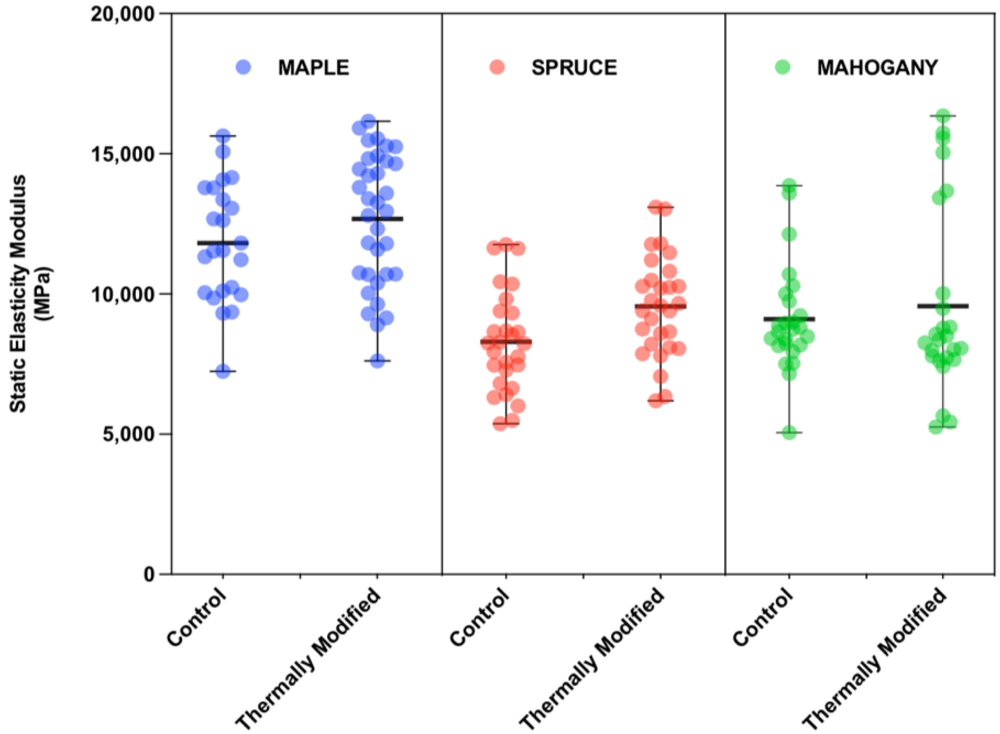


**Fig. 4.** Static elasticity modulus of the spruce, maple, and mahogany wood for unmodified and modified with heat treatment

*Mechanical properties changes*

The changes in mechanical properties (bending strength and static elasticity modulus) of wood samples after heat treatment are shown in Table 1, Fig. 3, and Fig. 4.

The spruce wood was analyzed and it was found that there was a statistically significant difference in the values of the bending resistance and the static modulus of elasticity ($p < 0.05$). According to the results, the bending strength of the spruce decreased after thermal modification, but the static MOE increased after thermal modification. In a review of the literature, Bengtsson *et al.* (2002) found a decrease in bending strength values after heat treatment for spruce samples. Similarly, Bonastra (2007) stated that the bending resistance values of spruce wood decreased approximately 30% after heat treatment with the PLATO process. In contrast, Allegretti *et al.* (2012) reported that there was no statistically significant difference in the static MOE and bending resistance values after heat treatment with the *Thermowood* method for *Picea abies*. However, Tankut *et al.* (2014) found an 18% decrease in the bending strength and static modulus of elasticity values of spruce wood after Thermowood process at 180 °C for 2 h. In contrast, Kozakiewicz *et al.* (2014) stated that there was some increase in the bending strength and static modulus of elasticity values of yellow pine samples after heat treatment at 180 °C. Similarly, Holeček *et al.* (2017) emphasized that spruce wood showed some increase in static modulus of elasticity after heat treatment at 210 °C. In contrast, Kubojima *et al.* (2000) determined that static modulus of elasticity and bending strength decreased in spruce after heat treatment at 160 °C. Likewise, for spruce, after heat treatment at 200 °C, a reduction in bending strength of 44 to 50% was observed (Bekhta and Niemz 2003).

**Table 1.** Acoustic and Mechanical Properties of the Samples

| | N | Bending Strength (MPa) | Static Modulus of Elasticity (MPa) | Dynamic Elasticity Modulus (MPa) | Sound Velocity (m/s) | $E/\gamma$ (MPa·m³ / kg) | Acoustic Radiation (m⁴ / kg·s) | Acoustic Impedance (MPa·s /m) | Sound Radiation (m⁴ / kg·s) |
|---|---|---|---|---|---|---|---|---|---|
| Maple – Control | 20 | 170.9 (31.1) | 11817.3 (2126.1) | 16656.5 (1877.1) | 4965.2 (291.1) | 27.34 (3.3) | 8.57 (0.63) | 3.18 (0.57) | 270.99 (21.05) |
| Maple – TM* | 20 | 136.8 (22.1) | 12674.3 (2365.1) | 17617.2 (1044.1) | 5276.3 (328.1) | 30.69 (1.86) | 9,.80 (0.72) | 4.82 (0.78) | 308.86 (18.72) |
| Spruce – Control | 20 | 126.4 (24.9) | 8291.8 (1781.1) | 14080.5 (1316.1) | 5596 (291.1) | 32.54 (2.4) | 13.22 (0.63) | 2.46 (0.27) | 419.80 (20.67) |
| Spruce – TM* | 20 | 104.1 (21,1) | 9488.1 (1780.1) | 11876.2 (1202.1) | 5438.4 (178.1) | 29.31 (3.6) | 13.43 (0.82) | 2.32 (0.20) | 424.69 (25.72) |
| Mahogany – Control | 19 | 134.5 (26.8) | 9104.8 (1915.1) | 13408.3 (4173.1) | 4362.7 (409.1) | 20.87 (1.96) | 7.10 (0.73) | 2.90 (0.53) | 224.63 (23.5) |
| Mahogany – TM* | 19 | 80.1 (26.6) | 9435.6 (2623.1) | 1501.9 (4703.1) | 4507.7 (505.1) | 24.31 (1.26) | 7.43 (0.85) | 2.77 (0.57) | 252.99 (27.57) |

