Evaluation of Heat Treatment Parameters' Effect on Some Physical and Mechanical Properties of Poplar Wood with Multi-criteria Decision Making Techniques

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Effects of the heat treatment parameters were evaluated relative to some physical and mechanical properties of poplar wood (*Populus alba* L.) with use of two of the prominent multi criteria decision-making (MCDM) techniques: Entropy and The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). To meet this objective, the test samples were heat-treated at 120, 150, 180, and 210 °C for 2 and 4 h in a laboratory-scale oven. With increasing temperature and duration, the shrinkage and swelling ratios of heat-treated samples were improved. However, the bending strength, modulus of elasticity, and compression strength generally decreased with increasing process temperature and duration. According to (MCDM) analyses, thermal modification definitely improved the physical properties of wood up to a point. Bending strength was found to be the most important determinant of heat treatment success. The other determinants were identified as swelling, compression strength, shrinkage, and modulus of elasticity, respectively. Also, the best results were obtained at 120 °C for 2 h. In general, heat treatment above 150 °C or 4 h is not recommended.

Keywords: Heat treatment; Physical properties; TOPSIS; Decision making; Entropy weight method

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INTRODUCTION

The increasing demand for wood-based products has caused serious reductions in global forest resources. Therefore, the most efficient use of wood raw material is of great importance. Considering the primary (timber, veneer, plywood, particleboard, fiberboard) and secondary (parquet, woodwork, furniture, *etc*.) usage of wood raw material, the demand for wood products is unlimited (Göker and Dündar 1999; Kabakci and Kesik 2020).

Although a wide variety of methods have been implemented to meet the wood raw material need, the most effective method is undoubtedly the prevention of loss of wood raw material and taking various saving measures. It is possible to specify the measures as to meet the wood need by import, to increase wood raw material production, and to focus on growing fast growing tree species through industrial plantations. For this purpose, *Eucalyptus camaldulensis*, *Eucalyptus grandis*, *Pinus pinaster*, *Pinus radiata*, *Pinus taeda*, *Pseudotsuga menziesii*, *Pinus brutia*, *Pinus nigra*, *Fraxinus excelsior*, and *Populus* (*Populus nigra*, *Populus* x *euramericana* and *Populus deltoides*) species are being evaluated as fast-growing tree species (Birler 2009).

Due to its many advantageous features, wood has a wide range of uses. Wood material is a very important raw material especially for the building industry because of its easy processing, enabling surface treatment, different pattern and color alternatives, heat, sound and electrical insulation, and acoustic properties (Aydin 2019). Despite these advantages, wood material also has some negative properties. Examples include the easy destruction of wood material by microorganisms and insects, low dimensional stability, and the fact that color and surface appearance are not homogeneous. In order to eliminate these disadvantages, modifications can be carried out on wood material using various methods. All methods for protecting wood against biotic and abiotic factors are generally classified as wood modification methods. These methods include chemical, surface, impregnation, and thermal modification.

Thermal modification allows the chemical structure of polymer compounds in the cell wall to change permanently (Boonstra 2008). This method improves wood properties without addition of any chemical substance. Within the scope of thermal modification, many types of wood, different temperatures, heating rate and durations have been studied to determine the optimum process conditions (Syrjänen and Kangas 2000; Zaman *et al*. 2000; Militz 2002; Mazela *et al*. 2003; Esteves *et al*. 2007; Kesik *et al*. 2017; Durmaz *et al*. 2019).

The physical and mechanical properties of the thermally modified wood change permanently due to the thermal degradation of hemicellulose, which starts at approximately at 150 °C and continues with increasing temperature. Temperature is the most important factor in heat treatment. In addition, the type of wood directly affects the heat treatment durations, process atmosphere, and moisture content and temperature distribution (Yildiz 2002). The success of the heat treatment depends on several factors. Heat treatment can be completely successful only with the application of these factors at optimum values. This process is a decision-making problem that consists of various and related criteria. The best thermal modification variation and its parameters can be determined with multi-criteria decision making (MCDM) methods.

There are many MCDM techniques, and they diverge in the complexity of use and the need of introducing further subjective variables such as weights (Bakhoum and Brown 2013). TOPSIS and entropy methods were selected because they are appropriate for the goal, and a hybrid approach consisting of these was applied. Entropy was used to evaluate the weights of criteria that will be used at TOPSIS to rank the alternatives.

