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# The Evaluation of Tree Bark as Filler for Wood-Plastic Composites: Experimental Study and Modelling

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***Research Article***

**Abstract** − Tree bark is one of the waste materials produced during harvesting. In this study, tree bark was evaluated for the production of WPCs. Three tree barks (Oak, Calabrian pine, and Cedar) were added to the matrix as an alternative for wood flour (20-80 mesh). Different tree bark content (10, 20, 40%) were also selected. The tree bark-based WPCs were produced with the flat-pressed method. The effect of tree bark on water absorption (WA) and thickness swelling (TS) were investigated during the 14 days. Tree barks have a significant effect on the WA and TS properties of the composites. As the bark content increased, the WA and TS values decreased. While the WA values increased up to 11.27% for control samples, it is only 3.27% for 40% of tree bark. Similar results were also observed for TS values. Also, the prediction models were developed using multiple linear regression (MLR). Correlation coefficient (R2) values of models were determined as 0.882, 0.853, and 0.850 for oak, Calabrian pine, and cedar WA values and 0.889, 0.839, and 0.879 for oak, Calabrian pine, and cedar TS values, respectively. The results showed that tree bark has the potential as an alternative to wood flour for WPC production.

***Keywords** – Tree bark, regression model, water absorption, thickness swelling*

# Ağaç kabuklarının Dolgu Maddesi Olarak Odun Plastik Kompozitlerinde Değerlendirilmesi: Deneysel Çalışma ve Modelleme

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***Araştırma Makalesi***

**Öz** − Ağaç kabuğu üretim sırasında oluşan atık malzemelerden biridir. Bu çalışmada ağaç kabuğu OPK üretiminde değerlendirilmiştir. Odun ununa alternatif olarak matrise üç ağaç kabuğu (Meşe, Kızılçam ve Sedir) eklenmiştir. Farklı ağaç kabuğu oranları da (%10, 20, 40) seçilmiştir. Ağaç kabuğu bazlı OPK'lar düz presleme yöntemiyle üretilmiştir. Ağaç kabuğunun su alma (WA) ve kalınlığa şişme (TS) üzerine etkisi 14 gün boyunca incelenmiştir. Ağaç kabuklarının kompozitlerin WA ve TS özellikleri üzerinde önemli bir etkisi vardır. Kabuk içeriği arttıkça WA ve TS değerleri azalmıştır. WA değerleri kontrol örneklerinde %11.27'ye kadar yükselirken, %40 ağaç kabuğunda bu oran sadece %3.27'dir. Benzer sonuçlar TS değerleri için de gözlenmiştir. Ayrıca tahmin modelleri çoklu doğrusal regresyon (MLR) kullanılarak geliştirilmiştir. Modellerin korelasyon katsayısı (R2) değerleri meşe, kızılçam ve sedir WA değerleri için sırasıyla 0.882, 0.853 ve 0.850, meşe, kızılçam ve sedir TS değerleri için ise 0.889, 0.839 ve 0.879 olarak belirlenmiştir. Sonuçlar, ağaç kabuğunun OPK üretimi için odun ununa alternatif olma potansiyeline sahip olduğunu göstermiştir.

***Anahtar Kelimeler** – Ağaç kabuğu, regresyon modelleme, su alma, kalınlığa şişme*

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## 1. Introduction

Composites are composed of two or more components, which provide advantages to manufacturers due to the ability to evaluate different materials in production (Kim and Pal, 2010). The combination of various properties of components gains new materials with superior properties. Moreover, not just raw materials but also waste materials can be used in production, allowing manufacturers to struggle with the raw material shortage. Today, the rapid population increase in the world forces manufacturers to search for raw materials for sustainable production.

Wood plastic composites (WPCs) are one of the wood-based composites. They have been evaluated in various applications in recent years, such as decking, fences, siding, furniture, etc. (Durmaz et al., 2023; Xu et al., 2017). One of WPCs' main components is plastic, a petroleum-based polymer. However, increased environmental concerns have increased pressure on plastic consumption. Combining plastic and lignocellulosic relatively makes WPCs environmentally friendly as well as being gained to green label, which is vital for preference of products for customers. Moreover, the production cost decreases with adding lignocellulosic material (Satyanarayana et al., 2009). Meanwhile, wood is one of the most preferred lignocellulosic materials for WPC production.