TM*: Thermally modified; Numbers in parentheses represent as a standard deviation

**Table 2.** Logarithmic Damping Values of the Samples Depending on the Distance

| | Distance from Sensors (cm) | | | | | Logarithmic Decreasing Curve Equation |
|---|---|---|---|---|---|---|
| | 3 | 10 | 17 | 24 | 31 | |
| | dB | | | | | |
| Maple – Control | 86.69 | 80.42 | 76.61 | 69.53 | 66.04 | y= -13.076 ln(x) + 88.644 |
| Maple – Thermally Modified | 87.67 | 81.80 | 76.79 | 72.43 | 69.91 | y= -11.202 ln(x) + 88.446 |
| Spruce – Control | 91.1 | 81.63 | 76.99 | 70.5 | 62.01 | y= -12.344 ln(x) + 89.559 |
| Spruce – Thermally Modified | 89.35 | 81.73 | 75.48 | 72.28 | 69.95 | y= -12.852 ln(x) + 90.299 |
| Mahogany – Control | 89.83 | 81.89 | 74.02 | 69.42 | 64.48 | y= -15.729 ln(x) + 90.989 |
| Mahogany – Thermally Modified | 89.08 | 81.20 | 74.44 | 68.79 | 64.20 | y= -15.415 ln(x) + 90.902 |

An examination of maple and mahogany woods revealed a statistically significant decline in bending resistance values for both species after undergoing heat treatment. However, while numerical increases and decreases in MOE values were observed for maple and mahogany, respectively, these changes were not statistically significant. In other words, for maple and mahogany after heat treatment, no difference in MOE was found. In the literature, according to Korkut *et al.* (2008), studies have shown that the flexural strength of red maple (*Acer trautvetteri*) wood remains constant following the heat treatments within the temperature range of 150 to 180 °C. Similarly, Kozakiewicz *et al.* (2020) found no significant difference between the static MOE values of black poplar (*Populus nigra*) after 2 h heat treatment at 220 °C. Furthermore, Rokeya *et al.* (2021) found a similar reduction in bending strength values after heat treatment in mahogany, Jimenez *et al.* (2011) in Malapaya, and Owoyemi *et al.* (2016) in *Gmelina arborea* wood.

It is thought that the decrease in mechanical properties is due to wood polymers degrading as a result of acidic by-products (*e.g.*, acetic acid) being released during thermal modification (Stamm and Tarkow 1947; Tjeerdsma and Militz 2005a; Hon and Shiraishi 2013). Moreover, it is also assumed that the decrease in bending strength of wood due to heat treatment is correlated with an increase in mass loss (Tankut *et al.* 2014).

In contrast, it was hypothesized that the observed increases in mechanical properties would be attributable to a decrease in the moisture content of the wood material following heat treatment, rather than a chemical change in the wood polymers resulting from thermal modification (Kollmann and Côté 1968; Sakai *et al.* 1990; Tsoumis 1991; Obataya *et al.* 1998).

*FTIR analysis*

The thermal modification of all wood blocks was characterized by FTIR spectra analysis. The FTIR spectra of modified and unmodified (control) groups are shown in (Fig. 5).

The presence of increasing peaks between 1054, 1176 and 1236 cm$^{-1}$ were indicative of the cellulose component and were associated with the content in crystallized and amorphous cellulose. The intensity of these bands increased for all wood species, indicating that amorphous cellulose was more affected during the heat treatment process. The presence of increasing peaks between 1054 and 1176 cm$^{-1}$ can be attributed to the stretching of C-O and C-O-C bonds of cellulose and wood hydrocarbons (Özgenç *et al.* 2017).

The enhancement of the peak at 1360 cm$^{-1}$ indicates the C-H deformation of the lignin ($CH_3$)-carbohydrate ($CH_2$) complexes. Moreover, the peak around 1426 and 1515 cm$^{-1}$ are ascribed to the aromatic structures of C=C lignin. The increase in absorption at these wavenumbers was predominantly attributable to the rise in relative lignin content observed in the heat treatment samples (Silverstein *et al.* 2005; Timar *et al.* 2016). A reduction in the peak at approximately 2900 cm$^{-1}$ is attributable to the $CH_2$ – $CH_3$ sp$^3$ hybridization of hemicelluloses, as these components are subject to degradation following heat treatment.