TOPSIS is one of the well-known MCDM methods (Ouyang *et al*. 2014), which was first developed by Hwang and Yoon in 1981. Today, TOPSIS has been employed as a decision-making tool for numerous areas (Abidin *et al*. 2016). Each method has its own advantages. Entropy is robust, versatile, and efficient, and it can cope with the deficiencies of subjective weighting methods (Bakhoum and Brown 2013; Wang *et al*. 2017). TOPSIS is practical and logically represents the rational human selection by considering both the best and worst attributes of the alternatives at the same time; both the computation and the presentation of the results are simple (Abidin *et al*. 2016; Long *et al*. 2019). It is suitable for cases with many attributes and alternatives, as well as being practical for objectives with quantitative data (Sayareh and Alizmini 2014).

There are many published studies of effects of process conditions such as temperature and duration on the results of thermal modification of wood. However, the use of multi-criteria decision-making methods in determining the effect of optimum process parameters on the thermal modification of wood have not been studied extensively. Accordingly, this study focused on the evaluation of heat treatment parameters' effects on some physical and mechanical properties of wood with multi-criteria decision making techniques. Two well-known MCDM techniques were used: entropy and TOPSIS. A hybrid approach of these methods was implemented.

EXPERIMENTAL

Materials

Poplar (*Populus alba* L.) wood specimens were obtained from forest product companies in İstanbul, Turkey. The mean age of the trees was 23 years, and diameter at breast height was 35 cm. Defect-free test samples were sized in dimensions of 20 mm × 20 mm × 30 mm and 20 mm × 20 mm × 300 mm. Heat treatment was carried out in a laboratory-scale oven at 120, 150, 180, and 210 °C for 2 and 4 h. Samples were kept in a conditioning chamber until 12% moisture content was reached.

Methods

Heat treatments were conducted in a temperature-controlled small heating unit. Three different temperatures (120, 150, 180, and 210 °C) and two durations (2 and 4 h) were applied to specimens under atmospheric pressure (O_2). After heat treatment, treated and untreated samples were conditioned at 20 ± 2 °C and 65 ± 5% relative humidity (RH). Prior to the tests, the dimensions were measured by digital calliper (resolution: 0.001 mm) and their weights were recorded by digital weight scale (accuracy: 0.001 g).

Tests of bending strength, compression strength, modulus of elasticity, shrinkage, and swelling were carried out based on related Turkish Standards (TS) 2474 (1976), TS 2478 (1976), TS 2495 (1976), TS 4083 (1976) and TS 4084 (1982), respectively

After obtaining experiment results (see Tables 1 and 2), entropy and TOPSIS methods were employed. To be able to use the mentioned methods, a decision matrix is needed. A decision matrix is composed of rows and columns that allow the evaluation of the alternatives relative to multiple decision criteria (Chang 2015). In the matrix (Table 3), the criteria are listed in the first row, while the alternatives are listed in the first column. Whilst the entropy method was used to calculate the importance level (weights) of experiment criteria, TOPSIS method was adopted to rank the experiment samples.

Entropy is one of the objective weighting methods (Zhou *et al*. 2016). It is based on Shannon Entropy, developed by Shannon (1948). Entropy is a simple yet effective technique for determining the weights of evaluation criteria in a MCDM problem (Ouyang *et al*. 2014). It presents no serious modelling difficulties and makes decision making more accurate and certain (Song *et al*. 2017). The steps of entropy method can be summarized simply as: 1) Construct a decision matrix, 2) Normalize the decision matrix, 3) Calculate the entropy value for each evaluation criterion, 4) Compute the weight vector for all evaluation criteria.

The executed calculations in the Results and Discussion are based on the algorithm given in Zhou *et al*. (2016). According to evaluation indexes that are the maximal index or minimal index, the standardization of the indexes is calculated and shown. After calculation of the weights with Entropy, TOPSIS method was used for ranking the alternatives. The steps of TOPSIS method can be listed simply as: 1) Construct a decision matrix, 2) Normalize the decision matrix, 3) Determine the weighted decision matrix, 4) Determine ideal and negative-ideal solutions, 5) Calculate the distance, 6) Calculate the relative degree of approximation, 7) Ranking (The executed calculations in results and discussion are based on the algorithm given in Li *et al*. 2011; for details see therein).

RESULTS AND DISCUSSION

Physical Properties

Table 1 shows the changes in the shrinkage and swelling ratios of poplar wood at varying treatment temperature and durations. The heat treatment process diminished the magnitudes of dimensional changes of poplar wood, according to the conditions employed in the shrinkage and swelling tests. The lowest shrinkage ratio obtained was after wood heat treatment at 210 °C for 4 h (9.65 %), where the total decrease compared to the control was 28.72%. Similarly, the lowest swelling ratio resulted was after treatment at 210 °C for 4 h (10.25 %); total decrease compared with the control was 34.16%.