The threat against global warming is gradually increasing due to the effect of greenhouse gas emissions in recent years. $CO_2$ emissions are only consisted of 58.8% of greenhouse gas emissions (Al Mamun et al., 2014). Therefore, developing materials inspired by nature can increase the wood industry's usage and help decrease the pressure on the environment with environmentally friendly designs for construction and packing (Busquets, 2023).

Tree bark is one of the waste biomaterials that form up to 15% of trees, a significant material for production (Kofujita et al., 1999; Sjostrom, 1993). However, it is mainly left to decay in the forest after harvesting, while it is sometimes burned to obtain energy (Durmaz et al., 2016; Wenig et al., 2021). In Turkey, more than 31 million $m^3$ of wood was produced in 2022 (OGM, 2022). Twenty-five million was for industrial production. Considering this was a massive production, vast amounts of tree bark were left or burned. The main cell wall composition of tree bark makes the evaluation complicated, as the extractive content of tree bark is very high compared to wood, while cellulose is lower. Meanwhile, the potential of tree bark as a lignocellulosic material is significant for manufacturers. However, the chemical difference between wood and bark decreases the technological properties of composites, especially mechanical properties. Moreover, tree bark's hydrophobic character limits water penetration, which is significant for outdoor applications. Avcı et al. (2018) stated that tree bark improved the TS and WA values of WPCs due to the hydrophobic components of barks. However, there is a decrease in the mechanical properties. Najafi et al. (2018) also highlighted that composites containing a high content of tree bark were less hygroscopic.

Tree bark has the potential as a raw material for wood-based panels as well as their controversy (Sahin and Arslan, 2011). As in previous studies, various tree barks have been evaluated as filling material in adhesive (Ndiwe et al., 2019; Pandet and Plant, 2023), particleboard (Christy et al., 2020), thermal insulation boards (Gößwaldet al., 2021; Pásztory and Novotní, 2020), and also polymer-based composites (Yemele et al., 2010; Borysiuk et al., 2021).

Researchers often work with limited data when solving a problem, so methods that can predict intermediate values are needed. Modeling, in its simplest form, refers to predicting an independent variable, which is the output of a problem, using dependent variable(s) or variable(s) that affect the output. One of the simplest methods used for this purpose is regression models. In many contemporary problems, there are two or more independent variables. In such cases, multiple linear regression models (MLRs) should be used instead of simple regression models (Nimon and Oswald, 2013).

This study investigated the evaluation of tree barks in the production of WPCs. For this purpose, three tree barks (Oak, Calabrian pine, and Cedar) were selected as an alternative for wood flour. Tree barks with different content (10, 20, 40%) were added to the matrix. The flat-pressed method was used for production. The effects of tree barks on WPCs' physical properties (WA, TS) were investigated during the 14 days. The prediction models were also developed using MLR.

## 2. Material and Method

### 2.1. Materials

The pine wood flour (*Pinus sylvestris* L.) was used as wood flour with dimensions of between 20-80 mesh in this study. Three different tree bark, Cedar (*Cedrus libani* L.) Calabrian pine (*Pinus brutia* L.) and oak (*Quercus pontica* L.) were selected as alternatives for wood flour. The dimensions of tree bark were between 20-80 mesh. The low density of polyethylene (LDPE) was used as a thermoplastic polymer in this study. The polymer's density and melt flow index (MFI) were 0.919 g/cm$^3$ and 22 g/10 min (190°C/2.16 kg), respectively. The maleated anhydride grafted polyethylene (MAPE) (Licocene PE MA 4351 Fine Grain) was used as a coupling agent in all groups due to decreasing incompatibility between the WPC's components. The density was 0.99 g/cm$^3$.

### 2.2. Methods

The wood flour and tree bark were oven-dried before the production at 80ºC under the 2% moisture content. The wood flour and tree bark were mixed with a mechanical mixer at 1200 rev/min and then rotary drum blender at 30 rev/min for 5 min, according to Table 1. The mixture was laid on the aluminum plate with dimensions of 500x500x4 mm$^3$. The draft was pressed at 170ºC with a pressure of 100 bar for 15 min. The boards were removed from the press after the cooling. The panels were conditioned according to the ASTM D618-21.