Furthermore, the peak observed at 3405 cm$^{-1}$ corresponds to the O-H stretching vibration (Kotilainen *et al.* 2000; Lyu *et al.* 2024). A reduction in peak intensity at 2900 and 3405 cm$^{-1}$ was observed in wood samples that had undergone thermal modification (Fengel and Wegener 1984; Hill *et al.* 2021).

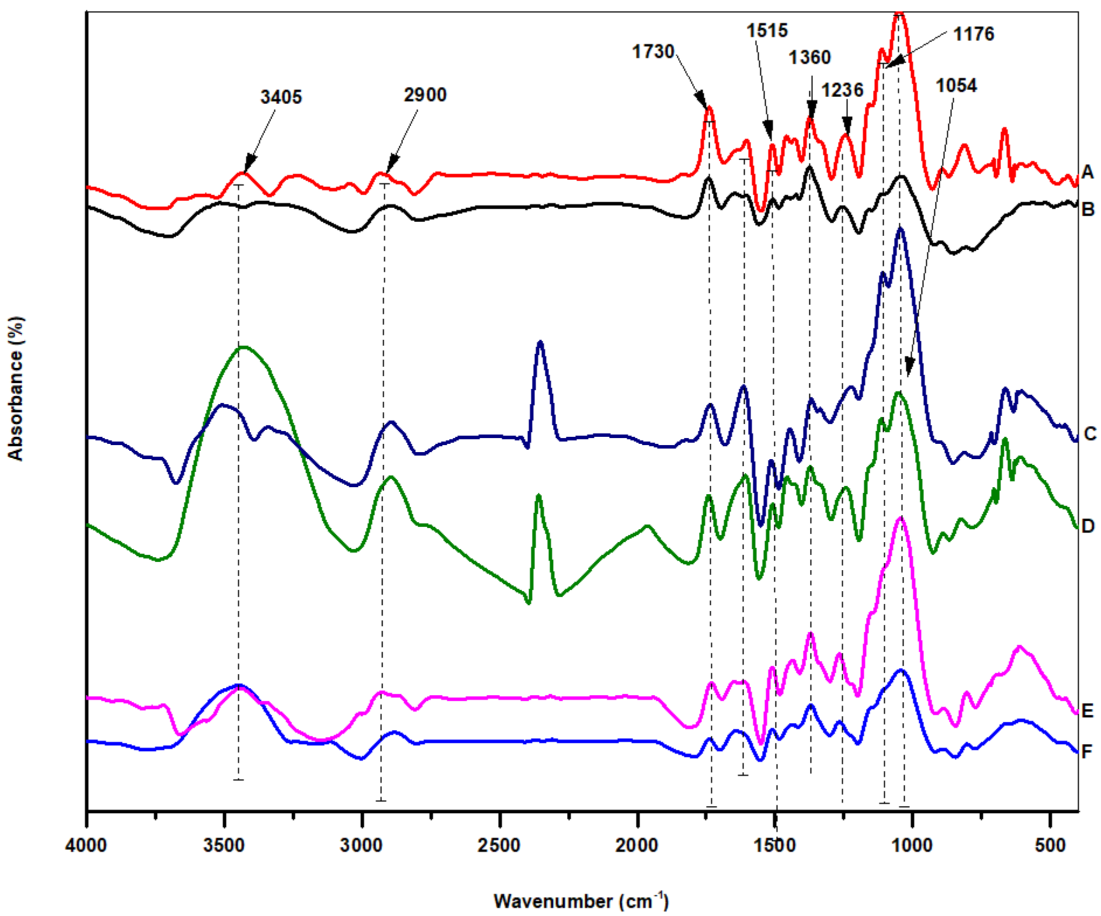


**Fig. 5.** (A) FTIR spectra of thermally modified maple, (B) FTIR spectra of maple, (C) FTIR spectra of thermally modified mahogany, (D) FTIR spectra of mahogany, (E) FTIR spectra of thermally modified spruce, (F) FTIR spectra of spruce

Changes in absorbance peaks are believed to occur due to an increase in lignin and cellulose and a decrease in hemicellulose in wood after thermal modification (Pandey 2005; Tjeerdsma and Militz 2005b; Pandey and Vuorinen 2008; Lyu *et al.* 2024).

*Damping changes (distance depending)*

The logarithmic decrement of wood influences its acoustic properties. Many researchers (Yano 1994; Obataya *et al.* 1998, 2000; Matsunaga *et al.* 2000; Wegst 2006) have stated that wood with a lower damping ratio is ideal for good wooden sounding boards.

It was found that all wood samples in this study exhibited a decrease in damping values after the thermal modification process (Fig. 6). Kang *et al*. (2016) reported a decrease in the logarithmic decrement values after heat treatment for spruce and oak wood samples, while this value increased for pine wood samples. Similarly, Zatloukal *et al.* (2021) found that the damping properties of spruce wood decreased after heat treatment. Moreover, in his studies, Merhar (2024) stated that the damping of spruce (*Picea abies*) wood first decreased and then increased as moisture content increased. A study was conducted to investigate the damping behaviour of 130-year-old and new spruce wood samples; it was found that the damping of new spruce wood was generally higher than that of old spruce wood. Furthermore, the results showed that damping in new wood is less sensitive to changes in moisture content (Göken 2021). Additionally, Ono and Norimoto (1984) reported that the damping ratio was mainly influenced by the S2 layer orientation of the cell wall. Therefore, the changes in the S2 layer after heat treatment should also be investigated in another study.

