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EFFECT OF HEAT TREATMENTS ON THE STRENGTH AND STIFFNESS OF POPLAR

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ABSTRACT

The influence of environmental conditions on wood material properties is known. Temperature is one of them and its effect on poplar wood has been examined in a limited way which this study tried to figure out this issue in a limited context. The influence of heat treatment (110 °C, 160 °C, and 210 °C for 3 h and 6 h) on the density, ultrasonic wave velocity, modulus of rupture, and modulus of elasticity of poplar wood was evaluated. A 2,25 MHz longitudinal ultrasonic wave was used to determine both the ultrasonic wave velocity and the dynamic modulus of elasticity. A three-point bending test was conducted to determine the static modulus of elasticity and the modulus of rupture. The average values for the control samples were 350 kg/m³ for density, 3 598 m/s for ultrasonic wave velocity, 4 552 MPa for dynamic modulus of elasticity, 5 864 MPa for static modulus of elasticity, and 64,1 MPa for modulus of rupture. When samples were treated at 210 °C for 6 h, these properties decreased by 14,3 %, 3 %, 18,7 %, 25 %, and 50,2 %, respectively. In general, the dynamic modulus of elasticity values were lower than the static ones across all treatment conditions. The greatest difference between dynamic and static modulus (34 %) was observed at 110 °C for 6 h, while the smallest difference (18,8 %) occurred at 210 °C for 6 h. Improvements of up to 8,9 %, 2,4 %, and 0,85 % were observed in the modulus of rupture, static modulus of elasticity, and ultrasonic wave velocity, respectively, at 110 °C treatments.

Keywords: Bending strength, non-destructive testing, thermal modification, modulus of elasticity, *Populus canadensis*, ultrasound.

INTRODUCTION

Wood, a natural and biomaterial, is generally influenced by external factors such as temperature, moisture, and biological diversity such as insects or fungi, etc. The influence of these factors on the physical and mechanical properties of wood is one of the main investigation areas in wood science and technology. One of the modification methods used for reducing the effects of external factors on wood properties is heat treatment.

Heat treatment (HT), also known as thermal modification, can significantly impact the properties of wood. The process involves subjecting the wood to high temperatures, typically between 160 °C and 240 °C, in a controlled environment. HT provides some improvements for wood materials as follows. Improved dimen-

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sional stability by reducing the equilibrium moisture content, making the wood less prone to shrinkage and swelling caused by changes in humidity. This results in improved dimensional stability and reduced warping. Increased durability by enhancing the resistance of wood against decay and insect attack. The high temperatures modify the wood's chemical composition, making it less attractive to pests and fungi.

Enhanced color by darkening the color of wood, ranging from light amber to rich brown tones. The extent of color change depends on the treatment temperature and duration. Decreased moisture absorption by exhibiting reduced water absorption properties, making the wood less susceptible to moisture-related damage. Reduced thermal conductivity by lowering the thermal conductivity which makes wood a more effective insulating material.

In the literature, the following studies dealt with the effect of HT on poplar wood in terms of different aspects. Villasante *et al.* (2022) evaluated the influence of olive oil HT and densification on the physical properties of I-214 clone of canadian poplar (*Populus canadensis* Moench). Taraborelli *et al.* (2022) evaluated the effect of HT on the hardness, density, and color properties of canadian poplar (*Populus canadensis* Moench) 'I-214'. Goli *et al.* (2014) evaluated the influence of HT on gluing performance and modulus of elasticity (MOE) and modulus of rupture (MOR) of I-214 clone veneer. Bak and Nemeth (2012a) determined the MOE and MOR of hot oil (sunflower, linseed, and rape seed) treated Pannonia poplar at 160 °C and 200 °C for 2, 4 and 6 h. Authors reported that application caused more than 10 % decreases in strength properties. Düzkale Sözbir *et al.* (2019) evaluated the effect of HT (120 °C, 160 °C and 200 °C for 1 and 3 h) and densification (120 °C 5 MPa pressure for 30 min) combination on MOR and MOE of uzbek poplar (*Populus usbekistanica* Kom.). Todaro *et al.* (2021) HT (180 °C, 200 °C, and 220 °C) black poplar (*Populus nigra* L.) and stated that results indicate that after HT at 180 °C, MOE averages slightly increased but considerably decreased when treatment conditions elevated.