Tablo 1

The wood flour, tree bark, and polymer content

| Groups | LDPE (%) | Wood Flour (%) | Tree Bark (%) | MAPE (%) |
|---|---|---|---|---|
| LDPE | 98 | - | - | |
| Control | 58 | 40 | - | |
| Cedar | 58 | 30 | 10 | |
| | 58 | 20 | 20 | |
| | 58 | - | 40 | |
| Oak | 58 | 30 | 10 | 2 |
| | 58 | 20 | 20 | |
| | 58 | - | 40 | |
| Calabrian pine | 58 | 30 | 10 | |
| | 58 | 20 | 20 | |
| | 58 | - | 40 | |

### 2.3. Water absorption and thickness swelling

The WA and TS values of WPCs were determined according to ASTM D570-98. The samples with dimensions of 50 × 50 × 4 mm were entirely soaked in the water at 20°C ± 1°C. The samples' surfaces were then cleaned and dried. The measurements for WA and TS were recorded at one day, three days, seven days, and 14 days. Five replications were taken for each group.

### 2.4. Multiple Linear Regression

A multiple linear regression model was used to develop prediction models. The general formula of the MLR is given in Equation 1;

$$y=a_0+b_1x_1+b_2\,x_2+\cdots+b_n\,x_n \quad (1)$$

where y is the dependent variable and $x_1,x_2,\ldots,x_n$ are the independent variables of problems.

In the study, 6 prediction models were developed using MLR, in total. To develop MLR models, wood and bark content rate (%) and exposure time (days) were used as independent variables, while WA and TS values of oak, Calabrian pine, and cedar were used as dependent variables, respectively.

The performance of models was evaluated Correlation coefficient (R2) using Equation 2;

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(e_i - p_i)^2}{\sum_{i=1}^{n}(p_i - p_m)^2} \quad (2)$$

where, e is the experimental result, p is the prediction result, p_m is the mean of the prediction results and n is the number of samples.

### 2.5. Statistical Analysis

The variance analysis was performed at a level of 0.05 to determine the differences between the factors of tree bark type, tree bark ratio, and exposure time.

## 3. Results and Discussion

### 3.1. WA and TS of WPCs

Wood flour, one of the other main components of WPCs, is sensitive to water due to its hydrophilic structure (Vercher et al., 2020). The effect of tree bark on WA and TS as an alternative to wood flour on the WPCs was investigated. The WA and TS values with statistical data were also given in Table 2-7. The WA values increased with increasing exposure time. However, there is nearly no change for the neat-LDPE due to the hydrophobic character of the polymer. On the other hand, the highest WA value was obtained from the control sample (wood-containing). The water molecules bind the -OH groups in the wood fiber structure, which absorb the water. Meanwhile, WA values showed that the increase in the tree bark content in the matrix improved the resistance against water absorption. The suberin in the tree bark structure makes it more hydrophobic, limiting water absorption (Giannotas et al., 2021). Similarly, Avcı et al. (2018) stated that suberin is crucial in WA for WPCs. As in previous studies, the lower holocellulose content in wood affects -OH groups, primarily found in the amorphous structure of hemicellulose and cellulose, increasing or decreasing the WA (Durmaz et al., 2016).

According to statistical analysis, tree bark type, ratio, and exposure time were the main factors related to WA and were statistically significant ($p<0.05$). The lowest WA values were obtained from WPCs containing 40% Calabrian pine tree bark, depending on the variance test. The WA values increased with increasing exposure time. The WA values were higher for the control group than WPCs containing tree bark.

Tablo 2
WA values of WPCs.

| Group | Wood/Bark/LDPE Content (%) | Exposure time (days) | | | |
|---|---|---|---|---|---|
| | | 1 | 3 | 7 | 14 |
| Control | 0/0/100 | 0.14 | 0.20 | 0.20 | 0.26 |
| | 40/0/60 | 2.34 | 5.03 | 7.82 | 11.27 |
| Cedar | 30/10/60 | 1.87 | 4.42 | 8.12 | 11.16 |
| | 20/20/60 | 1.42 | 3.70 | 6.36 | 8.00 |
| | 0/40/60 | 1.04 | 3.24 | 4.60 | 5.63 |
| Oak | 30/10/60 | 2.26 | 4.22 | 6.28 | 9.56 |
| | 20/20/60 | 1.65 | 3.70 | 6.77 | 8.24 |
| | 0/40/60 | 0.78 | 1.86 | 3.18 | 4.03 |
| Calabrian pine | 30/10/60 | 1.43 | 4.20 | 7.29 | 10.69 |
| | 20/20/60 | 1.14 | 2.24 | 4.40 | 6.58 |
| | 0/40/60 | 0.58 | 0.80 | 2.20 | 3.27 |