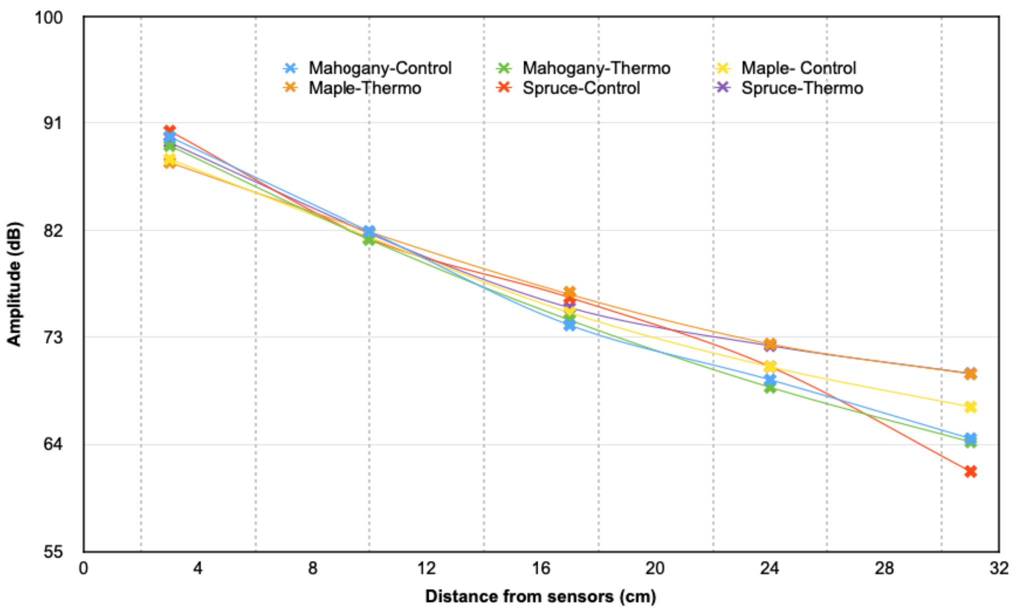


**Fig. 6.** Damping curves depending on distance by using pencil break method

## CONCLUSIONS

1. The thermal modification process improved the acoustic performance of maple wood but reduced the acoustic performance of spruce wood. However, there was no change in the acoustic values of mahogany wood after thermal modification.
2. Examining changes in mechanical properties revealed a decrease in bending strength in all wood samples after thermal modification. In contrast, an increase in modulus of elasticity (MOE) values was observed in spruce, while no change was observed in mahogany and maple woods.
3. The Fourier transform ingrared (FTIR) analysis revealed an increase in the intensity of the 1054, 1176, 1350, and 1515 $cm^{-1}$ absorbance peaks. Meanwhile, a decrease in the 2900 and 3405 $cm^{-1}$ peaks were observed in the wood samples after thermal modification. These changes are believed to stem from a reduction in hemicellulose content and an increase in lignin and cellulose content following thermal modification.
4. For all wood samples in this study, it was exhibited that there was a decrease in damping values after the thermal modification processes.

## REFERENCES CITED

Ahmed, S. A., and Adamopoulos, S. (2018). "Acoustic properties of modified wood under different humid conditions and their relevance for musical instruments," *Appl. Acoust.* 140(5), 92-99. DOI: 10.1016/j.apacoust.2018.05.017

Allegretti, O., Brunetti, M., Cuccui, I., Ferrari, S., Nocetti, M., and Terziev, N. (2012). "Thermo-vacuum modification of spruce (*Picea abies* Karst.) and fir (*Abies alba* Mill.) wood," *BioResources* 7(3), 3656-3669. DOI: 10.15376/biores.7.3.3656-3669

Aydogmus, A., and Cetin, N. S. (2024). "Change in some acoustic properties of woods used in musical instruments after chemical modification with propionic anhydride," *Wood Res.* 69(2), 324-336. DOI: 10.37763/wr.1336-4561/69.2.324336

Bengtsson, C., Jermer, J., and Brem, F. (2002). *Bending Strength of Heat-treated Spruce and Pine Timber* (Document No. IRG/WP 02-40242), International Research Group on Wood Protection, Stockholm, Sweden.

Bekhta, P., and Niemz, P. (2003). "Effect of high temperature on the change in color, dimensional stability and mechanical properties of spruce wood," *Holzforschung* 57(5), 539-546. DOI: 10.1515/HF.2003.080

Boonstra, M. J., Acker, J., Tjeerdsma, B. F., and Kegel, E. V. (2007). "Strength properties of thermally modified softwoods and its relation to polymeric structural wood constituents," *Ann. For. Sci.* 64(7), 679-690. DOI: 10.1051/forest:2007048

Buchelt, B., Krüger, R., and Wagenführ, A. (2023). "The vibrational properties of native and thermally modified wood in dependence on its moisture content," *Eur. J. Wood Wood Prod.* 81(4), 947-956. DOI: 10.1007/s00107-022-01919-y

Bucur, V. (2006). *Acoustics of Wood*, 2nd Ed., Springer Series in Wood Science, Springer, Berlin, Germany. DOI: 10.1007/978-3-662-03898-7

Burmester, A. (1975). "Zur Dimensionsstabilisierung von Holz [For dimensional stabilization of wood]," *Holz Roh. Werkst.* 33(9), 333-335. DOI: 10.1007/BF02612789

