

Development and Mechanical Characterization of Tea Fiber Residue/Hazelnut Shell-based Sustainable Biocomposites

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Biocomposites are environmentally friendly and biodegradable materials produced from renewable resources or agricultural residue. In this study, biocomposite boards were produced using tea fiber residue and hazelnut shell. These boards were designed to degrade naturally and mix into the soil within 2 years, depending on climatic conditions, without causing environmental pollution. Test sheets were produced from the raw materials using urea-formaldehyde glue as a binder, and diammonium phosphate fertilizer was used to regulate the decomposition time and nutrient contribution. A total of 32 groups of boards were produced with different raw material ratios. The boards were 6 and 10 mm thick, and bending and tensile strength tests were performed to determine their mechanical performance. The highest bending strength was measured at 3.96 N/mm² in the 10 mm thick board containing 89% tea fiber residue, 5% diammonium phosphate, and 6% adhesive. The lowest bending strength was obtained in the board containing 41% walnut shell, 41% tea fiber residue, 15% phosphate, and 3% glue, with a value of 0.58 N/mm². In tensile tests, the highest value obtained was 0.48 N/mm² in a board containing 84% tea fiber residue, 10% phosphate, and 6% adhesive; while the lowest value was 0.06 N/mm² in a board containing 44.5% walnut shell, 44.5% tea fiber, 5% diammonium phosphate, and 10% adhesive.

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INTRODUCTION

In recent years, increased public and environmental awareness has created significant pressure on the industry to implement renewable resources, sustainable processing, and efficient residue management. The materials industry is one of the main industries undergoing radical transformation today and achieving significant successes in green technology (Faruk *et al.* 2014; Dönmez 2019). The properties of fiber composites vary depending on factors such as the weight percentage, fiber length, and orientation (Ergun *et al.* 2020; Khalil *et al.* 2012; Sreenivasan *et al.* 2012; Palanisami *et al.* 2023). Natural fiber composites are attracting significant attention due to their sustainability and their alignment with user and environmental awareness, and they generally present a viable alternative to traditional composite materials made with synthetic fibers (Alici and Dalkilic 2022; Palaniappan *et al.* 2024). Natural fibers can be classified as animal or plant fibers. Coconut fiber, pineapple, bamboo, jute, ramie, and similar materials are classified as bio-

fibers derived from plants (Bhuvaneshwaran *et al.* 2025). Plant fibers have attracted interest due to their renewable nature, biodegradability, cost-effectiveness, and abundance (Tanobe *et al.* 2014; Koruk and Genc 2015; Sonmez 2017). Because of increasing environmental awareness, natural fiber biocomposites are becoming more widely used. Furthermore, the relatively low cost and low density of natural fibers, their acceptable specific properties, ease of separation, increased energy recovery, CO₂ neutrality, biodegradability, and recyclability have led to increased studies on the use of natural fiber materials in biocomposites. These materials, which are durable, reliable, lightweight, and have acceptable mechanical properties depending on the application, are significantly better than traditional materials and are increasing the demand for natural fibers in the automotive, construction, and various other industries (Uitterhaegen *et al.* 2018).