Tablo 3
Multifactorial ANOVA analysis of variance for WA values of day and bark type ($p<0.05$).

| Source | Degrees of Freedom (DF) | Adjusted Sums of Squares (Adj SS) | Adjusted Means of Squares (Adj MS) | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Bark types (A) | 2 | 45.300 | 22.650 | 85.991 | 0.000 |
| Bark ratio (B) | 2 | 340.759 | 170.379 | 646.850 | 0.000 |
| Day (C) | 3 | 822.384 | 274.128 | 1040.734 | 0.000 |
| A*B | 4 | 24.966 | 6.241 | 23.696 | 0.000 |
| A*C | 6 | 9.639 | 1.607 | 6.099 | 0.000 |
| B*C | 6 | 110.614 | 18.436 | 69.991 | 0.000 |
| A*B*C | 12 | 13.769 | 1.147 | 4.356 | 0.000 |

Tablo 4
Tukey test homogeneity groups of variables related to WA values.

| Bark Type | | Bark ratio (%) | | Days | |
|---|---|---|---|---|---|
| LDPE | 0.2030 **a** | 0 (LDPE) | 0.2030 **a** | 1 | 1.3131 **a** |
| WPC40 | 6.6165 **e** | 0 (WPC40) | 6.6165 **e** | 3 | 3.0571 **b** |
| Red Pine | 3.7347 **b** | 10 | 5.9595 **d** | 7 | 5.2004 **c** |
| Quercus | 4.3787 **c** | 20 | 4.5165 **c** | 14 | 7.1544 **d** |
| Cedar | 4.9630 **d** | 40 | 2.6003 **b** | | |

Similar results were obtained for TS of WPCs, as seen in Table 5. The exposure time increased the TS values. There is nearly no change in the TS of neat-LDPE. However, the TS values significantly increased with increasing time for control samples (wood-containing). The addition of tree bark to the matrix resulted in a decrease in TS values. The lowest TS values were obtained from the highest tree bark content. As stated above, suberin gained tree bark hydrophobic character. The lowest TS values were obtained from WPCs containing 40% oak tree bark. The decrease in WA and TS values is vital for outdoor applications. The hygroscopic nature of lignocellulosic fibers results in changing the dimensions of composites, which causes degradation of materials at the end. However, tree barks indicate superiorities compared to wood flour in this aspect.

Tablo 5
TS values of WPCs.

| Group | Wood/Bark/LDPE Content (%) | Exposure time (days) | | | |
|---|---|---|---|---|---|
| | | 1 | 3 | 7 | 14 |
| Control | 0/0/100 | 0.24 | 0.33 | 0.57 | 0.65 |
| | 40/0/60 | 2.35 | 3.65 | 4.49 | 5.34 |
| Cedar | 30/10/60 | 2.09 | 3.34 | 3.68 | 4.73 |
| | 20/20/60 | 1.20 | 2.65 | 3.28 | 3.63 |
| | 0/40/60 | 0.67 | 1.16 | 1.34 | 1.64 |
| Oak | 30/10/60 | 1.71 | 3.26 | 3.41 | 4.27 |
| | 20/20/60 | 1.39 | 2.64 | 2.99 | 3.34 |
| | 0/40/60 | 0.20 | 0.47 | 0.68 | 0.94 |
| Calabrian pine | 30/10/60 | 1.73 | 3.39 | 4.08 | 4.43 |
| | 20/20/60 | 0.92 | 1.48 | 1.97 | 2.61 |
| | 0/40/60 | 0.21 | 0.48 | 0.90 | 1.10 |

Tablo 6
Multifactorial ANOVA analysis of variance for TS values of the day and bark type ($p<0.05$).

| Source | Degrees of Freedom (DF) | Adjusted Sums of Squares (Adj SS) | Adjusted Means of Squares (Adj MS) | *F*-value | *P*-value |
|---|---|---|---|---|---|
| Bark types (A) | 2 | 8.080 | 4.040 | 17.128 | 0.000 |
| Bark ratio (B) | 2 | 194.394 | 97.197 | 412.090 | 0.000 |
| Day (C) | 3 | 81.833 | 27.278 | 115.650 | 0.000 |
| A*B | 4 | 8.275 | 2.069 | 8.711 | 0.000 |
| A*C | 6 | 0.680 | 0.113 | 0.480 | 0.822 |
| B*C | 6 | 13.165 | 2.194 | 9.303 | 0.000 |
| A*B*C | 12 | 2.451 | 0.204 | 0.866 | 0.583 |

