Mechanical and Physical Properties of Particleboard Produced from Hemp Plant

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Effects of annual hemp (*Cannabis sativa* L.) material on the mechanical and physical properties of particleboard was investigated. For this purpose, various levels of hemp shives 10%, 20%, and 30% were added to the middle layer of the chip blank. Urea formaldehyde (UF) resin was used at a 7% level in the middle layer and 12% in the top layer, in proportion to the dry chip weight, as an adhesive. Chip blanks were pressed in a hydraulic press at 195±5 °C temperature, 30 kg/cm² pressure, and 300 s. Test samples of P1 type with dimensions of 550 × 550 × 19 mm and a density of 580 kg/m³ were produced. It was understood from the test results that hemp sawdust had a positive effect on the mechanical properties of particleboard. Accordingly, a 16.7% increase in tensile strength, 18.4% in bending strength, 23.6% in elasticity modulus, 17.2% in surface strength, and 7.5% in screw holding force were detected. Physical properties showed a 3.8% increase in thickness and a 15.5% increase in water absorption values. Free formaldehyde values decreased by 24.6%. As a result of the research, it was determined that hemp sawdust could be an alternative to wood raw material in P1 type particle board production.

DOI: 10.15376/biores.20.3.5361-5376

Keywords: Particleboard; Hemp shives; Melamine urea formaldehyde (UF); Mechanical and physical properties

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INTRODUCTION

Particleboard is a large surface material obtained by pressing wood chips or small particles with synthetic resins under heat and pressure (Bozkurt and Göker 1990). In the particle board industry, wood, forest wastes, annual plants, industrial waste (covers, slats, sawdust, planer sawdust) are used. Particleboards are classified according to different parameters such as place of use, production methods, density, *etc*. (Göker 2000). Particleboard has a special place among the wood-based materials available in the market. In 2020, particleboard production in the world was 102 million cubic meters (FAOSTAT 2020).

The rapid population growth in the world has increased the need for forest resources. The unconscious cutting of natural forests, which initially seemed abundant and inexhaustible, has caused them to disappear in some regions (Usta 2011). The decrease in natural forest assets has increased the importance of non-wood fibers (Ganapathy 1997). To overcome this negative situation, the use of idle agricultural residues in composite panel production has gained scientific and commercial importance (Youngquist *et al*. 1994). Particleboard has been produced with many agricultural residues to provide cheap raw materials for the particleboard industry (Sevinçli 2014). Particleboard was produced with tea plant residues and red pine chips (Nemli and Kalaycıoğlu 1997; Filiz *et al*. 2011). Three-layer particleboard was produced from sunflower shives and white poplar chips (Bektaş *et al*. 2005). Wang and Sun (2002) produced particleboard from wheat straw and corn shives. Particleboards were produced by mixing sunflower shives and red pine chips in certain ratios (Güler *et al*. 2006).

One of the promising raw material sources for particleboard production is the hemp plant (*Cannabis sativa* L.), which has been grown for thousands of years. Hemp, which has many uses in the industry, is used to make high-strength composites (Sawpan *et al*. 2011), pulp and paper (Kovacs *et al*. 1992), particleboard (Pecenka *et al*. 2009), and insulation materials (Yates 2006), *etc*. Papadopoulos *et al*. (2003) mixed 10%, 20%, 30% hemp fiber with wood chips and compared the test samples produced at a density of 750 kg/m³ with reference groups. There was a 10% to 20% decrease in tensile strength, a 25% to 65% decrease in flexural strength, and a 40% to 180% increase in thickness with the increase in hemp fiber content. However, the product met the EN requirements. As a result, it was stated that the fiber structure and low bulk density of hemp are more suitable for MDF production. Vos (2005) stated that the low ratio of dust and fine material in hemp sawdust increases the internal bonding in the middle layer.