Biocomposites are multi-phase engineering materials containing at least one natural component. In these systems, the matrix acts as a binder, while the filler acts as a reinforcing element to improve mechanical strength (Respati *et al.* 2021; Dalkilic *et al.* 2025). In recent years, lignocellulosic waste from agricultural and wood production has been used as a filler in the manufacturing process of thermoplastic composites (Ayrılmış *et al.* 2025). The proper combination of the matrix and filler is of fundamental importance for the development of the mechanical properties of biocomposites. In addition, compatibility enhancers are often used to improve the interfacial bonding between phases (Asrofi *et al.* 2024). Matrices used in composite structures are classified into three main categories: polymer-based, metal-based, and ceramic-based matrix composites (Paladugu *et al.* 2022). Biocomposites are generally composed of polymer-based matrices. In improving mechanical properties, the uniform distribution of reinforcement, prevention of agglomeration, and strong bonding at the matrix–reinforcement interface are of great importance (Adetunji *et al.* 2022; Akter *et al.* 2024; Asrofi *et al.* 2025). The advantages of natural fiber-reinforced biocomposites are highlighted by their environmentally friendly properties throughout all stages, from production to waste management. The environmentally sustainable production of natural fibers reduces energy consumption per unit of production. These composites offer numerous engineering advantages, including high specific strength and modulus, low density, low cost, high toughness, superior creep and corrosion resistance, and biodegradability (Zanuttini and Negro 2021; Irbe *et al.* 2024). Owing to these characteristics, biocomposites have a wide range of applications in buildings, the automotive industry, the packaging industry, transportation applications, decorative products, and various equipment used in everyday life (Rimdusit *et al.* 2011; Gao *et al.* 2018; Jiang *et al.* 2024). Agricultural waste, which is a by-product of certain agricultural activities, is an abundant and renewable resource that is often overlooked (Palanisamy *et al.* 2023; Kumar *et al.* 2024; Manickaraj *et al.* 2025).

The study evaluated the formation process and quantities of tea fiber waste as a biodegradable material. Based on 2020 TÜİK data, 1,450,556 tons of fresh tea harvest were obtained from 786,813 decares of land as a result of fresh tea cultivation (TÜİK 2021; Ataman 2022). Tea fiber waste refers to all products that do not fall under the definition of tea, such as fiber, dust, and debris extracted from fresh tea. The fiber ratio (tea waste) obtained from tea plants harvested under optimal conditions ranges between 3% and 15%, depending on the quality of the tea (Newton *et al.* 2018; Ataman 2022).

Hazelnuts are an important agricultural crop in Turkey, considering their commercial status. Turkey is a leading country, accounting for 75% of the world's total hazelnut production. According to 2019 data, annual hazelnut production is 776,046 tons (URL-1 2020). Among lignocellulosic materials used as filler and reinforcement materials

in biocomposite production are hazelnut barks, cotton, wheat straw, coconut, rice husks, bamboo fiber, wood fiber, and banana fiber (Dönmez *et al.* 2011; Dong and Davies 2012; Peng *et al.* 2014; Zulkifli *et al.* 2015). The main areas of application for wood plastic composites (WPCs) are automotive interior and exterior trim materials. The application area of WPCs is much broader, with a 30% growth observed in recent years. Window and door frames, thermal insulation systems, benches, garden sheds, and sun protection systems are made from WPCs (URL1 2011; Çavdar A. F. 2011).

The long, fibrous structure of tea fibers, which has the ability to form mats, can counterbalance the structural weakness caused by hazelnut shell particles by “binding” them together. In other words, while tea fibers form a matrix skeleton that provides mechanical strength, hazelnut shells can function as a volumetric filler that fills the spaces within this skeleton.

The aim of the study was to determine some mechanical properties of biocomposite boards designed and produced as a new industrial product using tea fiber residue and hazelnut bark’ residue, which are not industrially evaluated in Türkiye, to ensure fast and safe growth in saplings.

MATERIALS AND METHODS

Material

Tea fiber residue

Tea fiber residue was used as a raw material in the study. Tea fiber residues measuring 1 to 5 mm in size, which remain after the tea processing stage in tea factories, were used as a reinforcing material in the production of biocomposites. According to information provided by the General Directorate of Tea Enterprises in Turkey, the consumption and production of tea plants are carried out in significant quantities. Following tea processing, an estimated amount of over 20,000 tons of tea waste is generated in factories each year, and this amount increases further when the private sector is included. Tea waste in the form of dust and fibers creates storage problems in the areas where factories operate, and environmental issues arise in the disposal of this waste (Kütük *et al.* 1995). The tea fiber residue was obtained from the Giresun Tea Enterprises Directorate.