Perçin *et al.* (2024) figured out the influence of HT (140 °C to 200 °C by 20 °C increment for 2h) on impact bending strength, weight loss, density, shore d hardness, and thermal conductivity of black poplar (*Populus nigra* L.). Kamperidou and Barboutis (2021) evaluated the natural weathering resistance of heat treated the *Populus* sp. at 180 °C and 200 °C for 3 h, 5 h, and 7 h. Bak and Nemeth (2012b) determined the swelling behavior of oil heat-treated pannónia poplar (*Populus euramericana* cv. Pannónia). Kamperidou and Barboutis (2018) and Kamperidou *et al*. (2013) figured out the influence of HT on hygroscopic properties of *Populus* sp. Kamperidou (2019) studied the influence of thermal and chemical modification on the biological durability of *Populus* sp. Bytner *et al*. (2022a) measured the color of heat-treated (160 °C to 220 °C for 2 h to 8 h by 2 h increments) black poplar (*Populus nigra* L.). Zamani *et al.* (2023) evaluated the effect of brown rot fungus on density, CS, impact strength, mass loss of heat treated eastern cottonwood (*Populus deltoids* W. Bartram ex Marshall) and black poplar (*Populus nigra* L.). Hassani *et al.* (2022) revealed the effect of tree age, thickness, and depth of timber on the density and MOR, MOE and impact strength of HT black poplar. Karagöz *et al*. (2011) figured out the influence of HT (120 °C, 160 °C, and 180 °C for 2h and 6 h) on the surface roughness of canadian poplar (*Populus canadensis* Moench) after CNC milling. YingJie *et al.* (2017) determined the MOE, MOR, and CS of the heat-treated canadian poplar (*Populus canadensis* Moench) and golden poplar (*Populus euramericana* (Dode) Guinier cv. Gelrica). Pelit and Yorulmaz (2024) determined some physical properties of heat treated (140 °C to 200 °C by 20 °C increments for 7 and 9 h) and densified black poplar (*Populus nigra* L.).

Apart from HT, the following studies dealt with poplar wood in different aspects. Wang *et al.* (2020) determined the MOE and MOR of densified eastern cottonwood (*Populus deltoids* W. Bartram ex Marshall) 9 black poplar (*Populus nigra* L.). Demirkır *et al.* (2017) produced plywood using plasma-treated eastern cottonwood (*Populus deltoids* W. Bartram ex Marshall) veneer and determined MOE and MOR. Kánnár and Csiha (2021) compared the four different growing site values for MOE of pannónia poplar (*Populus euramericana* cv. Pannónia) determined by Fakopp-PLG and bending test. Gallego *et al.* (2021) evaluated the influence of age and stand density on the MOE dyn (20 kHz and vibration) and MOE (4-point bending) of I-214 golden poplar (*Populus euramericana* (Dode) Guinier cv. Gelrica). Giovannelli *et al.* (2007) revealed the effect of drought on the stem growth of canadian poplar (*Populus canadensis* Moench) 'I-214'. Danilović *et al.* (2022) investigated the effect of pruning on tree development in canadian poplar (*Populus canadensis* Moench) 'I-214'.

In the literature, there are limited studies that figured out the HT-influenced properties of canadian poplar (*Populus canadensis* Moench). One of the recent studies evaluated the influence of HT on the mechanical properties of canadian poplar (*Populus canadensis* Moench) (Aydın and Yılmaz Aydın 2024). Authors dynamically determined the effect of HT (110 °C, 160 °C, and 210 °C for 3 h and 6h) on elasticity and shear moduli and Poisson's ratio. However, the influence of HT on strength and stiffness properties was not evaluated either dynamically or statically. Furthermore, such HT-related elastic and strength values may provide the required data for numerical modeling and analysis of the structural behavior evaluation as Chang (1986) figured out. In this study, the influence of HT on density, ultrasonic wave velocity (UWV), dynamic and static modulus of elasticity (MOEdyn and MOEstat), and static modulus of rupture (MORstat) of canadian poplar (*Populus canadensis* Moench) which has not been presented before was figured out.

Materials and methods

Canadian poplar (*Populus canadensis* Moench) log, cultivated in Atabey (37°57'03''N 30°38'19''E) located in the Mediterranean Region of Türkiye, was used. The samples cut from plain-sawn air-dried timbers were exposed to temperatures (110 °C, 160 °C and 210 °C) for 0 (control), 3 h and 6 h using an FN 500 oven (Nüve Company, Ankara, Türkiye). The 20 mm × 20 mm × 350 mm (Radial-R×Tangential-T×Longitudinal-L) final-sized samples were acclimatized at a constant temperature (20 °C ± 1 °C) and relative humidity (65 %) using a chamber (Memmert Gmbh+Co. KG, Schwabach, Germany).