Byeon, H., Park, J., Hwang, K., and Park, H. (2010). "Sound absorption property of heat-treated wood at low temperature and vacuum conditions," *J. Korean Wood Sci. Technol.* 38(2), 101-107. DOI: 10.5658/WOOD.2010.38.2.101

Byrne, C. E., and Nagle, D. C. (1997). "Carbonization of wood for advanced materials applications," *Carbon* 35(2), 259-266. DOI: 10.1016/S0008-6223(96)00136-4

Conard, N. J., Malina, M., and Mu, S. C. (2009). "New flutes document the earliest musical tradition in southwestern Germany," *Nature* 460(7256), 737-740. DOI: 10.1038/nature08169

Danihelová, A., Vidholdová, Z., Gergeľ, T., Spišiaková Kružlicová, L., and Pástor, M. (2022). "Thermal modification of spruce and maple wood for special wood products," *Polymers* 14(14), article 2813. DOI: 10.3390/polym14142813

Del Menezzi, C. H. S., Amorim, M. R. S., Costa, M. A., and Garcez, L. R. O. (2014). "Evaluation of thermally modified wood by means of stress wave and ultrasound nondestructive methods," *Mater. Sci.* 20(1), 61-66. DOI: 10.5755/j01.ms.20.1.3341

Esteves, B., Domingos, I., and Pereira, H. (2007). "Improvement of technological quality of eucalypt wood by heat treatment in air at 170–200 °C," *For. Prod. J.* 57(1-2), 47-52.

Esteves, B. M., Domingos, I. J., and Pereira, H. M. (2008). "Pine wood modification by heat treatment in air," *BioResources* 3(1), 142-154. DOI: 10.15376/biores.3.1.142-154

Esteves, B. M., and Pereira, H. M. (2009). "Wood modification by heat treatment: A review," *BioResources* 4(1), 370-404. DOI: 10.15376/biores.4.1.esteves

Esteves, B., and Pereira, H. (2008). "Quality assessment of heat-treated wood by NIR spectroscopy," *Holz Roh. Werkst.* 66(5), 323-332. DOI: 10.1007/s00107-008-0262-4

Fengel, D., and Wegener, G. (1984). *Wood, Chemistry, Ultrastructure, Reactions*, Walter de Gruyter, Berlin and New York, 1984, 613 pp. DOI: 10.1002/pol.1985.130231112

Göken, J. (2021). "Temperature-dependent damping of the tonewood spruce," *Journal of Alloys and Compounds* 856, article 158182. DOI: 10.1016/j.jallcom.2020.158182

Hill, C. A. S. (2006). *Wood Modification: Chemical, Thermal and Other Processes*, John Wiley & Sons, Chichester, UK.

Hill, C., Altgen, M., and Rautkari, L. (2021). "Thermal modification of wood — A review: Chemical changes and hygroscopicity," *J. Mater. Sci.* 56(11), 6581-6614. DOI: 10.1007/s10853-020-05722-z

Holeček, T., Gašparík, M., Lagaňa, R., Borůvka, V., and Oberhofnerová, E. (2017). "Measuring the modulus of elasticity of thermally treated spruce wood using the ultrasound and resonance methods," *BioResources* 12(1), 819-838. DOI: 10.15376/biores.12.1.819-838

Homan, W., and Tjeerdsma, B. (2000). "Structural and other properties of modified wood," in: *Proceedings of the World Conference on Timber Engineering (WCTE)*, Whistler, Canada, pp. 3.5.1-1–3.5.1-8.

Hon, D. N.-S., and Shiraishi, N. (2013). *Wood and Cellulosic Chemistry*, 2nd Ed., CRC Press, Boca Raton, FL, USA. DOI: 10.1201/b14649

Hsu, N. N., and Breckenridge, F. (1981). "Characterization of acoustic emission sensors," *Mater. Eval.* 39(1), 60-68.

ISO 13061-3 (2014). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 3: Determination of ultimate strength in static bending," International Organization for Standardization, Geneva, Switzerland.

ISO 13061-4 (2014). "Physical and mechanical properties of wood – Test methods for small clear wood specimens – Part 4: Determination of modulus of elasticity in static bending," International Organization for Standardization, Geneva, Switzerland.

de Jesus, D. S., Castro, J. P., Guedes, T., da Silva, J. R. M., Latorraca, J. V. F., and Nascimento, A. M. (2022). "Assessment of the acoustic change in heat-treated *Pinus elliottii* and *Bertholletia excelsa* wood from homogeneous plantations in Brazil," *South. For.* 84(4), 320-324. DOI: 10.2989/20702620.2022.2151385

Jimenez, J. P., Acda, M. N., Razal, R. A., and Madamba, P. S. (2011). "Physico-mechanical properties and durability of thermally modified malapapaya [*Polyscias nodosa* (Blume) Seem.] wood," *Philipp. J. Sci.* 140(1), 13-23.