Fig. 1a. Tea fiber residue

Hazelnut Shell

The study used hazelnut shell as a raw material. The particle size of ground hazelnut shells typically ranges from 5 mm to 10 mm, depending on the milling process. Turkey produces approximately 350,000-600,000 tons of hazelnuts annually, accounting for 65 to

70% of global hazelnut production. The majority of this production is sold without shell, with the barks mostly used as fuel, while a small portion is ground into powder and used as a food additive in products such as chocolate (Yıldırım 2007). The reason for using hazelnut shell is to convert residue material into a value-added product. The hazelnut bark was obtained from a company operating in the hazelnut sector in Düzce, Türkiye.



Fig. 1b. Hazelnut shell

Diammonium Phosphate

Diammonium phosphate (DAP) was used as a fertilizer in the study to promote sapling growth. It was obtained from a fertilizer company in Kastamonu, Türkiye.

Adhesive

In this study, the following adhesives was used: urea-formaldehyde adhesive with a 65% solids content and a 20% solution of the hardener (ammonium chloride) prepared with water was supplied by Kastamonu Entegre, Türkiye.

During the preparation stage, the hazelnut shells were ground into wood flour using a grinder. The reason for choosing adhesive ratios of 3% and 6% is to minimize soil damage by using as little adhesive as possible. Diammonium phosphate was chosen for use in the production of biocomposite material because, according to literature research, it has a positive effect on the growth of saplings. The recipe used to produce the biocomposite material is presented in Table 1.

In the production of biocomposite materials, sheets of two different thicknesses, 6 mm and 10 mm, with dimensions of 50 × 50 cm, have been produced. Sheet production was carried out on a press machine at 20 kg/cm² pressure and 200 °C temperature. The pressing process was applied for 6 min to 6 mm thick sheets and 9 min to 10 mm thick sheets. Some physical and mechanical tests were performed to examine the behavior and degradation processes of the produced biocomposite materials in the external environment, as well as their usability. As a result of the preliminary tests, it was decided that the production recipe should be as such because when a high percentage of walnut bark was used (more than 50%), they fragmented and dispersed.

Table 1. Production Recipe for Biocomposite Material

GN	HS (%)	TFR (%)	DF (%)	A (%)	PT (mm)	GN	HB (%)	TFW (%)	DF (%)	A (%)	PT (mm)
1	0	97	0	3	6	17	48.5	48.5	0	3	6
2	0	92	5	3	6	18	46	46	5	3	6
3	0	87	10	3	6	19	43.5	43.5	10	3	6
4	0	82	15	3	6	20	41	41	15	3	6
5	0	97	0	3	10	21	48.5	48.5	0	3	10
6	0	92	5	3	10	22	46	46	5	3	10
7	0	87	10	3	10	23	43.5	43.5	10	3	10
8	0	82	15	3	10	24	41	41	15	3	10
9	0	94	0	6	6	25	47	47	0	6	6
10	0	89	5	6	6	26	44.5	44.5	5	6	6
11	0	84	10	6	6	27	42	42	10	6	6
12	0	79	15	6	6	28	39.5	39.5	15	6	6
13	0	94	0	6	10	29	47	47	0	6	10
14	0	89	5	6	10	30	44.5	44.5	5	6	10
15	0	84	10	6	10	31	42	42	10	6	10
16	0	79	15	6	10	32	39.5	39.5	15	6	10

(GN: Group number, HB: Hazelnut Shell, TFW: Tea fiber residue; DF: Diammonium phosphate, A: Adhesive, PT: Panel thickness)

Density tests were conducted in accordance with standard 323. The densities of the biocomposite materials were determined by weighing them on a precision scale and measuring their width, length, and thickness with a digital caliper. They were then left in a climate-controlled chamber set to 65% relative humidity for 3 days. The weights of the biocomposite materials left in the climate chamber for 3 days were measured on a precision scale, and their width, length, and diameter were measured with a digital caliper. Based on these measurements, the densities of the biocomposite materials were determined using the following formula (Eq. 1):

$$d = \left(\frac{m}{a \times b \times c}\right) \times 100 (g/cm^3) \quad (1)$$

In Eq. 1, d is density (g/cm^3), m denotes mass (g) a is width (cm), b is length (cm), and c indicates thickness (cm).