Three-point bending test was performed using a universal test machine (Marestek, İstanbul, Türkiye) to determine MOEstat and MORstat via Equation 1 and Equation 2, respectively.

$$MOE_{stat} = \frac{\Delta F L^3}{\Delta d\, 4 b h^3} \qquad (1)$$

Where, ΔF is the difference between the two loads (F2-F1) in the linear elastic region, L is the span (mm), Δd is the deflection (mm), b and h are the width (mm), and thickness (mm) of the sample, respectively.

$$MOR_{stat} = \frac{3FL}{2bh^2} \qquad (2)$$

Where, F is the load at failure (N), L is the span between supports (mm), b, and h are the depth (mm) and width (mm) of the sample, respectively.

The 20 mm × 20 mm × 20 mm (R×T×L) cubic samples were cut from the end of the static test samples to figure out the MOEdyn using EPOCH 650 flaw detector (Olympus, USA). The contact type transducers (Panametrics-NDT, USA) which have 2,25 MHz central frequency was used for longitudinal ultrasonic wave propagation. The propagation time of the wave on the display was used to calculate longitudinal ultrasonic wave velocity (V_{LL}) which was used to determine MOEdyn as seen in Equation 3.

$$MOE_{dyn} = \rho\, V_{LL}^2 10^{-6} \qquad (3)$$

Where, ρ is the density of the sample (kg/m³) and V_{LL} is the velocity of ultrasound (m/s).

The relationship between the MOEdyn and MOEstat was figured out using the R^2 (coefficient of determination) values. The influence of temperature on physical and mechanical properties was figured out by ANOVA tests. Duncan's multiple range test (DMRT) was used to present statistically significant differences between the means.

RESULTS AND DISCUSSION

In the literature, there are considerable temperature-dependent physical and mechanical data for canadian poplar presented in the literature, while this study contributes to the literature by presenting both destructive and non-destructive data in tables and graphs below which are novel. The means and variation coefficients of the physical and mechanical properties are presented in Table 1. It's observed that an increase in temperature (following the 110 °C) with exposure duration caused remarkable adverse effects on the properties. The order of the adverse influence on the properties was MORstat > MOEstat > MOEdyn > density > V_{LL}. However, positive influences (approx. 9 % advancement) of the HT were also observed particularly for MORstat at initial conditions that were followed by decreasing trend. Therefore, treatment at moderate temperatures can be applicable for MOEstat and MORstat.

Reported density averages for the canadian poplar (*Populus canadensis* Moench) are 334 kg/m³ to 374 kg/m³ (Casado *et al.* 2010), 395 kg/m³ (Papandrea *et al.* 2022), 405,6 kg/m³ (Hodoušek *et al.* 2017), 464 kg/m³ (Villasante *et al.* 2022), and 372 kg/m³ to 468 kg/m³ (YingJie *et al.* 2017). The average density of the control samples in this study is in the reported range and decreased up to 14,3 % with the increase in temperature and duration. According to ANOVA results seen in Table 2, the influence of HT on density is significant and Table 3 presents which means are statistically different. This is because thermal degradation of hemicelluloses leads to mass loss, causing a reduction in density. This adverse effect of HT is more pronounced at temperature levels higher than 110 °C and extended treatment durations. Düzkale Sözbir *et al.* (2019) stated that HT affects the density but not homogeneously which is opposed to this study and others such as Pásztory *et al.* (2017).

Taraborelli *et al.* (2022) heat-treated (200 °C 45 min) canadian poplar (*Populus canadensis* Moench) 'I-214' and observed 10 % decrease in density from the control value (400 kg/m³) which is comparable. The 13,1 % (Bytner *et al.* 2022b) and 4,3 % (Düzkale Sözbir *et al.* 2019) decreases in density for black poplar (*Populus nigra* L.) and uzbek poplar (*Populus usbekistanica* Kom.) were reported, respectively. As can be seen in this study, a linear decrease (up to 14,3 %) in density was observed. Contrary, Meija *et al.* (2020) reported 300 kg/m³ (control), 295 kg/m³ (204 °C 120 min), 289 kg/m³ (214 °C 120 min), 312 kg/m³ (217 °C 180 min), and 309 kg/m³ (218 °C 30 min) average densities for canadian poplar (*Populus canadensis* Moench) veneer.