Kačíková, D., Kačík, F., Čabalová, I., and Ďurkovič, J. (2013). "Effects of thermal treatment on chemical, mechanical and colour traits in Norway spruce wood," *Bioresource Technol.* 144, 669-674. DOI: 10.1016/j.biortech.2013.06.110

Kamdem, D. P., Pizzi, A., and Jermannaud, A. (2002). "Durability of heat-treated wood," *Holz Roh. Werkst.* 60(1), 1-6. DOI: 10.1007/s00107-001-0261-1

Kang, C. W., Jang, E. S., Jang, S. S., Cho, J. I., and Kim, N. H. (2019). "Effect of heat treatment on the gas permeability, sound absorption coefficient, and sound transmission loss of *Paulownia tomentosa* wood," *J. Korean Wood Sci. Technol.*

47(5), 644-654. DOI: 10.5658/WOOD.2019.47.5.644

Kang, H.-Y., Kang, C.-W., Hong, S.-H., and Matsumura, J. (2016). "Effect of heat treatment on the acoustic properties of a wooden xylophone keyboard," *J. Fac. Agric. Kyushu Univ.* 61(1), 157-163. DOI: 10.5109/1564098

Karami, E., Matsuo, M., Brémaud, I., Bardet, S., Froidevaux, J., and Gril, J. (2013). "Modification of wood acoustic, hygroscopic and colorimetric properties due to thermally accelerated ageing," *Eur. J. Wood Prod.* 71(2), 239-246. DOI: 10.1007/s00107-013-0672-2

Kaya, A. I. (2023). "Combined effects of linseed oil and heat treatment on the properties of cypress and maple wood. Part 1: Water absorption, mechanical properties, and sound absorption capacity," *BioResources* 18(2), 2940-2963. DOI: 10.15376/biores.18.2.2940-2963

Kim, D. Y., Nishiyama, Y., Wada, M., Kuga, S., and Okano, T. (2001). "Thermal decomposition of cellulose crystallites in wood," *Holzforschung* 55(5), 521-524. DOI: 10.1515/HF.2001.084

Kim, J.-Y., Hwang, H., Oh, S., Kim, Y.-S., Kim, U.-J., and Choi, J. W. (2014). "Investigation of structural modification and thermal characteristics of lignin after heat treatment," *Int. J. Biol. Macromol.* 66, 57-65. DOI: 10.1016/j.ijbiomac.2014.02.013

Kocaefe, D., Huang, X., and Kocaefe, Y. (2015). "Dimensional stabilization of wood," *Curr. For. Rep.* 1(3), 151-161. DOI: 10.1007/s40725-015-0017-5

Kol, H. S., Aysal Keskin, S., and Gündüz Vaydogan, K. (2017). "Effect of heat treatment on the mechanical properties and dimensional stability of beech," *J. Adv. Technol. Sci.* 6(3), 820-830.

Kollmann, F. F. P., and Côté, W. A. (1968). *Principles of Wood Science and Technology, Vol. 1: Solid Wood*, Springer-Verlag, New York, NY, USA. DOI: 10.1007/978-3-642-87931-9

Korkut, D. S., and Guller, B. (2008). "The effects of heat treatment on physical properties and surface roughness of red-bud maple (*Acer trautvetteri* Medw.) wood," *Bioresource Technol.* 99(8), 2846-2851. DOI: 10.1016/j.biortech.2007.06.043

Korkut, S., Akgül, M., and Dündar, T. (2007). "The effects of heat treatment on some technological properties of Scots pine (*Pinus sylvestris* L.) wood," *Bioresource Technol.* 99(6), 1861-1868. DOI: 10.1016/j.biortech.2007.03.038

Korkut, S., Kök, M. S., Korkut, D. S., and Gürleyen, T. (2008). "The effects of heat treatment on technological properties in red-bud maple (*Acer trautvetteri* Medw.) wood," *Bioresource Technol.* 99(6), 1538-1543. DOI: 10.1016/j.biortech.2007.04.021

Kotilainen, R. A., Toivanen, T. J., and Alén, R. J. (2000). "FTIR monitoring of chemical changes in softwood during heating," *J. Wood Chem. Technol.* 20(3), 307-320. DOI: 10.1080/02773810009349638

Kozakiewicz, P., Drozdzek, M., Laskowska, A., Grześkiewicz, M., Bytner, O., Radomski, A., Mróz, A., Betlej, I., and Zawadzki, J. (2020). "Chemical composition as a factor affecting the mechanical properties of thermally modified black poplar (*Populus nigra* L.)," *BioResources* 15(2), 3915-3929. DOI: 10.15376/biores.15.2.3915-3929

Kozakiewicz, P., Jankowska, A., and Cichy, A. (2014). "Influence of thermal modification on selected properties of Scots pine wood (*Pinus sylvestris* L.)," in: *Proceedings of the Conference on Chipless and Chip Woodworking*, Zvolen, Slovakia, pp. 239-245.

Kubojima, Y., Okano, T., and Ohta, M. (1998). "Vibrational properties of Sitka spruce heat-treated in nitrogen gas," *Journal of Wood Science* 44(1), 73-77. DOI: 10.1007/BF00521878

Kubojima, Y., Okano, T., and Ohta, M. (2000). "Bending strength and toughness of heat-treated wood," *Journal of Wood Science* 46(1), 8-15. DOI: 10.1007/BF00779547

Lekounougou, S., Kocaefe, D., Oumarou, N., Kocaefe, Y., and Poncsak, S. (2011). "Effect of thermal modification on mechanical properties of Canadian white birch (*Betula papyrifera*)," *International Wood Products Journal* 2(2), 101-107. DOI: 10.1179/2042645311Y.0000000016

Lyu, J., Wang, J., and Chen, M. (2024). "Effects of heat treatment on the chemical composition and microstructure of *Cupressus funebris* Endl. wood," *Forests* 15(8), article 1370. DOI: 10.3390/f15081370