Schopper *et al*. (2009) produced experimental samples with different resins (UF, MF, FF) at densities of 450 and 550 kg/m³ in order to reduce formaldehyde emissions of wood and hemp-based particleboards. Although improvements in mechanical and technological properties were detected due to the increase in density, it was stated that DIN standards were partially met. Nikvash *et al*. (2010) used sugar cane (*Saccharum officinarum* L.), canola (*Brassica napus* L.), and hemp (*Cannabis sativa* L.) residues between 0 and 100% and produced particleboard panels with a density of 700 kg/m³ and compared them with control samples. The best values were observed in panels produced with hemp chips between 10% and 20%. Tensile strength increased by 12%, flexural strength by 19%, and modulus of elasticity by 9%. Although the use of agricultural residues increased the thickness and water absorption, it was understood that the product met EN requirements with usage of up to 50% hemp material. Moulana (2012) produced test samples at 350-450-550 kg/m³ density by mixing 0-25%-50%-75-100% wood sawdust and hemp sawdust. Results were compared with reference groups. As a result of the use of hemp in the middle layer, tensile strength increased by 94%, bending strength by 3%, surface strength increased by 65%, while thickness decreased by 32%. This was explained by the better compression of hemp during the pressing stage as a result of its low bulk density. Hosseinaei *et al.* (2011) explained that hemp is easier to compress due to the low mechanical properties of the cell wall. Li *et al*. (2014) produced particleboard test samples with a density of 0.55, 0.65, 0.70, 0.75 g/cm³ by gluing chip drafts prepared in hemp sawdust/wood chip mixture ratios (0:5, 1:4, 2:3, 1:1, 3:2, 4:1, 5:0) with 10% urea formaldehyde (UF) resin. From the test results, a 27% increase in tensile strength (3:2), a 35% increase in flexural strength, a 29% increase in modulus of elasticity, and a 3% decrease in thickness increase (1:1) at 0.75 g/cm³ density to optimum values were determined. These results are explained by better compaction of hemp sawdust as a result of lower bulk density. Sam-Brew and Smith (2017) produced particleboards with a density of 500 to 620 kg/m³ by gluing pure wood and hemp chips with 2.5% to 5% diphenylmethane diisocyanate (pMDI) resin. From the test results, the best values were found in the samples produced from hemp chips with 5% (pMDI) resin. Accordingly, an increase of 32% in tensile strength, 44% in flexural strength, and 30% in modulus of elasticity was observed in mechanical properties. On the other hand, the high absorption property of hemp was found to meet the ANSI requirements, although the physical properties showed increases of 138% and 166% in 24-hour thickness increase and water absorption values, respectively. This was attributed to the low bulk density of hemp, anatomical differences such as cell structures, chip geometry, *etc*. and chemical properties that are thought to affect resin curing. Kawalerczyk *et al*. (2020) saw a 34% decrease in the free formaldehyde content of the panels produced by mixing hemp flour with MUF resin. This was explained by the chemical composition of hemp flour reducing the resin curing time and pH. Grigorov *et al*. (2022) compared the test samples obtained with 10% UF resin using vine and hemp particles between 0 and 100% in the middle layer of the chip draft with control groups. The test results showed a 94% (2:3) increase in tensile strength, 65% (0:5) increase in flexural strength, and 34% (0:5) increase in modulus of elasticity. On the other hand, a 35% (4:1) increase in thickness and a 17% (4:1) decrease in water absorption were determined. This is explained as the low bulk density of hemp content increases the compression ratio and thus improves the strengths by providing more contact area. Zvirgzds *et al*. (2022) produced test specimens at a density of 300 kg/m³ with 10% UF resin with hemp chips in the ranges 0.5 to 2 mm and 2 to 5.6 mm. The test results showed an increase in thickness and 50% increase in water absorption values compared to control samples. As a result, it was understood that hemp size has an effect on mechanical and physical properties. Auriga *et al*. (2022) compared the panels produced at a density of 650 kg/m³ by adding 10% and 25% hemp in particleboard draft with control samples. At the end of the study, 25% hemp chips had a positive effect on tensile strength, flexural strength, modulus of elasticity, and thickness increase. Pépin *et al*. (2024) mixed biobased resin with hemp sawdust to produce particleboards with a density of 250 to 300 kg/m³, which resulted in panels with low volatile organic compounds (VOC), formaldehyde emission, high thermal conductivity, and sound absorption.

In recent years, political and economic developments around the world have made it difficult for the forest products industry to access limited forest resources and have led to increased costs. These global developments have led to an increased interest in the use of idle natural resources and agricultural residues such as hemp with wood-based materials. The incorporation of hemp flour or shives into particleboard production introduces a dual-function bio-additive that not only reinforces mechanical integrity but also intrinsically mitigates formaldehyde emissions through its reactive lignocellulosic matrix, thus offering a sustainable pathway toward low-emission, high-performance panels. Therefore, the effect of hemp (*Cannabis sativa* L.) on the mechanical and physical properties of particleboard was investigated over P1 type particleboard specifications presented in Turkish Standard TS EN 312 (2012) by 10%, 20%, and 30% addition in the middle layer.

EXPERIMENTAL

Wood or Wood-based Materials

In this study, the wood chips and sawdusts of Black pine (*Pinus nigra* A.) and Aspen (*Populus tremula* L.) were used as the main ingredient of the boards. Materials were obtained from Taşköprü/Kastamonu region and Kastamonu Entegere Ağaç Sanayi A.Ş. in dried form.

Hemp Shives

Hemp plant (*Cannabis sativa* L.) was preferred from agricultural residues as a substitute for wood raw material in this research and was obtained from a company engaged in hemp cultivation in the Sinop region. In the selection of the hemp plant, attention was paid to the fact that the fibers of the stem part were peeled, as well as 1 to 3 cm in diameter and 120 to 200 cm in length. Hemp shives were processed into sawdust at Kastamonu Enteğre Ağaç Sanayi A.Ş. Chipboard Factory using a 1990 model Alphina hammer mill with a sieve size of 4 × 40 mm. The dimensions and bulk densities of wood and hemp shive used as raw materials are given in Table 1 and Fig. 1.