As can be seen in Table 1, in general, MOE decreased by HT. However, this increase was not linearly occurred with the increase in temperature and duration, particularly for 110 °C applications. Contrary, a slight increase (2,4 %) in MOEstat was observed. Such advancement (3,3 %) in dynamically determined elasticity moduli after treatment at moderate temperature levels for Canadian poplar (*Populus canadensis* Moench) was reported by (Aydın and Yılmaz Aydın 2024). Similarly, authors reported 4361 MPa Young's or elasticity modulus (E_L) which 11,9 % decreased after HT at 210 °C for 6 h. In this study, the decrease percentage of MOE is considerably higher at the same treatment conditions. Bytner *et al.* (2022b) reported 8,7 % increase in MOE for black poplar (*Populus nigra* L.) heat treated at 160 °C 6 h. Furthermore, decreases in MOE (max. 2 %) started following the 200 °C 4 h treatment which is not compatible with this study.

Comparable control means (5693 MPa) and decrease percentages (10,3 % at 200 °C for 3 h) for uzbek poplar (*Populus usbekistanica* Kom.) were reported by Düzkale Sözbir *et al.* (2019). Furthermore, the authors also achieved 4,7 % advancement at 120 °C for 1 h. Todaro *et al.* (2021) heat-treated the black poplar (*Populus nigra* L.) and observed 10,8 % increase and 5,9 % decrease in MOE when samples were treated at 180 °C and 220 °C, respectively. Such a positive effect of high temperatures was not observed in this study. As in MOE, MORstat notably increased at 110 °C application and significantly decreased with intense treatment. Such significant decreases (81,5 MPa to 45,5 MPa, -44,2 %, 220 °C for 8 h) were reported by Bytner *et al.* (2022b) for black poplar (*Populus nigra* L.). A similar reduction (43,6 % decrease from 59,2 MPa, 200 °C for 3 h) was reported by Düzkale Sözbir *et al.* (2019) for Uzbek poplar (*Populus usbekistanica* Kom.) The notable and comparable decreases in MOE, MOR, and density for heat-treated Taurus cedar (Yılmaz Aydın 2021) and oak (Yılmaz Aydın and Aydın 2020) were reported.

As can be seen in Table 2, the influence of HT on MOE and MOR is statistically significant and Table 3 presents which means are statistically different. Significant differences can be explained as HT reduces the number of hydroxyl groups (-OH) (Zheng *et al*. 2023) and the -OH is responsible for creating hydrogen bonds between the macromolecules of the wood polymers (Faruk and Ain 2013). The loss of hemicellulose and hydroxyls can result in a modest decrease in mechanical strength, even though cellulose, which contains a large portion of the strength, is more resistant to heat.

In the literature, it was stated that the properties dynamically predicted by Ultrasound (US) are generally higher than destructively determined values. For example, 12,1 % (120 °C 8 h or 150 °C Control) to 20,5 % (80 °C Control) higher values reported for MOEdyn vs MOEstat of heat-treated Taurus cedar, respectively (Yılmaz Aydın 2021). However, as seen in Table 1, MOEstat values in all treatment groups are higher (18,8 % to 34 %) than MOEdyn. Furthermore, Papandrea *et al.* (2022) obtained higher static values than dynamic ones.

There are different gradings of construction timber and Eurocode is one of them. The C14 (lowest values corresponding to the bending strength 14 MPa, basic structural grade, light-duty purpose, unsuitable for outdoor utilization) to C50 (highest) are strength classes classified by strength, stiffness, and density values in EN 338 (2016). When considering the C14 (350 kg/m³) grading class, the lowest density class for structural utilization, HT makes poplar wood unsuitable for structural purposes, particularly for outdoor applications. As seen in Table 1, neither dynamic nor static MOE means fulfilling the minimum requirements of the C14 structural timber strength class for softwood species in Eurocode 5. The highest mean of this study is around 14,2 % lower than the lowest value. On the contrary, except for the 210 C 6 h application, all MOR means are higher than the C40 class which is the 3rd highest strength class corresponding to the 40 MPa bending value. Therefore, even though some improvements in MOEstat and MOR were obtained, density drops below the lower bound for classification.

As can be seen in Table 1, the UWV (V_{LL}) presented unstable behavior by HT. The intense HT caused around 3 % decrease which is comparable to 4,9 % decrease for red pine treated at 210 °C 8 h (Aydın 2022). Except for 210 °C 6 h, slight and neglectable decreases, and increases were observed and the influence of HT on UWV was insignificant (Table 2) and means did not present significant differences (Table 3). However, due to density which is the multiplier term in Equation 3, MOEdyn also remarkably decreased with the increase in treatment conditions.