Bending resistance is determined in accordance with EN 310. The dimensions of the sample to be used for the test are set as 50 mm in width and (sheet thickness $\times$ 20 + 50 mm) in length. The bending force and elasticity value at the maximum force at which the sample breaks under a constant force applied to the sample are calculated using the following formula.

$$Bs = \left(\frac{3 \times F_{max} \times l_1}{2 \times b \times t^2}\right) (N/mm^2) \quad (2)$$

where B_s is bending resistance (N/mm^2), F_{max} denotes maximum force, l_1 is the distance between support axes (mm), b is width of the material (mm), and t is thickness of the material (mm). The tensile strength test was performed in accordance with EN 319. After being cut into 50 $\times$ 50 mm pieces, the samples were bonded to metal surfaces using hot silicone. When the applied load reached its maximum, the samples cracked. The maximum force reached was automatically measured by the machine and calculated using Eq. 3:

$$Ts = \left(\frac{F_{max}}{axb}\right)(N|mm^2) \quad (3)$$

In Eq. 3, Ts is the Tensile strength, F_{max} is the Load (unitN), a is the width of the material (unit mm), and b is the length of the material (unit mm).

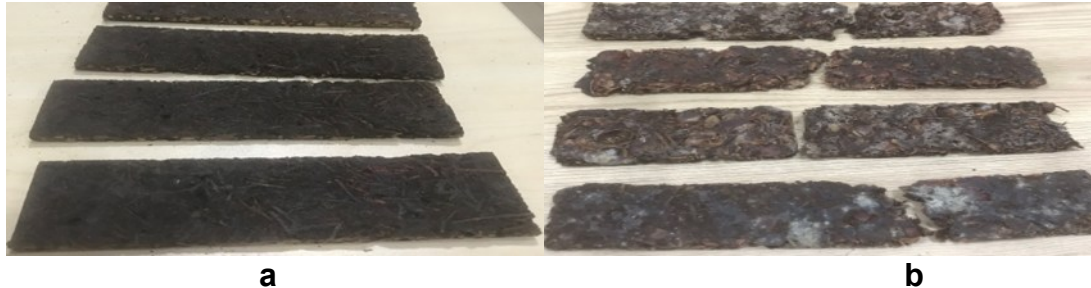


Fig. 2a. Samples used for bending resistance tests (a: before test, b: after test)

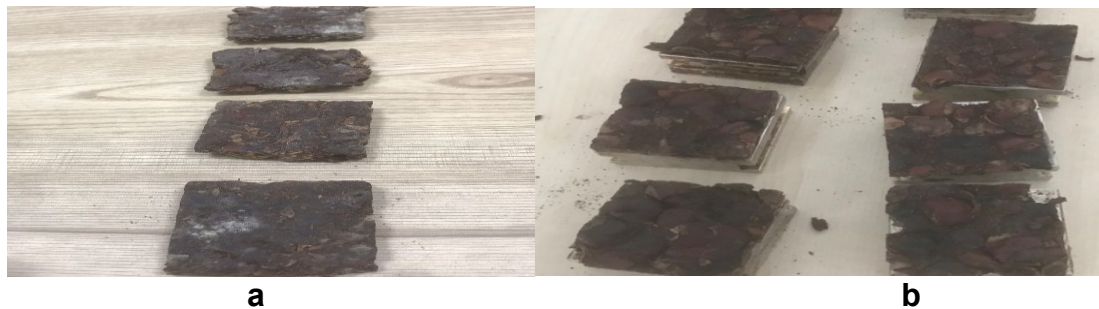


Fig. 2b. Samples used for tensile strength tests (a: before test, b: after test)

Statistical Analysis

Bending or tensile tests were performed on a total of 320 samples, divided into 32 groups, each consisting of 10 repetitions, with two different raw materials and two different thicknesses. A multivariate analysis of variance was performed on the data to determine whether there were differences between the samples. Following the analysis, a Duncan test was performed on the data to determine the level of significance of the differences.