Table 1. Sizes of Raw Material Types (Chips and Sawdust)

Raw Material Type	Chip Thickness (mm)	Chip Width (mm)	Chip Length (mm)	Bulk Density (g/cm³)
Industrial sawdust	0.15-0.3	0.5-1	0.3-1.5	206.77
Wood chips	0.3-0.6	2-5	10-30	163.13
Hemp shive	1-1.5	3-6	20-40	85.88

Fig. 1. Bulk densities of raw material types

Glue and Chemicals

Resin, paraffin emulsion and other chemicals used in the production of the test samples were obtained from Kastamonu Entegre Ağaç Sanayi A. Ş. Particle Board Factory. The properties of the chemicals used in the study are given in Table 2.

Table 2. Properties of Glue and Chemicals

Chemicals		Solids Content (%)	Density (g/cm³)	Viscosity (cP)	pH	Molar Ratio (Mr)	Flow Time (s)	Gel Time (s)
Glue (UF)	Core layer	62	1.27	280	8.3-8.5	1.05	60	44-45
	Surface layer	57	1.25	75	8.3-8.5	1.1	18	-
Paraffin emulsion		60	0.94-0.98	13-23	9-10	-	12	-
Hardener (NH_4Cl)		20	1.06	7.5	8.2	-	-	-

Production of Test Boards

The production of the particleboard test samples was carried out in the laboratory environment and the production pattern of the research is given in Table 3.

Table 3. Production Design

Particle Board Draft	Raw Material Type	Experimental Groups			
		Control (A1)	A2	A3	A4
		Raw Material Usage Rates (%)			
Surface layer (SL)	Industrial sawdust	40	40	40	40
Core layer (CL)	Wood chips	60	50	40	30
	Hemp shives	0	10	20	30

Gluing and chip drafting

The mixing of wood and hemp shive was carried out with a specially designed experimental mixer. Glue and chemicals were added using pneumatic injectors on the mixer. Urea formaldehyde (UF) resin with 57% and 62% solids content was used for gluing the chips, 7% in the middle layer and 12% in the top layer in proportion to the full dry chip weight. Ammonium chloride (NH_4Cl) solution with a solid content of 3% in the middle layer and 0.5% in the top layer with a solid content of 20% was used as hardener. Paraffin emulsion with a solids content of 0.6% by weight of full dry sawdust and a solids content of 60% was used as water repellent.

Preparation of particleboard

As can be seen in Table 3, the surface layer of the particleboard consisted of 40% industrial sawdusts of black pine. The core layer was composed of 60 % wood chips of 1:1 black pine and aspen, respectively. For the effect of hemp shives utilization, wood chips were mixed with the hemp shives by 10%, 20%, and 30% dry wt. The mixture was laid in a 550 × 550 × 300 mm preparation container according to the three-layer particleboard production method.

Pressing

The pressing of the chip drafts was carried out with a German Bürkle brand hydraulic test press at a temperature of 195±5 ℃ and a pressure of 30 kg/cm^2 and a pressing time of 300 s. At the end of this process, test samples with 550 × 550 × 19 mm dimensions and 580 kg/m^3 density were obtained.

Fig. 2. Pressing of chip drafts (Bürkle press)

Surface treatment

The test specimens were kept at 20±2 °C and 65±5 relative humidity for 4 to 7 days and then sanded with 80 to 100 grit sanding belts with a net thickness of 18±0.1 mm with a Turkish origin EMC Explorer 2RK brand 2010 model caliber sanding machine. The Burkle press where the chip drafts prepared according to the production pattern were pressed is shown in Fig. 2.

Methods

Particleboard test specimens were prepared in accordance with TS EN 312 (2005) standards and 10 specimens were taken from each group and tested. Tensile strength, flexural strength, modulus of elasticity, surface strength, and screw retention tests were performed using ZwickRoell universal testing machine.

To determine the physical properties, the test samples were weighed on a precision balance and measured with the help of calipers to determine the thickness swelling and water absorption percentage after the first and 24 hours. Formaldehyde content in the board was determined according to the perforator method. The standards and limit values for the tests are given in Table 4.

Table 4. Standards and Limit Values for Tests

Mechanical and Physical Tests	Standard No.	Sample Dimension (mm)	Limit Values (P1)
Density (kg/m³)	TS EN 323-1	50 × 50	580
Tensile strength (N/mm²)	TS EN 319	50 × 50	≥ 0,24
Bending resistance – MOR (N/mm²)	TS EN 310	50 × 410	≥ 10
Modulus of elasticity MOE (N/mm²)	TS EN 310	50 × 410	≥ 1600
Surface strength (N/mm²)	TS EN 311	50 × 50	≥ 0,80
Screw tensile strength (N)	TS EN 320	75 × 75	≥ 450
24h Thickness swelling - TS (%)	TS EN 317	50 × 50	Max. 100
24h Water absorption - WA (%)	TS EN 317	50 × 50	Max. 20
Free formaldehyde (mg/100 g)	TS EN 12460-5	20 × 25 (150 g)	E1 ≤ 8 mg/100 g

P1: Dry environment and general-purpose particleboard

The SPSS 23 statistical package program was used for statistical analysis. Multi-way analysis of variance (ANOVA) was used to determine the effectiveness of the factors, and whether the differences between the factors were statistically significant was determined by the (DUNCAN) test with 95% confidence.