The bound water amount in the cell wall decreases with the HT (Hill *et al*. 2021) and the amount of bound water and free water decreases with the increasing treatment temperature (Gao *et al.* 2021). Therefore, the removal of the water from the lumen and cell wall due to HT causes relatively higher air volume in the wood. At this phase, considering the approx. speed of the longitudinal ultrasonic wave in the air (340 m/s) and water (1500 m/s), the speed should be decreased after the HT. But UWV was the least influenced property. It’s like an embedded multiple case study because even if there is no agreement on the effect of density on UWV.

Table 1: Descriptives of physical and mechanical properties.

Temp, (°C)	Exposure (Hours)	Density (kg/m³)		V_{LL} (m/s)		MOE_{dyn} (MPa)		MOE_{stat} (MPa)		MOR_{stat} (MPa)	
		Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV
Control	0	351	2,1	3598	3,1	4552	5,9	5864 (28,8)*	17,3	64,1	11,7
110	3	349 (0)	8,7	3565 (-0,91)**	5,4	4431 (-2,7)	10,0	5812 (-0,9) (31,2)	5,4	69,8 (8,9)	14,2
110	6	340 (-2,9)	3,1	3628 (0,85)	3,0	4483 (-1,5)	7,6	6005 (2,4) (34,0)	13,7	66,8 (4,3)	5,6
160	3	339 (-5,7)	3,3	3628 (0,83)	9,8	4467 (-1,9)	9,8	5674 (-3,2) (27,0)	9,1	62,7 (-2,2)	19,1
160	6	333 (-5,7)	4,7	3618 (0,57)	4,7	4364 (-4,1)	9,2	5410 (-7,7) (24,0)	6,6	59,9 (-6,5)	18,0
210	3	310 (-11,4)	5,4	3600 (0,06)	3,9	4028 (-11,5)	10,3	4939 (-15,8) (23,0)	9,7	42,3 (-34,0)	5,3
210	6	303 (-14,3)	5,5	3489 (-3,02)	4,9	3702 (-18,7)	11,4	4398 (-25) (18,8)	12,5	31,9 (-50,2)	11,1

* % difference between MOE_{dyn} and MOE_{stat}, ** % diffraction from the control value.

Table 2: ANOVA results.

	Density (kg/m^3)		V_{LL} (m/s)		MOE_{dyn} (MPa)		MOE_{stat} (MPa)		MOR_{stat} (MPa)	
Source	F	P	F	P	F	P	F	P	F	P
Corrected Model[a]	12,4	0	1,1	0,36	6,4	0	25,3	0	32,7	0
Intercept	26179	0	37896	0	7870	0	5091	0	3492	0
temperature	28,8	0	1,5	0,24	14,4	0	67,4	0	87,9	0
duration	2,7	0,11	0,25	0,6	1,6	0,22	0,75	0,39	7,1	0,01
temperature*duration	0,06	0,94	1,76	0,18	1,19	0,31	1,14	0,33	1,51	0,23
	a, R^2 = ,541		a, R^2 = ,097		a, R^2 = ,376		a, R^2 = ,707		a, R^2 = ,757	

Table 3: Duncan's homogeneity groups.

		V_{LL} (m/s)	MOE_{dyn} (MPa)		MOE_{stat} (MPa)		MOR_{stat} (MPa)		
Duration (h)	N	Subset	Subset		Subset		Subset		
		1	1	2	1	2	1	2	3
6	30	3579	4183		5039		52,9		
3	30	3598	4309	4309	5171			58,3	
Control	10	3598		4552		5864			64,1
Sig.		0,72	0,34	0,07	0,51	1	1	1	1
Temp. (°C)	N	Subset	Subset		Subset		Subset		
		1	1	2	1	2	1	2	3
210	20	3544	3865		3865		37,1		
160	20	3597		4415		5542		61,3	
110	20	3598		4457		5864		64,1	64,1
Control	10	3623		4552		5908			68,3
Sig.		0,18	1	0,36	1	0,10	1	0,32	0,13

When the results of this study are compared to the reported data seen in Table 4, there are remarkably high differences not only for canadian poplar (*Populus canadensis* Moench) but also for other sub-species. As well known, even if the tested species is the same, there can be great variations in the mechanical and physical properties of wood. However, around 2,2-2,3 times higher MOEdyn values were seen within the species. Furthermore, around 4,2 times higher MOEdyn value predicted by the US (Ettelaei *et al.* 2019) is beyond the comparison. Additionally, the velocity of the 22 kHz ultrasonic wave is 1,6 times higher than those of this study. When the role of density in the calculation is taken into consideration, 420 % difference becomes meaningful because there is 148 % to 169 % difference. Only Papandrea *et al.* (2022) reported comparable dynamic values. The MOEstat of this study is around 37 % and 42 % lower than the YingJie *et al.* (2017) and Hodoušek *et al.* (2017), respectively. Contrary to MOE, MOR values are in the reported 35 MPa to 88 MPa range seen in Table 4. However, within the sub-species, the control value of this study is 60,65 % higher than the upper bound of Casado *et al.* (2010). Indeed, such differences for MOE, MOR, etc. are rational, especially for a material that has an inhomogeneous orthotropic structure, and its structure is defined by the growing conditions such as climate, elevation, soil, among others.