Mania, P., and Gasiorek, M. (2020). "Acoustic properties of resonant spruce wood modified using oil-heat treatment (OHT)," *Materials* 13(8), article 1962. DOI: 10.3390/ma13081962

Mai, C., and Militz, H. (2023). "Wood modification," in: *Springer Handbook of Wood Science and Technology*, P. Niemz, A. Teischinger, and D. Sandberg (eds.), Springer, Cham, Switzerland, pp. 873-910. DOI: 10.1007/978-3-030-81315-4_16

Mania, P., and Skrodzka, E. (2020). "Modal parameters of resonant spruce wood (*Picea abies* L.) after thermal treatment," *Journal of King Saud University - Science* 32(1), 1152-1156. DOI: 10.1016/j.jksus.2019.11.007

Matsunaga, M., Sakai, K., Kamitakahara, H., Minato, K., and Nakatsubo, F. (2000). "Vibrational property changes of spruce wood by impregnation with water-soluble extractives of pernambuco (*Guilandina echinata* Spreng.): Structural analysis of extractive components," *The Japan Wood Research Society* 46, 253-257.

Merhar, M. (2024). "Identification of damping of spruce wood (*Picea abies*) under various levels of moisture content using time-scale decomposition," *Polymers* 16(10), article 1313. DOI: 10.3390/polym16101313

Metsä-Kortelainen, S., and Viitanen, H. (2010). "Effect of fungal exposure on the strength of thermally modified Norway spruce and Scots pine," *Wood Material Science and Engineering* 5(1), 13-23. DOI: 10.1080/17480271003786738

Morrell, Y., Yan, L., and Morrell, J. J. (2014). "Fir heartwood thermal mod," *BioResources* 9(4), 7152-7161. DOI: 10.15376/biores.9.4.7152-7161

Navi, B. P., and Girardet, F. (2000). "Effects of thermo-hydro-mechanical treatment on the structure and properties of wood," *Holzforschung* 54, 287-293. DOI: 10.1515/HF.2000.048

Navickas, P., Karpavičiūtė, S., and Albrektas, D. (2015). "Effect of heat treatment on wettability and modulus of elasticity of pine and spruce wood," *Medziagotyra* 21(3), 400-404. DOI: 10.5755/j01.ms.21.3.7304

Nourian, S. (2018). *Thermal Modification of Western Hemlock (Tsuga heterophylla)*, The University of British Columbia, Vancouver, BC, Canada.

Nuopponen, M., Vuorinen, T., Jámsä, S., and Viitaniemi, P. (2004). "Thermal modifications in softwood studied by FT-IR and UV resonance Raman spectroscopies," *Journal of Wood Chemistry and Technology* 24(1), 13-26. DOI: 10.1081/WCT-120035941

Obataya, E., Norimoto, M., and Gril, J. (1998). "The effects of adsorbed water on dynamic mechanical properties of wood," *Polymer* 39(14), 3059-3064. DOI: 10.1016/S0032-3861(97)10040-4

Obataya, E., Ono, T., and Norimoto, M. (2000). "Vibrational properties of wood along the grain," *Journal of Materials Science* 35(12), 2993-3001. DOI: 10.1023/A:1004782827844

Ono, T., and Norimoto, M. (1984). "On physical criteria for the selection of wood for soundboards of musical instruments," *Rheologica Acta* 23(6), 652-656. DOI: 10.1007/BF01438805

Özgenç, Ö., Durmaz, S., Boyaci, I. H., and Eksi-Kocak, H. (2017). "Determination of chemical changes in heat-treated wood using ATR-FTIR and FT Raman spectrometry," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 171, 395-400. DOI: 10.1016/j.saa.2016.08.026

Pandey, K. K. (2005). "Study of the effect of photo-irradiation on the surface chemistry of wood," *Polymer Degradation and Stability* 90(1), 9-20. DOI: 10.1016/j.polymdegradstab.2005.02.009

Pandey, K. K., and Vuorinen, T. (2008). "Comparative study of photodegradation of wood by a UV laser and a xenon light source," *Polymer Degradation and Stability* 93(12), 2138-2146. DOI: 10.1016/j.polymdegradstab.2008.08.013

Pfriem, A. (2015). "Thermally modified wood for use in musical instruments," *Drvna Industrija* 66(3), 251-253. DOI: 10.5552/drind.2015.1426

Puszynski, J., and Warda, M. (2014). "Possibilities of using the thermally modified wood in the electric string instruments," *Annals of Warsaw University of Life Sciences - SGGW. Forestry and Wood Technology* 85, 200-204.

Rokeya, U. K., Rahman, N. A., and Hossain, A. (2021). "Effect of heat treatment on physical and mechanical properties of mahogany (*Swielenia macrophylla* King) and acacia hybrid (*Mangiuni x Aiiriculiformis*) wood," *Bangladesh Journal of Forest Science* 37(2), 45-55.