RESULTS AND DISCUSSION

The effect of hemp shives at different ratios in the middle layer of the chip draft was studied, and test results and statistical analyzes are given in Table 5.

According to the results of the statistical analysis given in Table 5, it was determined that the rate of use of hemp sawdust had a significant effect on all tests and that there were significant differences between the factors ($p < 0.05$).

Table 5. Statistical Analysis of Test Results

Sample/Particleboard	Type	N	Mean*	Std. Dev.	Std. Error	95% Confidence Interval for Mean		Min.	Max.
						Lower Bound	Upper Bound		
Thickness (mm)	A1	10	18.03^{a}	0.03	0.01	18.00	18.06	17.99	18.1
	A2	10	18.03^{a}	0.02	0.01	18.01	18.04	17.99	18.05
	A3	10	18.04^{a}	0.03	0.01	18.02	18.06	17.99	18.09
	A4	10	18.03^{a}	0.02	0.01	18.01	18.05	17.99	18.06
Moisture (%)	A1	10	6.29^{ab}	0.31	0.11	6.03	6.55	5.80	6.70
	A2	10	6.36^{ab}	0.17	0.06	6.22	6.50	6.10	6.60
	A3	10	6.51^{b}	0.24	0.08	6.32	6.71	6.20	6.80
	A4	10	6.21^{a}	0.28	0.10	5.97	6.44	5.90	6.70
Density (kg/m^3)	A1	10	585.25^{a}	3.06	1.08	583	588	580	590
	A2	10	589.50^{b}	2.51	0.89	587	592	587	595
	A3	10	584.00^{a}	1.77	0.63	583	585	582	587
	A4	10	585.38^{a}	1.85	0.65	584	587	583	588
Tensile Strength (N/mm^2)	A1	10	0.30^{a}	0.02	0.01	0.28	0.32	0.27	0.34
	A2	10	0.32^{a}	0.03	0.01	0.29	0.34	0.29	0.36
	A3	10	0.35^{b}	0.02	0.01	0.33	0.36	0.32	0.38
	A4	10	0.31^{a}	0.02	0.01	0.29	0.33	0.28	0.34
Bending Strength (N/mm^2)	A1	10	11.10^{a}	0.47	0.16	10.71	11.49	10.65	11.80
	A2	10	12.08^{b}	0.62	0.22	11.56	12.60	11.48	13.17
	A3	10	13.14^{c}	0.45	0.16	12.76	13.51	12.72	13.84
	A4	10	12.68^{c}	0.34	0.12	12.40	12.97	12.40	13.27
Modulus of Elasticity (N/mm^2)	A1	10	1910^{a}	98.9	34.9	1830	1990	18.00	20.58
	A2	10	2060^{b}	112.8	39.9	1960	2150	19.18	22.35
	A3	10	2360^{c}	120.4	42.6	2260	2460	22.52	26.00
	A4	10	2170^{b}	130.0	46.0	2060	2270	20.00	23.76
Surface Strength (N/mm^2)	A1	10	0.88^{a}	0.07	0.02	0.82	0.93	0.79	0.97
	A2	10	0.92^{ab}	0.08	0.03	0.85	0.98	0.84	1.03
	A3	10	1.018^{c}	0.05	0.02	0.98	1.06	0.96	1.10
	A4	10	0.98b^{c}	0.07	0.03	0.92	1.04	0.92	1.10
Screw Tensile Strength (N)	A1	10	653^{a}	29.2	10.3	628	677	627	700
	A2	10	682^{ab}	34.3	12.1	653	711	645	743
	A3	10	702^{b}	31.7	11.2	675	728	662	753
	A4	10	666^{a}	28.6	10.1	642	690	624	704
Thickness Swelling 24 h (%)	A1	10	88.9^{a}	1.46	0.52	87.7	90.2	87.6	91.2
	A2	10	91.5^{b}	0.99	0.35	90.6	92.3	90.5	93.2
	A3	10	93.8^{c}	1.64	0.58	92.4	95.1	92.1	96.5
	A4	10	102.7^{d}	1.85	0.65	101.1	104.2	100.2	105.9
Water Absorption 24 h (%)	A1	10	19.3^{a}	0.21	0.07	19.2	19.5	19.1	19.8
	A2	10	19.8^{bc}	0.40	0.14	19.4	20.1	19.3	20.4
	A3	10	19.6^{ab}	0.34	0.12	19.4	19.9	19.2	20.2
	A4	10	20.1^{c}	0.41	0.15	19.7	20.4	19.6	20.7
Free Formaldehyde (mg/100 g)	A1	10	3.86^{c}	0.13	0.05	3.75	3.97	3.65	4.05
	A2	10	3.31^{b}	0.15	0.05	3.19	3.44	3.18	3.58
	A3	10	2.91^{a}	0.18	0.06	2.76	3.06	2.65	3.20
	A4	10	3.00^{a}	0.18	0.06	2.85	3.15	2.67	3.26

* The Duncan's multiple range test homogeneity groups of the means. The same letters mean insignificant differences between the means. A1 is the control sample (%0 hemp shives) while A2, A3, and A4 include 10%, 20, and 30% hemp shives in the middle layer, respectively.