Table 1. Shrinkage and Swelling Ratios of Heat Treated Poplar Samples

ID	Samples		Shrinkage (%)		Swelling (%)	
			Mean	SD	Mean	SD
O	Control		13.54	0.047	15.57	0.017
A	120 °C	2 h	12.87	0.019	14.80	0.027
B		4 h	12.58	0.019	14.47	0.023
C	150 °C	2 h	12.44	0.011	14.30	0.015
D		4 h	12.13	0.018	13.95	0.013
E	180 °C	2 h	11.94	0.014	13.73	0.031
F		4 h	11.21	0.016	12.90	0.017
G	210 °C	2 h	10.87	0.021	11.76	0.028
H		4 h	9.65	0.032	10.25	0.025

These findings are consistent with other studies; for example, Korkut and Guller (2008) stated that the swelling rates of red bud maple (*Acer trautvetteri* Medw.) wood decreased with increasing treatment temperature and duration. In addition, Yang *et al*. (2016) found similar results with the Japanese cedar (*Dryptomeria japonica*) wood. They found that the dimensional stability of the Japanese cedar wood was improved in response to increasing temperatures and long periods. The researchers attributed this to the reduction in the amounts of hydroxyl groups of wood during heat treatment. Improvement in dimensional stability properties can be explained by the heat degradation rate and loss of subsequent heat treatments. The improvement in dimensional stability is mainly due to the depolymerization of wood polymers (Kotilainen *et al*. 2000). The change in dimensional stability is due to the breakdown of hemicelluloses, which are less heat resistant than cellulose and lignin. Change or loss of hemicelluloses is important in the dimensional stability properties of wood heated at high temperatures (Hillis 1984).

Mechanical Properties

Table 2 displays results of compression strength, bending strength, and MOE for the control and heat-treated wood samples for combinations of temperature and duration. The heat treatment process generally decreased the compression strength, bending strength, and modulus of elasticity (MOE) of poplar wood. The lowest compressive strength determined was at 210 °C for 4 h; the total decrease was 21.63%. Similarly, the lowest bending strength and MOE was at 210 °C for 4 h; the total decrease compared with control samples was 46.27 and 28.10%, respectively.

Table 2. Compression Strength, Bending Strength, and Modulus of Elasticity of Heat Treated Poplar Samples

ID	Samples		Compression Strength (MPa)		Bending Strength (MPa)		Modulus of Elasticity (MOE) (MPa)	
			Mean	SD	Mean	SD	Mean	SD
O	Control		54.17	4.31	69.00	11.7	10231.0	1477.43
A	120 °C	2 h	59.10	5.54	66.47	13.74	9659.8	967.88
B		4 h	61.97	4.73	62.28	8.18	9333.4	774.43
C	150 °C	2 h	59.55	5.08	62.29	5.93	9040.4	374.72
D		4 h	59.26	5.62	60.74	11.74	8763.8	501.68
E	180 °C	2 h	58.11	5.58	54.62	8.01	8745.4	621.93
F		4 h	57.62	3.98	52.56	4.83	8695.9	302.65
G	210 °C	2 h	50.74	6.73	41.99	8.98	7587.9	741.88
H		4 h	42.45	11.29	37.07	10.05	7355.6	888.94

The primary reason for the loss of mechanical strength is the degradation of hemicelluloses. Hemicellulose losses play a key role in the mechanical strength properties of wood heated at high temperatures (Hillis 1984; Gündüz *et al*. 2009). Esteves and Pereira (2009) reported that the modulus of elasticity (MOE) increases for moderate heat treatments and decreases for more severe heat treatments. The decreases in the mechanical properties can be explained by the rate of thermal degradation and losses in or changes of substance after heat treatments. Percin *et al.* (2016) studied the effect of heat treatment on some physical and mechanical properties of beech wood. The higher temperature and duration of heat treatment clearly decreased bending strength and modulus of elasticity in bending. Kamdem *et al.* (2002) reported that bending strength values of the heat-treated samples showed a declining trend as the treatment temperature and duration were increased. The loss of strength may be attributed to embrittlement of fibers.