Tablo 7
Tukey test homogeneity groups of variables related to TS values.

| Bark Type | | Bark ratio (%) | | Days | |
|---|---|---|---|---|---|
| LDPE | 0.4485 **a** | 0 (LDPE) | 0.4485 **a** | 1 | 1.1551 **a** |
| WPC40 | 3.9605 **d** | 0 (WPC40) | 3.9605 **e** | 3 | 2.0773 **b** |
| Red Pine | 1.9405 **b** | 10 | 3.3430 **d** | 7 | 2.4893 **c** |
| Quercus | 2.1082 **b** | 20 | 2.3400 **c** | 14 | 2.9707 **d** |
| Cedar | 2.4497 **c** | 40 | 0.8153 **b** | | |

According to statistical analysis, tree bark type, ratio, and exposure time were the main factors related to TS and were statistically significant ($p<0.05$). Depending on the variance test, the lowest TS values were obtained from WPCs containing 40% Calabrian pine and Oak tree bark. The resinous materials and tannin could improve the WA and TS values of WPCs containing Calabrian pine and Oak tree bark (Nemli, 2005; Nemli et al., 2006). Meanwhile, Hafızoğlu and Usta (2005) investigated the 15 tree's bark and wood chemical composition. According to the findings, the bark's cellulose and lignin content were nearly similar. However, the solubilities of barks in different solvents were different due to varying the extractive's content and constituents depending on the tree type. The variability could be effective on WA and TS values in wood-based composites. Additionally, the TS values increased with increasing exposure time. The control group's TS values were higher than WPCs containing tree bark.

### 3.2. Prediction Modelling

Developed models to predict WA values of cedar, oak and Calabrian pine were given Equations 3-5, respectively.

$$WA_{Cedar} = 3.917 - 0.088\ WBR + 0.495\ ET \quad (3)$$

$$WA_{Oak} = 4.258 - 0.108\ WBR + 0.422\ ET \quad (4)$$

$$WA_{Calabrian\ pine} = 4.108 - 0.133\ WBR + 0.437\ ET \quad (5)$$

Developed models to predict TS values of cedar, oak, and Calabrian pine were given Equation 6-8. respectively.

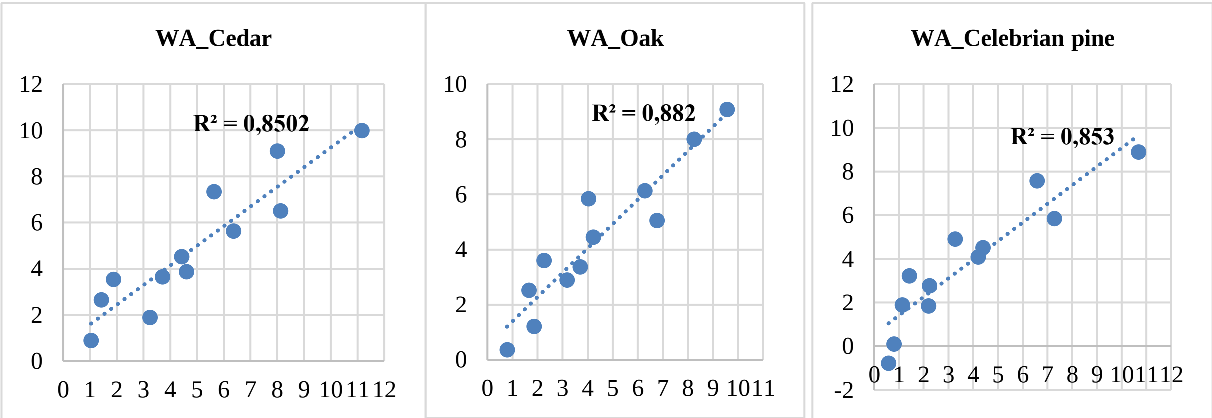
$$TS_{Cedar} = 3.666 - 0.075\ WBR + 0.134\ ET \quad (6)$$