Physical and Technological Properties

The physical properties such as average values of 24 h thickness swelling, water absorption and free formaldehyde tests, and technological properties of the test samples, are shown in Fig. 3.

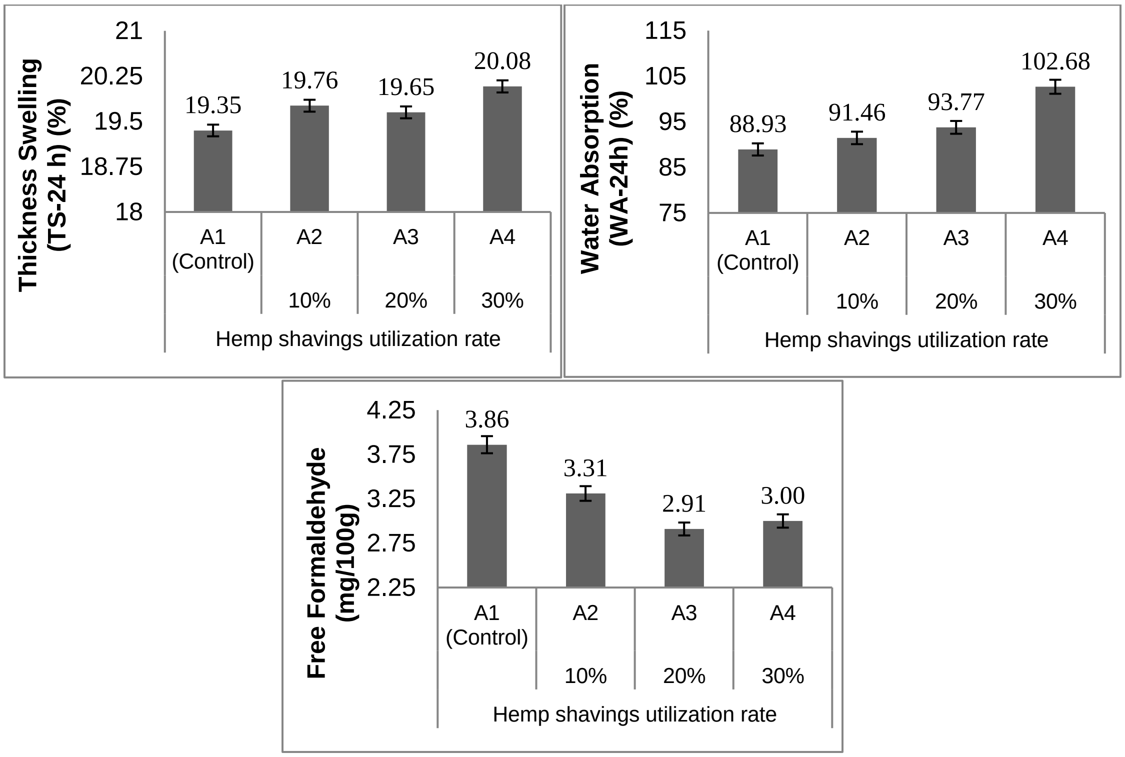

Fig. 3. Mean values of physical and technological properties

According to Table 5, there was a statistically significant effect of hemp shives utilization rate on 24-h thickness swelling and water absorption. In Fig. 3, the lowest thickness swelling and water absorption values were found in A1 control samples with 19.4% and 88.9%, respectively. The highest values were found in A4 experimental groups with 20.1% and 102.7%, showing an increase of 3.77% and 15.46% compared to control samples and using 30% hemp shives. From the test results, there was a significant increase in water absorption and thickness swelling values due to the increase in hemp shives in the chip draft. This can be attributed to the binding of more OH groups because of the high content of cellulose in hemp. The results obtained are compatible with similar studies in the literature. Papadopoulos *et al*. (2003) found a 40% to 180% increase in the thickness swelling of the particleboards obtained by mixing 0 to 30% hemp fiber with pure wood chips compared to the control groups. Nikvash *et al*. (2010) investigated the effect of annual plants on the dimensional stability of particleboard and it was stated that it caused an increase in thickness swelling and water absorption values and can be used at maximum 50% level. Sam-Brew and Smith (2017) found a 138% increase in thickness swelling and a 166% increase in water absorption in particleboards obtained with diphenylmethane diisocyanate (pMDI) resin by mixing wood and hemp shives at different ratios due to the water absorption feature of hemp shives. Zvirgzds *et al*. (2022) found a 50% increase in thickness increase and water absorption values of the experimental samples obtained with small-sized hemp chips compared to pure control samples. Auriga *et al*. (2022) found a slight decrease in the thickness increase values of the samples containing 25% hemp chips in the middle layer (Papadopoulos and Hague 2003; Schöpper *et al*. 2009; Reh 2013).