Table 3. Decision Matrix

	Compression Strength (N/mm^2)	Bending Strength (N/mm^2)	Modulus of Elasticity (MOE) (N/mm^2)	Shrinkage (%)	Swelling (%)
O	54.17	89.00	10231.0	13.5	15.6
A	59.10	86.47	9659.8	12.87	14.80
B	61.97	82.28	9333.4	12.58	14.47
C	59.55	82.29	9040.4	12.44	14.30
D	59.26	80.74	8763.8	12.13	13.95
E	58.11	74.62	8745.4	11.94	13.73
F	57.62	72.56	8695.9	11.21	12.90
G	50.74	41.99	7587.9	10.87	11.76
H	42.45	37.07	7355.6	9.65	10.25

According to the results, the decision matrix was formed as shown in Table 3. O, A, B, C, D, E, F, G, and H symbolize respectively the samples as: the control, 120 °C for 2 h, 120 °C for 4 h, 150 °C for 2 h, 150 °C for 4 h, 180 °C for 2 h, 180 °C for 4 h, 210 °C for 2 h, and 210 °C for 4 h. To rank the alternatives, determination of the criteria weights is necessary. Therefore, the calculations first started with entropy method. According to the evaluation indexes the standardization of the indexes was calculated and shown by the index below. The weights of indexes were calculated and shown in Table 4.

$$Rij = \begin{bmatrix} 0.10770 & 0.13755 & 0.12883 & 0.09690 & 0.09511 \\ 0.11751 & 0.13365 & 0.12164 & 0.10191 & 0.10002 \\ 0.12321 & 0.12717 & 0.11753 & 0.10424 & 0.10232 \\ 0.11841 & 0.12718 & 0.11384 & 0.10546 & 0.10351 \\ 0.11781 & 0.12479 & 0.11036 & 0.10814 & 0.10614 \\ 0.11553 & 0.11532 & 0.11013 & 0.10983 & 0.10780 \\ 0.11457 & 0.11215 & 0.10950 & 0.11695 & 0.11479 \\ 0.10088 & 0.06490 & 0.09555 & 0.12066 & 0.12588 \\ 0.08439 & 0.05730 & 0.09262 & 0.13591 & 0.14443 \end{bmatrix}$$

Table 4. Calculated Index Weights

	Compression Strength (N/mm^2)	Bending Strength (N/mm^2)	Modulus of Elasticity (MOE) (N/mm^2)	Shrinkage (%)	Swelling (%)
Wj	0.0927	0.6029	0.0825	0.0833	0.1387

According to the calculations, the "bending strength" was the most important criterion by far. Thus, the heat treatment may have significant effect on bending strength of the wood. On the basis of importance levels, other criteria were identified as swelling, compression strength, shrinkage, and modulus of elasticity. In particular, shrinkage and modulus of elasticity criteria have very close weight values. This situation could be interpreted as these two criteria are almost equally important.

After the calculation of weights, TOPSIS method was employed for ranking the test samples. Based on the data at Table 3, the normalized decision matrix is given below.

$$Rij = \begin{bmatrix} 0.32144 & 0.40031 & 0.38466 & 0.37707 & 0.38112 \\ 0.35072 & 0.38894 & 0.36319 & 0.35853 & 0.36238 \\ 0.36773 & 0.37009 & 0.35091 & 0.35049 & 0.35426 \\ 0.35340 & 0.37013 & 0.33990 & 0.34647 & 0.35019 \\ 0.35163 & 0.36315 & 0.32950 & 0.33787 & 0.34150 \\ 0.34480 & 0.33561 & 0.32881 & 0.33266 & 0.33623 \\ 0.34194 & 0.32637 & 0.32695 & 0.31242 & 0.31578 \\ 0.30109 & 0.18888 & 0.28529 & 0.30281 & 0.28794 \\ 0.25188 & 0.16674 & 0.27656 & 0.26883 & 0.25097 \end{bmatrix}$$

The weighted decision matrix was calculated, and the obtained ideal and negative ideal solutions are given below. The distance of every possible solution from the ideal solution and negative ideal solution was calculated. The relative degree of approximation was obtained. The ranking of test samples is according to the relative degree of approximation and is shown in Table 5.