Table 4: Some reported physical and mechanical properties of poplar species.

Species	Density (kg/m³)	MOE_{stat} (MPa)	MOE_{dyn} (MPa)	Nondestructive Test Method	WV (m/s)	MOR (MPa)	Reference
Populus × canadensis M.	300						(Meija *et al.* 2020)
Populus × canadensis.	405	10113	10002	Accelerometer			(Hodoušek *et al.* 2017)
Populus × canadensis.	405		10366	MTG			(Hodoušek *et al.* 2017)
Populus × euramericana I-‘214’	334-374	7053-7659	7699-9529	Vibration - Portable Lumber Grader	4697-4761	34,6-39,9	(Casado *et al.* 2010)
Populus × canadensis	372-468	9303				79,7	(YingJie *et al.* 2017)
Populus canadensis ‘I-214’	400						(Taraborelli *et al.* 2022)
I-214 (30-130 cm log height)	395	8249	5829	Stress Wave	3877		(Papandrea *et al.* 2022)
I-214 (130-230cm log height)	395	9091	6572	Stress Wave	4110		(Papandrea *et al.* 2022)
I-214 (230-330cm log height)	395	10364	7613	Stress Wave	4413		(Papandrea *et al.* 2022)
I-214 clone	400	8000-8600	8800-8900	longitudinal vibration and bending vibration		37,8	(Koman *et al.* 2013)
I-214 clone	320	4778				48,5	(Kurt 2010)
Populus × euramericana cv. Pannónia	420	11771	11891	US-Fakop		67,2	(Kánnár and Csiha 2021)
Populus × euramericana cv. Pannónia	409,6	10336	10969	US-Fakop		76,6	(Kánnár and Csiha 2021)
Populus × euramericana cv. Pannónia		9150	9876	US-Fakop		68,1	(Kánnár and Csiha 2021)
Populus × euramericana cv. Pannónia	459,6	12399	12139	US-Fakop		87,5	(Kánnár and Csiha 2021)
Pannonia		8400-10100	9800-10100	longitudinal vibration and bending vibration		38,4	(Koman *et al.* 2013)
Populus euramericana cv. ‘Guariento’	414	9620				65,8	(Jia *et al.* 2021)
Populus Euroamericana	517,5-593,1	8871-11860	15575-19121	Sylvatest Duo 22 kHz	5433-5887		(Ettelaei *et al.* 2019)
Eastern cotton wood (*Populus deltoids* USA Origin)	400	9400				59	(Kretschmann 2010)
Eastern cotton wood (*Populus deltoids* Canada Origin)	350	7800				52	(Kretschmann 2010)
Populus deltoides	370-380	5443-6066				59,8-61	(Kurt 2010)
Populus deltoides Clone 55/650	458	9970				68	(Jia *et al.* 2021)
Populus nigra Clone ‘N1790	408	9180				67,8	(Jia *et al.* 2021)
Poplar veneer		8157				84.95	(Atar and Mengenoğlu 2022)
Populus deltoides		8241-9640 (8503 Control)				79-85 (85 Control)	(Demirkir *et al.* 2017)

In the literature, reported R^2 between MOEdyn and MOEstat for canadian poplar (*Populus canadensis* Moench) ranged from 47,17 % to 76,97 % (Casado *et al.* 2010). Papandrea *et al.* (2022) reported 0,527 and 0,530 R^2 values between Stress Wave Velocity (SWV) vs MOEstat and SWV vs MOEdyn for I-214, respectively. Furthermore, the authors also reported 0,728 Pearson correlation coefficient between MOEdyn and MOEstat. As can be seen in Figure 1, R^2 for MOEdyn vs MOEstat ranged from 0,704 (110 °C 3 h) to 0,835 (160 °C 6 h). Apart from these values, 0,67-0,71 R^2 for MOEdyn vs MOEstat for I-214 golden Poplar (*Populus euramericana* (Dode) Guinier cv. Gelrica) (Gallego *et al.* 2021), 0,61 and 0,91 R^2 for MOR vs density and MOE vs density for densified eastern cottonwood (*Populus deltoids* W. Bartram ex Marshall) 9 black poplar (*Populus nigra* L.), respectively (Wang *et al.* 2020), 0,708-0,809 R^2 for MOE vs MOR of *Panonia* and I-214 (Koman *et al.* 2013), and 0,44-0,61 R^2 for MOEdyn (22 kHz) vs MOEstat (3 points) for pannónia poplar (*Populus euramericana* cv. Pannónia) (Ettelaei *et al.* 2019) were also noticed. When considering the above-mentioned ranges, it can be said that fair enough percentages (over 70 %) of the values can be predicted without destroying the samples via ultrasonic measurements. Furthermore, such successful models with 0,83 (Yılmaz Aydın 2021) and 0,897 (Yılmaz Aydın and Aydın 2020) R values for MOEdyn vs MOEstat of the heat-treated Taurus cedar and oak were also reported, respectively. But it should be kept in mind that such considerably high percentages were obtained because the samples were exactly matched pieces as explained in the method section.