RESULTS AND DISCUSSION

The boards produced in this study were obtained by using different combinations of tea fiber residue, hazelnut bark, diammonium phosphate, and glue in thicknesses of 6 and 10 mm. The density values of the biocomposite materials produced using tea fiber residue and hazelnut bark, which are considered waste, are given in Table 2.

Table 2. Density Values of the Produced Biocomposite Materials

Materials (%) (TFW/HB)-DAP-A-T	Density (g/cm ³)	Standard deviation	Material (%) (ÇLA/FK)-DAP-T-K	Density (g/cm ³)	Standard deviation
(97/0)-0-3-6	0.586	0.003	(48,5/48,5)-0-3-6	0.670	0.004
(92/0)-5-3-6	0.619	0.001	(46/46)-5-3-6	0.598	0.001
(87/0)-10-3-6	0.621	0.005	(43,5/43,5)-10-3-6	0.514	0.007
(82/0)-15-3-6	0.695	0.003	(41/41)-15-3-6	0.526	0.006

(97/0)-0-3-10	0.587	0.001	(48,5/48,5)-0-3-10	0.696	0.006
(92/0)-5-3-10	0.550	0.004	(46/46)-5-3-10	0.557	0.006
(87/0)-10-3-10	0.556	0.002	(43,5/43,5)-10-3-10	0.629	0.006
(82/0)-15-3-10	0.564	0.003	(41/41)-15-3-10	0.509	0.001
(94/0)-0-6-6	0.585	0.005	(47/47)-0-6-6	0.615	0.007
(89/0)-5-6-6	0.449	0.004	(44,5/44,5)-5-6-6	0.655	0.008
(84/0)-10-6-6	0.621	0.006	(42/42)-10-6-6	0.562	0.004
(79/0)-15-6-6	0.691	0.001	(39,5/39,5)-15-6-6	0.565	0.001
(94/0)-0-6-10	0.647	0.002	(47/47)-0-6-10	0.606	0.013
(89/0)-5-6-10	0.655	0.002	(44,5/44,5)-5-6-10	0.507	0.004
(84/0)-10-6-10	0.582	0.006	(42/42)-10-6-10	0.587	0.009
(79/0)15-6-10	0.560	0.007	(39,5/39,5)-15-6-10	0,590	0,005

TFW: Tea fiber waste, HB: Hazelnut shell, DAP: Diammonium phosphate, A: Adhesive, T: Thickness

Table 2 shows that the highest density was 0.836 g/cm³ for the group with a 10 mm thickness, 48.5% hazelnut shell, 48.5% tea fiber residue, and 3% adhesive addition. In their study, Rodney *et al.* (2015) found that the density of the biocomposite material obtained from tea tree trunks and tapioca starch to be 0.83 g/cm³. In his study, Yıldırım (2007) observed that the density of the material produced with 20% ground walnut shell and 80% polypropylene was 0.961 g/cm³. The data obtained is consistent with the literature (Yıldırım, 2007). The group with the lowest density, 0.449 g/cm³, was found to have a thickness of 6 mm and was produced with 89% tea fiber residue, 5% diammonium phosphate, and 6% glue addition. Nasution *et al.* (2018) reported the density of the biocomposite obtained from 30% acetic acid, 3% nanocrystalline cellulose, and Indian cane stalk as 0.26 g/cm³. The obtained data is consistent with the literature. The lower values reported in the literature than those obtained are thought to be due to differences in the raw materials used. A bending strength test was applied to the produced sheets, and the variance analysis results are given in Table 3.