$$Vij = \begin{bmatrix} 0.02978 & 0.24135 & 0.03172 & 0.03141 & 0.05285 \\ 0.03250 & 0.23450 & 0.02995 & 0.02986 & 0.05025 \\ 0.03407 & 0.22313 & 0.02894 & 0.02919 & 0.04912 \\ 0.03275 & 0.22316 & 0.02803 & 0.02886 & 0.04856 \\ 0.03258 & 0.21895 & 0.02717 & 0.02814 & 0.04735 \\ 0.03195 & 0.20234 & 0.02712 & 0.02771 & 0.04662 \\ 0.03168 & 0.19677 & 0.02696 & 0.02602 & 0.04379 \\ 0.02790 & 0.11388 & 0.02353 & 0.02522 & 0.03993 \\ 0.02334 & 0.10053 & 0.02281 & 0.02239 & 0.03480 \end{bmatrix}$$

$$V^{+} = \left(0.03407,\ 0.24135,\ 0.03172,\ 0.02239,\ 0.03480\right)$$

$$V^{-} = \left(0.02334,\ 0.10053,\ 0.02281,\ 0.03141,\ 0.05285\right)$$

Table 5. TOPSIS Results and Evaluation of Ranks

ID	Sample	S+	S-	c*	Evaluation rank
O	Control	0.02063	0.14125	0.8725842	2
A	120 °C and 2 h	0.01863	0.1345	0.8783331	1
B	120 °C and 4 h	0.02432	0.1233	0.8352714	4
C	150 °C and 2 h	0.02403	0.1232	0.8367679	3
D	150 °C and 4 h	0.02675	0.11903	0.8165139	5
E	180 °C and 2 h	0.04142	0.10252	0.7122533	6
F	180 °C and 4 h	0.04593	0.09726	0.6792287	7
G	210 °C and 2 h	0.12802	0.02012	0.1357924	8
H	210 °C and 4 h	0.14151	0.02017	0.1247769	9

Notes: S+ represents the distance of the alternative from the ideal solution. S- represents the distance of the alternative from the negative ideal solution. c* represents the success of the alternative.

Compared with the control sample, a slight improvement was recognized in the properties of the sample A, which was subjected to heat treatment at 120 °C for 2 h. In this case, the heat treatment provides an overall improvement in the properties of the wood. However, when results are examined in detail, especially after 150 °C, the physical and mechanical properties of the wood diminish. If either the duration or the temperature goes up to 4 h or 180 °C, the decrease becomes drastic. Thus, according to the present work, heat treatment above 150 °C or 4 h is not recommended.

The properties of samples that ranked 3rd (C) and 4th (B), and which were subjected to thermal modification at 150 °C for 2 h and at 120 °C for 4 h, are quite similar. In this case, if there are any time constraints, the thermal modification at 150 °C for 2 h is recommended. However, if there are any concerns about temperature the application of thermal modification at 120 °C for 4 h is recommended.

The main purpose of heat treatment is to improve the physical properties of wood. However, unfortunately this improvement causes the mechanical properties to decrease. The same circumstance exists in the present study. The decrease is acceptable up to a point. In the present work, both 120 and 150 °C were found as the optimum degrees for the application, and higher temperatures are not recommended. Considering the general situation, regardless of temperature application for 2 h has given better results. Thus, if there is no necessity, longer applications are not recommended.

A comprehensive literature review revealed that many studies have been conducted to reveal the effect of the heat treatment process on the basic performance of wood (Ates *et al.* 2009; Yang *et al.* 2016; Zhang *et al.* 2017). When these studies were examined, it was found out that the variety of experimental design and performance tests were determined by considering the effects that the wood is exposed to in the place of use. When the place of use performance requirements of wood are researched, it is possible to say that basic tests such as bending strength, modulus of elasticity, compression strength, shrinkage, and swelling are generally adequate to evaluate multiple criteria regarding the competence of the place of use. Therefore, based on the literature, the above-mentioned tests were used as the determinants to evaluate the success of heat treatment and identify the optimum parameters.

CONCLUSIONS

1. Heat treatment affected physical and mechanical properties of the poplar (*Populus alba*) wood. Shrinkage and swelling ratios of the heat-treated wood samples decreased with increasing treatment temperature and duration, and their minimum values were obtained in samples treated at 210 °C for 4 h.
2. Compression strength, bending strength, and modulus of elasticity (MOE) of the heat-treated wood decreased with increasing treatment temperature and duration.
3. The multi-criteria decision-making approach is convenient to be employed in studies that focus on physical and mechanical characteristics of wood.
4. According to Multi-Criteria Decision-Making (MCDM) techniques, thermal modification improves the physical properties of wood up to a point.
5. Bending strength was the determinant that most affected the success of heat treatment. The other determinants were swelling, compression strength, shrinkage, and modulus of elasticity.
6. Based on a multi-criteria analysis, the best results were obtained at 120 °C for 2 h. However, heat treatment above 150 °C or 4 h is not recommended.
7. Increasing the number of MCDM applications on related fields can be useful for a comparative analysis of the results obtained in subsequent heat treatment studies.

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