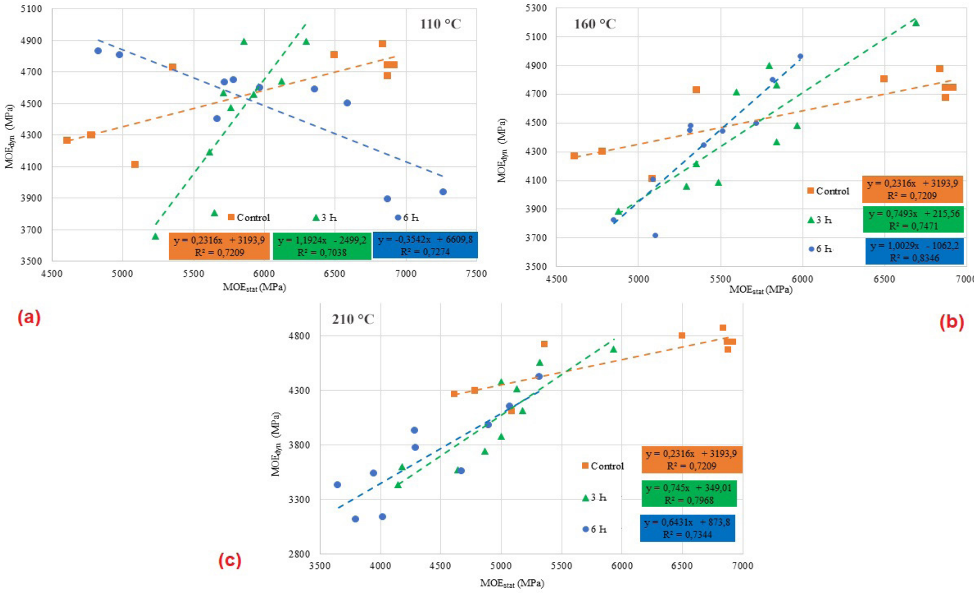

Figure 1: Relationship between MOEdyn and MOEstat in terms of temperature groups; (a) 110 °C, (b) 160 °C, and (c) 210 °C.

The influence of temperature on physical and mechanical properties is illustrated in Figure 2. The error bars in these graphs represent the variations relative to the means of HT groups. Therefore, error bars give a visual estimation of the diffraction between groups at the same temperature point. The 110 °C 3 h treatment caused higher variation in density (8,70) while the least was control (2,06).