Table 3. Variance Analysis of Bending Strength Test

Variance Source	Type III Sum of Squares	Df	Mean Square	F value	P value
Corrected Model	124.887 ^a	31	4.029	7.057	0
Intersection	329.706	1	329.706	577.580	0
Thickness	3.538	1	3.538	6.198	0.015
Material	87.129	15	5.809	10.176	0
Thickness *Material	34.220	15	2.281	3.996	0
Error	54.801	96	0.571		
Adjusted Total	509.394	128			
Corrected Total	179.688	127			

a. R² = 0.695 (Adjusted R² = 0.597)

According to the variance analysis, the effects of material type, adhesive ratio, and diammonium phosphate ratio were statistically significant, whereas material thickness was not. The interaction between the factors is statistically significant ($P \leq 0.05$). The results of the Duncan test, which indicate which applications show a significant difference, are given in Table 4. Table 4 shows that the best bending strength of 3.2716 N/mm² was obtained for the biocomposite produced with 6 mm thick 94% tea fiber residue and 6% adhesive addition. In a study by Kremensas *et al.* (2019), the bending strength value of the biocomposite obtained with hemp fiber and corn starch was determined to be 5.2 N/mm².

The lowest bending strength of 0.6698 N/mm² was observed in the biocomposite produced with 41% hazelnut bark, 41% tea fiber residue, 15% diammonium phosphate, and 3% adhesive. Ayırlmış *et al.* (2020) determined the flexural strength value of the biocomposite material obtained from wood and polylactic acid (PLA) to be 1.76 N/mm² in their study.

Table 4. Duncan Analysis of Bending Strength Test

Material (%) (TFW/FK)-DAP-A	Bending Strength (N/mm ²)	Homogeneous Group
(41/41)-15-3	0.6698	a
(46/46)-5-3	0.7992	a
(47/47)-0-6	0.8385	a
(39,5/39,5)-15-6	0.8484	a
(42/42)-10-6	0.9202	a
(43,5/43,5)-10-3	1.0284	a
(92/0)-5-3	1.0975	a,b
(48,5/48,5)-0-3	1.2113	a,b
(44,5/44,5)-5-6	1.3382	a,b
(97/0)-0-3	1.5052	a,b,c
(82/0)-15-3	1.9225	b,c,d
(89/0)-5-6	2.1874	b,c,d
(84/0)-10-6	2.3489	d,e
(79/0)-15-6	2.6717	d,e,f
(87/0)-10-3	3.0204	e,f
(94/0)-0-6	3.2716	f

TFW: Tea fiber residue, HB: Hazelnut bark, DAP: Diammonium phosphate, A: Adhesive

The values reported in the literature are higher than the results obtained in this study. This is considered due to differences in the fiber structure, density, and mechanical properties of the wood raw material used in the study. The natural fiber orientation and high elastic modulus of wood increase the material's load-bearing capacity under bending, thereby increasing flexural strength. Initially, the six groups were in the same group in terms of bending strength. The variance analysis for the tensile-strength test of the produced panels is presented in Table 5.

Table 5. Tensile Strength Test Variance Analysis

Variance Source	Type III Sum of Squares	Df	Mean Square	F value	P value
Corrected Model	1.282 ^a	31	0.041	2.811	0
Intersection	3.450	1	3.450	234.444	0
Thickness	2.608	1	2.608	0	0.989
Material	0.827	15	0.055	3.747	0
Thickness *Material	0.455	15	0.030	2.062	0.018
Error	1.413	96	0.015		
Adjusted total	6.144	128			
Corrected total	2.695	127			

a. R² = 0.476 (Adjusted R² = 0.307)

According to the results of the variance analysis, material thickness alone was not significant for surface detachment, while material type and adhesive type were significant, and interactions with other factors were also significant. The interaction between factors is

statistically significant ($P \leq 0.05$). Duncan test was conducted to determine in which applications the difference is significant and the results are given in Table 6.