Table 5 shows that the use of hemp shive had a statistically significant effect on free formaldehyde, one of the technological properties of the experimental samples. According to Fig. 3, the lowest free formaldehyde value was found in A3 control samples with 2.91 mg/100 g, which showed a 24.6% decrease compared to the control sample when 20% hemp shives was used. The highest value of 3.86 mg/100 g was observed in the A1 control group. This was explained by the retention of free formaldehyde in the board due to the increase in the strength properties of the boards. The high performance of hemp biomass may reduce the free formaldehyde rate due to less resin content in the prepared boards. Kawalerczyk *et al*. (2020) showed a 34% decrease in the free formaldehyde values of the panels produced by mixing hemp flour with MUF resin. This decrease was explained based on the chemical composition of hemp flour decreasing the curing time and pH of the resin. Pépin *et al*. (2024) stated that panels with lower VOC and formaldehyde values can be produced from hemp sawdust with biobased resin (Schöpper *et al*. 2009). It is thought that the observed reduction formaldehyde emission is primarily due to chemical composition of hemp more so than reduced resin utilization. It is because hemp contains lignin and phenolic compounds which can chemically bind formaldehyde, thereby forming stable bonds that reduce off-gassing. Furthermore, tannins and flavonoids are natural formaldehyde scavengers. Cellulose and hemicellulose provide a porous matrix that may help trap or absorb some formaldehyde. However, reduction in resin utilization lower initial formaldehyde input which cause decreased emission.

Mechanical Properties

The average values of tensile strength, flexural strength, modulus of elasticity, surface soundness, and screw retention resistance of the mechanical properties of the test specimens are given in Fig. 4.

According to Table 5, the use of hemp shives had a statistically significant effect on tensile strength. The results indicate that all values were above the upper limit determined for P1 type particleboards following TS EN 312, (2012). In Fig. 4, the highest tensile strength of 0.35 N/mm² was found in A3 samples with 16.7% increase compared to A1 control samples and 20% hemp shives. The lowest was 0.30 N/mm² in the A1 control sample. An increase in tensile strength was detected in the test specimens because of hemp shavings. This increase is explained as the increase in the fibrous material per unit volume as a result of the low bulk density of hemp and thus increasing the strengths by creating more contact area. The results obtained from the study were similar to the studies conducted in the literature. Nikvash *et al*. (2010), in their research with annual plants, found the highest tensile strength in the experimental groups using 20% hemp shavings with a 12% increase. Moulana (2012) found a 94% increase in tensile strength in particleboard samples obtained by using hemp chips at different ratios depending on the increase in density and hemp. This was expressed as an increase in the bonding between the chips during the pressing stage as a result of the low bulk density of hemp. Li *et al*. (2014) produced test samples at different densities with a mixture of hemp and wood sawdust. In the study, the optimum tensile strength was found in high density specimens using 60% hemp sawdust with an increase of 27%. These results were explained by achieved low bulk density due to more uniformly and better compacted hemp sawdust. Sam-Brew and Smith (2017) found a 32% increase in the tensile strength of particleboards produced from wood and hemp chips with 5% diphenylmethane diisocyanate (pMDI) resins.