$$TS_{Oak} = 3.464 - 0.088\ WBR + 0.113\ ET \quad (7)$$

$$TS_{Calabrian\ pine} = 3.186 - 0.086\ WBR + 0.121\ ET \quad (8)$$

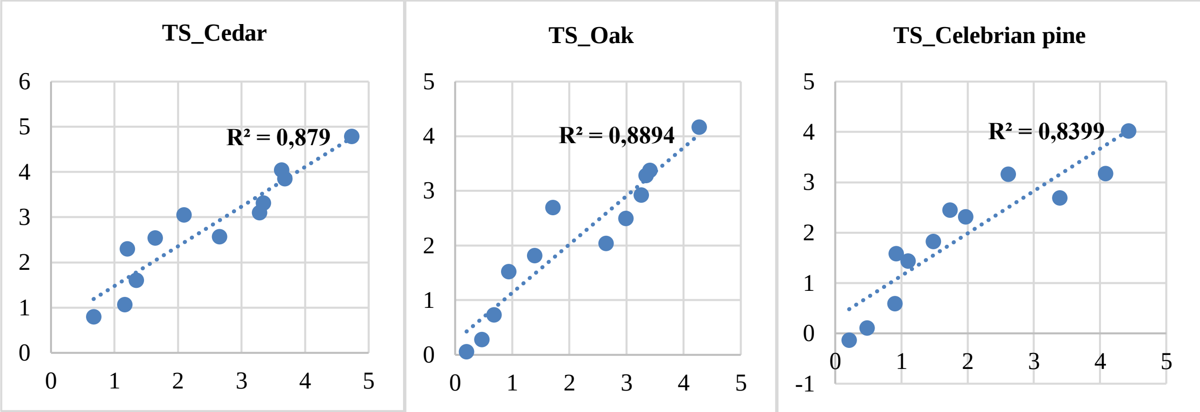
where WBR was the wood&bark rate (%), and ET was the exposure time (days).

The $R^2$ is a measure that indicates the strength of the relationship between the dependent variable and the independent variables. This value varies between 0 and 1, increasing as the accuracy of the model improves. $R^2$ graphs of studied parameters were given in Figures 1 and 2, respectively.




(a) (b) (c)

Figure 1. Correlation coefficient ($R^2$) graphs of WA values of Cedar (a), Oak (b), Celebrian pine (c)




(a) (b) (c)

Figure 2. Correlation coefficient ($R^{2)}$ graphs of TS values of Cedar (a), Oak (b), Celebrian pine (c)

$R^2$ values of developed models were calculated at 0.850, 0.882, and 0.853 of models developed to predict WA values of cedar, oak, and Calabrian pine, while 0.879, 0.889, and 0.839 of models developed to predict TS values of cedar, oak and Calabrian pine, respectively.

## 4. Conclusion

It is well-known that the differentiation in wood and tree bark structure limits its usability. However, the raw material shortage increases the pressure on the manufacturer. This study investigated the potential of tree bark as an alternative to wood flour for WPC production. The different bark content was selected and added to the matrix instead of wood flour. The effect of tree bark on TS and WA was investigated. As the tree bark content increased, the WA and TS values decreased. The highest WA value of 11.27% was obtained from the control sample (wood-containing), while the lowest of 3.27% was WPCs containing 40% of Calabrian pine. Similarly, the highest TS value of 5.34% was obtained from the control sample (wood-containing), while the lowest of 0.94% was from WPCs containing 40% of oak. As stated above, it can be stated that the suberin in the tree bark structure may have improved the WA and TS values. Additionally, resinous materials and tannins may have also had an impact on increased water resistance. Meanwhile, it is also stated that the chemical structure of tree bark can be changed depending on edaphic, climatic, physiographical, and biotic factors, which cause the results to differ due to having a non-homogeneous structure. After experimental studies, prediction models were developed using the experimental data through the MLR method. The R2 values were calculated to assess the predictive capability of the developed models. R2 values of developed MLRs were varied between 0.839 and 0.889. The differences in the R2 values of the models vary depending on the tree type and the conducted analysis. Therefore, it has been observed that the prediction capabilities of all established models are high. These results indicate that tree bark has a potential for usability instead of wood flour, especially outdoors.

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## Authors Contributions

Emre AKSOY: The study was planned and produced.

Sefa DURMAZ: The study was planned and wrote the article.

Ayşenur GÜRGEN: The data modelled and analyzed.

Uğur ARAS: The data analyzed statistically.

**Conflict of Interest**

The authors declare that there is no conflict of interest.

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