Table 6. Tensile Strength Test Duncan Analysis

Material (%) (ÇL/FK)-DAP-T	Tensile Strength (N/mm ²)	Homogeneous Group
(44,5/44,5)-5-6	0.0650	a
(46/46)-5-3	0.0746	a
(42/42)-10-6	0.0756	a
(47/47)-0-6	0.0865	a,b
(43,5/43,5)-10-3	0.0994	a,b,c
(39,5/39,5)-15-6	0.1059	a,b,c
(48,5/48,5)-0-3	0.1227	a,b,c,d
(41/41)-15-3	0.1429	a,b,c,d
(92/0)-5-3	0.149 ²³	a,b,c,d
(97/0)-0-3	0.1675	a,b,c,d
(87/0)-10-3	0.1983	a,b,c,d,e
(94/0)-0-6	0.2186	b,c,d,e
(89/0)-5-6	0.2396	c,d,e
(82/0)-15-3	0.2621	d,e
(84/0)-10-6	0.3046	e
(79/0)-15-6	0.3142	e

TFW: Tea fiber residue, HB: Hazelnut shell, DAP: Diammonium phosphate, A: Adhesive

Table 6 shows that the best tensile strength resistance of 0.3142 N/mm² was obtained with the biocomposite material produced from 6 mm-thick 79% tea fiber residue, 15% diammonium phosphate, and 6% adhesive. Rodney *et al.* (2015) reported a tensile strength value of 0.36 N/mm² for the biocomposite material they produced using tapioca starch and glycerol. The lowest tensile resistance was observed in the biocomposite material containing 44.5% hazelnut shell, 44.5% tea fiber residue, 5% diammonium phosphate, and 6% adhesive, with a value of 0.0650 N/mm². In their study, Bourdot *et al.* (2017) reported the tensile strength value of the composite material obtained from hemp and starch (HS8-1) as 0.08-0.001 N/mm². When the results of this study are compared with data reported in the literature, they are found to be consistent. The fact that the results obtained support the data reported in the literature demonstrates the accuracy of the experimental method and the suitability of the material components used.

CONCLUSIONS

1. When examining the bending strength results, it was found that hazelnut shell was not used in groups with high bending strength values, while hazelnut shell was added in groups with low values. This finding indicates that hazelnut shell negatively affects the bending strength of biocomposite panels. In panels produced from tea fiber residue, a decrease in the amount of residue led to a decrease in flexural strength in most cases. In some cases, the decrease in flexural strength in panels with low tea fiber content is related to the structural felting property of tea fiber.
2. Analysis of tensile resistance tests revealed that the samples with the highest values did not use hazelnut shell reinforcement, had lower tea fiber ratios, and had relatively high

diammonium phosphate (DAP) ratio. In these samples, where hazelnut shell was not present, and the tea fiber ratio was kept high, it was observed that the decrease in the amount of tea fiber residue increased the tensile resistance. This increase is considered to stem from the fiber morphology and surface structure, which provide high adhesion in the interaction of tea fiber with the matrix. This strong bond at the fiber-matrix interface is particularly effective at transferring loads perpendicular to the surface and contributes to increased peel strength. Therefore, the use of tea fiber residue in appropriate proportions is a critical design parameter for surface strength.

3. When the bending tests and internal bonding test results are examined holistically, it was found that the mechanical performance was significantly higher in samples without hazelnut shell reinforcement; in samples with hazelnut shell addition, both bending and internal bonding strengths decreased significantly. These findings reveal that hazelnut shell cannot form sufficient fiber-matrix adhesion within the biocomposite matrix, thereby negatively affecting the composite's overall mechanical behavior. It was determined that tea fiber residue reinforcement generally increases flexural strength. However, it was observed that the tensile strength decreased in panels without walnut shell and with high proportions of tea fiber waste. This situation leads to an inhomogeneous distribution of fiber density within the matrix when tea fiber is used in high quantities, thereby weakening interfacial adhesion. Therefore, while tea fiber residue improves flexural performance when used in appropriate proportions, excessive use can limit tensile strength.

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