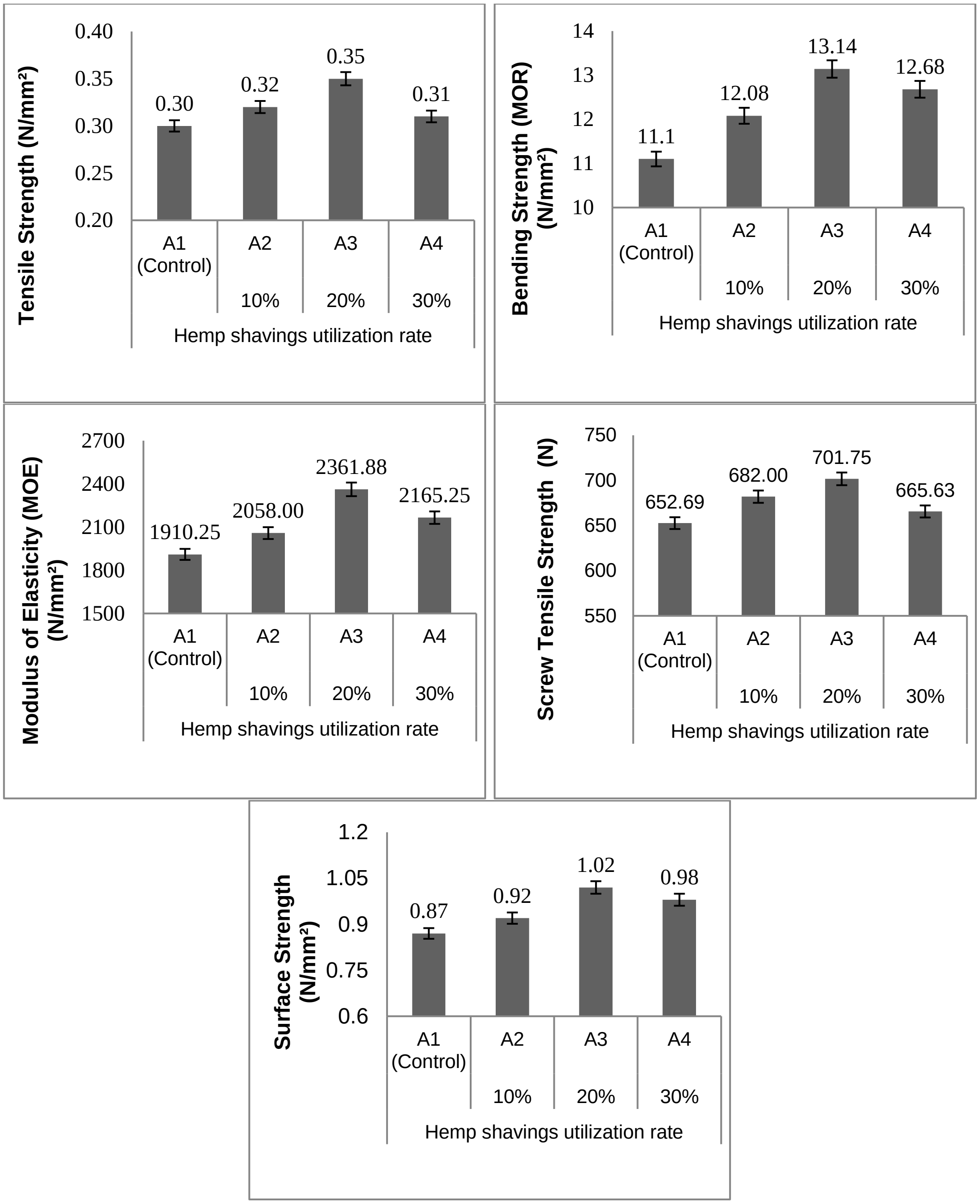

Fig. 4. Average values of mechanical properties (corresponding to dry conditions)

This was explained by the cell structures of hemp, chip geometry, and chemical properties thought to affect resin curing. Grigorov *et al*. (2022) showed a 94% increase in tensile strength in their research using 60% hemp chips in the chip draft. This increase was evaluated as an increase in the compression ratio as a result of the falling density of hemp and thus increasing the bonding ability between the chips. Auriga *et al*. (2022) found significant increases in the tensile strength of samples containing 25% hemp chips in the middle layer in their study. Vos (2005) stated that the lower proportion of fine material in hemp chips compared to wood particles will increase the mechanical and physical properties of the test samples produced (Hosseinaei *et al*. 2011; Réh and Vrtielka 2013; Kallakas *et al*. 2018).

Considering the overall board density, the higher density provides higher MOR and MOE due to better compaction. For surface layer, increase in density provides increase in resistance to outer fiber stress. An increase in modulus of elasticity in surface layers causes stiffness increases but decreases in deflection. Based on Table 5, the use of hemp chips had a statistically significant effect on flexural strength and modulus of elasticity. From the test results, it was seen that all values were above the upper limit determined for P1 type particleboards TS EN 312 (2012). In Fig. 4, the highest flexural strength and modulus of elasticity were found in A3 test specimens with 13.1 N/mm² and 2360 N/mm², respectively, which showed an increase of 18.4% and 23.6% compared to the control specimens and 20% hemp was used, while the lowest values were seen in A1 control specimens with 11.1 and 1910 N/mm². From the test results, an increase in flexural strength and modulus of elasticity values was determined with the increased content of hemp chips in the chip draft. This can be said to be due to the fact that the lower bulk density of hemp, the upper and lower surface layers gain elastic structure by receiving more uniform pressure during the pressing stage. It is understood that the findings obtained from the research are compatible with the studies conducted in the literature. Nikvash *et al*. (2010) investigated the effect of sugar cane, canola, and hemp residues from annual plants and found 19% and 9% increase in flexural strength and modulus of elasticity, respectively, in the experimental groups using 10% to 20% hemp sawdust. Moulana (2012) mentioned the positive effect of the use of hemp sawdust on bending strength in experimental samples obtained by mixing wood and hemp sawdust in the range 0 to 100%. Li *et al*. (2014) found a 35% increase in bending strength and a 29% increase in elastic modulus in experimental samples obtained by mixing 60% hemp sawdust and 40% wood chips in the chip blank. Sam-Brew (2017) found a 44% increase in bending strength and a 30% increase in elastic modulus in particleboards obtained from pure wood and hemp sawdust with 5% diphenylmethane diisocyanate (pMDI) resins. Grigorov *et al*. (2022) found a 65% increase in bending strength and a 34% increase in elastic modulus in experimental samples produced with UF resin using 100% hemp particles in the middle layer of the chip blank. Zvirgzds *et al*. (2022) stated in their research that as the hemp shive size increases, the bending strength improves and that plant residues with suitable geometry can be used in particleboard production. Auriga *et al*. (2022) mentioned increases in bending strength and elasticity modulus in the experimental samples obtained by using 25% hemp shives in the middle layer. Vos (2005) stated that as the ratio of fine material decreases in the middle layer of the chip draft, the bending strength and elasticity modulus would increase proportionally.