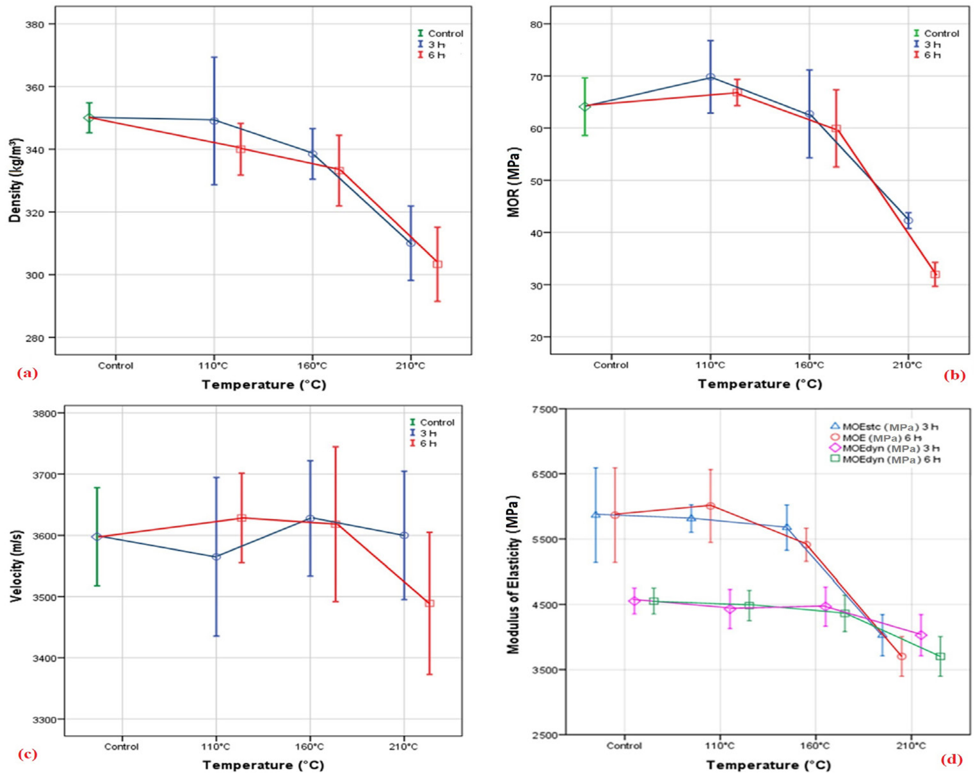

Figure 2: Effect of temperature on the properties; (a) density *vs.* temperature, (b) MOR *vs.* temperature, (c) velocity *vs.* temperature, and (d) MOE *vs.* temperature.

HT can improve certain properties of poplar wood, such as dimensional stability and durability, but it often leads to a reduction in mechanical strength, particularly stiffness (MOE) and bending strength (MOR). These reductions are mainly due to the degradation of hemicelluloses and lignin caused by high temperatures.

The impact of HT on MOE and MOR depends on treatment temperature, duration, and the wood's characteristics. Generally, higher temperatures and longer durations lead to greater reductions in strength, while milder conditions can minimize these effects.

Both temperature and duration must be carefully balanced to optimize benefits without overly compromising mechanical properties. Higher temperatures can accelerate the desired transformations, such as the degradation of hemicelluloses and lignin, which can result in improved stability and durability. However, excessively high temperatures can lead to undesirable effects, such as excessive wood color change or a significant reduction in mechanical strength. On the other hand, longer durations allow for more extensive chemical reactions and transformations within the wood. However, there is a limit to the duration beyond which the benefits plateau or even decline. Extended exposure to high temperatures can result in excessive degradation and reduction in mechanical properties. The ideal HT parameters depend on the specific application and desired characteristics of the treated wood.

CONCLUSIONS

The experimental investigation evaluated the influence of thermal treatment parameters, specifically temperature (110 °C, 160 °C, 210 °C) and exposure duration (3 h and 6 h), on the physical and mechanical properties of Canadian poplar (*Populus canadensis* Moench). The data demonstrated a clear temperature-dependent degradation in density, with up to a 14.3% reduction at 210 °C for 6 hours, which corresponded to notable declines in mechanical properties such as MOEstat and MORstat. ANOVA results confirmed that temperature had a statistically significant effect on density, MOE_{dyn}, MOE_{stat}, and MOR_{stat}, indicating it is the primary factor influencing structural degradation. Exposure duration was significant only for MOR_{stat}, suggesting time plays a secondary role.

The longitudinal ultrasonic wave velocity exhibited minor fluctuations. The MOE_{dyn}, derived from ultrasonic measurements, remained relatively stable across treatments and exhibited a strong positive correlation with MOEstat, supporting the reliability of nondestructive testing for estimating stiffness. Duncan's multiple range tests showed that the most pronounced reductions in MOR and MOE_{stat} occurred at 210 °C, especially at 6 hours, with MOR decreasing by more than 50% compared to the control. Meanwhile, treatment at 160 °C, particularly for 3 hours, caused minimal changes and may represent a thermal modification threshold below which mechanical integrity is largely preserved.

In conclusion, high-temperature exposure substantially compromises wood performance, primarily through degradation of mechanical strength and stiffness, whereas lower-temperature, short-duration treatments could be utilized to modify properties without critical losses in structural behavior. Therefore, the intensity of the treatments should be considered by optimizing the factor combinations to achieve balanced properties including appearance or color. These findings provide critical thresholds for thermal modification processes where optimization of mechanical performance and dimensional stability is required.

Authorship contributions

T. Y. A.: Conceptualization, resources, investigation, methodology, formal analysis, writing-original draft, writing-review&editing. M. A.: Investigation, resources, formal analysis, writing-original draft, writing-review&editing. U. Ö.: Investigation, writing-original draft, writing-review&editing.

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