Roszyk, E., Stachowska, E., Majka, J., Mania, P., and Broda, M. (2020). "Moisture-dependent strength properties of thermally-modified *Fraxinus excelsior* wood in compression," *Materials* 13(7), article 1647. DOI: 10.3390/ma13071647

Rowell, R. (2005). *Handbook of Wood Chemistry and Wood Composites*, CRC Press Taylor & Francis Group, Boca Raton, FL, USA. DOI: 10.1016/j.jclepro.2015.07.070

Rusche, H. (1973). "Die thermische Zersetzung von Holz bei Temperaturen bis 200 °C—erste Mitteilung: Festigkeitseigenschaften von trockenem Holz nach thermischer Behandlung [The thermal decomposition of wood at temperatures up to 200 °C—First report: Strength properties of dry wood after thermal treatment]," *Holz als Roh- und Werkstoff* 31(7), 273-281. DOI: 10.1007/BF02607297

Sakai, H., Minamisawa, A., and Takagi, K. (1990). "Effect of moisture content on ultrasonic velocity and attenuation in woods," *Ultrasonics* 28(6), 382-385. DOI: 10.1016/0041-624X(90)90060-2

Sandberg, D., Kutnar, A., Karlsson, O., and Jones, D. (2021). *Wood Modification Technologies: Principles, Sustainability, and the Need for Innovation*, CRC Press, Boca Raton, FL, USA.

Sarni, B. F., Moutounet, M., Puech, J., and Rabier, P. (1990). "Effect of heat treatment of oak wood extractable compounds," *Holzforschung* 44(6), 461-466.

Schultz, T. P., Nicholas, D. D., and Preston, A. F. (2007). "A brief review of the past, present and future of wood preservation," *Pest Management Science* 63(8), 784-788. DOI: 10.1002/ps.1386

Silverstein, R. M., Webster, F. X., and Kiemle, D. (2005). *Spectrometric Identification of Organic Compounds*, 7th Ed., John Wiley & Sons, New York, USA. ISBN: 9781118311653.

Stamm, A. (1956). "Thermal degradation of wood and cellulose," *Industrial & Engineering Chemistry* 48(3), article 63. DOI: 10.1021/ie51398a614

Stamm, A. J., and Tarkow, H. (1947). "Dimensional stabilization of wood," *The Journal of Physical and Colloid Chemistry* 51(2), 493-505.

Tankut, N., Tankut, A. N., and Zor, M. (2014). "Mechanical properties of heat-treated wooden material utilized in the construction of outdoor sitting furniture," *Turkish Journal of Agriculture and Forestry* 38(1), 148-158. DOI: 10.3906/tar-1211-9

Timar, M. C., Varodi, A., Hacibektasoglu, M., and Campean, M. (2016). "Color and FTIR analysis of chemical changes in beech wood (*Fagus sylvatica* L.) after light steaming and heat treatment in two different environments," *BioResources* 11(4), 8325-8343. DOI: 10.15376/biores.11.4.8325-8343

Tjeerdsma, B. F., Boonstra, M., Pizzi, A., Tekely, P., and Militz, H. (1998). "Characterisation of thermally modified wood: Molecular reasons for wood performance improvement," *Holz als Roh- und Werkstoff* 56(3), 149-153. DOI: 10.1007/s001070050287

Tjeerdsma, B. F., and Militz, H. (2005a). "Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood," *Holz als Roh- und Werkstoff* 63(2), 102-111. DOI: 10.1007/s00107-004-0532-8

Tjeerdsma, B. F., and Militz, H. (2005b). "Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood," *Holz als Roh- und Werkstoff* 63(2), 102–111. DOI: 10.1007/s00107-004-0532-8

Tsoumis, G. (1991). *Science and Technology of Wood. Structure, Properties, Utilization*, Van Nostrand Reinhold, New York, NY, USA.

Wegst, U. G. K. (2006). "Wood for sound," *American Journal of Botany* 93(10), 1439-1448. DOI: 10.3732/ajb.93.10.1439

Weiland, J. J., and Guyonnet, R. (2003). "Study of chemical modifications and fungi degradation of thermally modified wood using DRIFT spectroscopy," *Holz als Roh- und Werkstoff* 61(3), 216-220. DOI: 10.1007/s00107-003-0364-y

Wu, Y., Sha, T., Zhao, Z., He, Z., and Yi, S. (2016). "Influence of different pretreatments on the acoustic properties of dawn redwood (*Metasequoia glyptostroboides* Hu et Cheng)," *BioResources* 11(1), 2734-2743. DOI: 10.15376/biores.11.1.2734-2743

Yano, H. (1994). "The changes in the acoustic properties of western red cedar due to methanol extraction," *Holzforschung* 48(6), 491-495. DOI: 10.1515/hfsg.1994.48.6.491

Yildiz, S., Gezer, E. D., and Yildiz, U. C. (2006). "Mechanical and chemical behavior of spruce wood modified by heat," *Building and Environment* 41, 1762-1766. DOI: 10.1016/j.buildenv.2005.07.017

Yun, K. E., Kim, G. H., and Kim, J. J. (1999). "Effect of heat treatment on the dimensional stability and the bending properties of radiata pine sapwood," *Journal of Korean Wood Science and Technology* 27(4), 30–37.

Zatloukal, P., Suchomelová, P., Dömény, J., Doskočil, T., Manzo, G., and Tippner, J. (2021). "Possibilities of decreasing hygroscopicity of resonance wood used in piano soundboards using thermal treatment," *Applied Sciences* 11(2), 1-10. DOI: 10.3390/app11020475

Zhu, L., Liu, Y., and Liu, Z. (2016). "Effect of high-temperature heat treatment on the acoustic-vibration performance of *Picea jezoensis*," *BioResources* 11(2), 4921-4934. DOI: 10.15376/biores.11.2.4921-4934

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