Table 5 shows that the hemp shives usage had a statistically significant effect on the surface strength values. It was stated from the test results that all values were above the standard values determined for P1 type particleboards by TS EN 312 (2012). In Fig. 4, the highest surface strength value was seen in the A3 test sample with 1.02 N/mm², which showed a 17.2% increase compared to the control samples and 20% hemp, while the lowest was seen in the A1 control sample with 0.87 N/mm². According to the test results, an increase in surface strength resistances was detected due to the increase in hemp shives. This situation was explained by the fact that the chip blank received more uniform pressure as a result of the low bulk density of hemp and the increase in bonding and surface densities between the surface and the middle layer. It was understood that the findings obtained from the study overlap with the studies conducted in the literature. In his study, Moulana (2012) detected a 65% increase in surface strength resistance due to the increase in hemp in the middle layer of the chip blank. This increase was explained by the chip draft taking better pressure and increasing the surface contact between the chips. Vos (2005) and Zvirgzds *et al*. (2022) stated that as a result of their studies, the mechanical strength of the panels obtained by using hemp sawdust with low dust content and not fine.

The use of hemp sawdust had a statistically significant effect on the screw holding resistance as well. It was seen from the test results that all values were above the value determined in TS-EN 312 standards. As can be understood from Fig. 4, the highest screw holding resistance was determined in A3 test samples using 20% hemp, which increased by 7.5% compared to the control samples with 702 N. The lowest was seen in A1 control samples with 653 N. From the test results, it was determined that the use of hemp sawdust in the middle layer of the chip blank had a positive effect on the screw holding resistance. This was evaluated as the increased chip blank height as a result of the low bulk density of hemp receiving better pressure during the pressing stage and thus increasing the bonding between the chips. It was seen that the results obtained from the study were compatible with the literature. Grigorov *et al*. (2022) mentioned significant increases in screw holding resistances depending on the use and increase in hemp. Zvirgzds *et al*. (2022) and Sam-Brew and Smith (2017) stated that when hemp sawdust of appropriate size and geometry is mixed with wood chips, particleboards with high mechanical performance can be obtained. Increase surface density of the particleboard improves the mechanical interlock between screw threads and wood particles. Densified surfaces have reduced porosity (leading to better contact area between the screw and the board) and higher local strength (enabling greater resistance to withdrawal or lateral forces) which results in higher screw withdrawal resistance and improved lateral (side) screw-holding capacity.

Considering the TS-EN 312 (2012) requirements, except for WA 24 h of A4 type product, values of all mechanical and physical properties were considerably higher than the minimum values. Therefore, hemp utilized boards commercially marketable. However, influence of production parameters and modification agent utilization on the board features should be taken into consideration as Çamlıbel and Aydın (2022) and Çamlıbel *et al.* (2025) expressed.

CONCLUSIONS

The study investigated the usability of hemp plants in particleboard production. For this purpose, hemp shives and wood chips were mixed in different proportions to obtain particleboards. The results obtained from the research are given below.

1. It was understood that the use of hemp shives in the chip draft has a statistically significant effect on the mechanical, technological, and physical properties of the particleboards and meets the limit values specified in the standards. All the mechanical features were positively affected by hemp shives utilization. Physical properties were negatively affected. The highest mechanical properties were obtained by 20% utilization. The formaldehyde emission was decreased by hemp utilization but reached its highest advancement by 20% hemp share.
2. Considering the thickness swelling and water absorption features, the dimensional stability of the boards weakens by hemp utilization. This issue should ba taken into consideration especially for surrounding conditions in application sites.

3. There are advantages and disadvantages of low bulk density hemp shive utilization in particleboard production but with proper processing and formulation adjustments, it can contribute to the production of sustainable and performance-compliant particleboard.

As a result, it was understood that with the use of hemp shives, P1 type particleboards with higher performance at low densities that the furniture industry may need can be produced. It was also determined that hemp plant can be used as an alternative source to wood raw material in the future. In this direction, it is recommended to carry out new studies with different resin types and chemicals.

ACKNOWLEDGMENTS

I would like to thank the Kastamonu Entegre Ağaç Sanayi ve Ticaret A.Ş. Kastamonu factory management for their support in supplying materials and conducting tests in this study.

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Article submitted: February 21, 2025; Peer review completed: April 19, 2025; Revised version received and accepted: April 30, 2025; Published: May 13, 2025.
DOI: 10.15376/biores.20.3.5361-5376