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Properties of lightweight particleboard made with sunflower stalk particles in the core layer

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Properties of lightweight particleboard made with sunflower stalk particles in the core layer

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Abstract

In this study we assessed the possibility of manufacturing lightweight particleboards using sunflower (*Helianthus annuus* L.) stalk particles. Three-layer lightweight particleboards with target densities of 350, 450 and 550 kg/m^3 were produced with different proportions of wood-to-sunflower stalk particles (100:0%, 75:25%, 50:50%, 25:75%, 0:100%) in the core layer. The outer layers consisted only of wood particles. The boards made entirely with wood particles in the outer and core layers were reference boards. Conventional urea-formaldehyde (UF) resin was used to bond the particles. It was found that the replacement of wood particles in the core layer with sunflower stalk particles led to an improvement in the physical and mechanical properties of lightweight UF-bonded particleboards. Three-layer boards with the optimum combination of 100% wood particles in the outer layers and 100% sunflower stalk particles in the core layer had slightly higher bending strength (MOR) and modulus of elasticity (MOE) than boards made entirely from 100% wood particles, but much greater internal bonding strength (IB), lower water absorption (WA) and less thickness swelling (TS) at the same board density. The MOR, MOE and IB values for 550 kg/m^3 boards containing 100% sunflower particles in the core layer were higher than the reference boards by 16.3%, 16.6% and 62.7%, respectively. The MOR, MOE and IB of lightweight particleboards with densities of 450 and 550 kg/m^3 made with 100% sunflower particles in the core layer fully complied with the CEN/TS 16368 standard for both types of board, LP1 and LP2. Substitution of wood particles with sunflower stalk particles does not cause negative changes in the formaldehyde content of the boards.

Keywords: lightweight particleboard; sunflower stalks; wood particles; urea-formaldehyde resin; physical and mechanical properties.

1. Introduction

Over the last decade, manufacturers of wooden boards have faced the acute problem of a shortage of wood raw materials and higher prices caused by growing demand for wood from the woodworking, construction and energy industries. The consumption of wood around the world, especially in developing countries, has led to deforestation rates 10 times higher than afforestation (Mantau, 2012). Thus, most countries are already experiencing a shortage of forests, especially yielding wood of industrial importance. One of the ways to solve this problem is to reduce the use of whole wood in making wooden products by substituting lightweight particleboards with a lower density than conventional boards, and using non-wood raw materials to produce them. Alternatives to wood include agricultural waste, fast-growing and annual plants and recycled wood products. The density of conventional particleboard typically ranges from 600 to 750 kg/m^3 (Suchsland and Woodson, 1986). According to CEN/TS 16368 (2014), lightweight particleboards are those with a density of less than 600 kg/m^3.

Lightweight particleboards have several advantages for manufacturers, designers and consumers over conventional boards. They are flexible in design (use of thick elements, easier installation), easier to transport and handle, and involve lower transport and raw material costs (Bekhta et al., 2022; Michanickl, 2006). Weight ranks third (after design and price) on the list of priority attributes for a buyer when purchasing household furniture (Khojasteh-Khosro et al., 2020). However, it should be remembered that the operational properties and, above all, the mechanical characteristics of wood materials depend significantly on their density. The lower the density, the lower the strength and stiffness of the material; the proportion of small voids and pores increases significantly, which complicates processing.

One of the various trends in reducing the density of wood boards is the use of annual or perennial plants (Balducci et al., 2008; Meinlschmidt et al., 2008) and the combination of wood raw materials with agricultural fibres (Dziurka and Mirski, 2013; Meinlschmidt et al., 2008; Mirski et al., 2021). The use of agricultural waste can both benefit the environment and solve socio-economic problems since otherwise it is usually ploughed into the soil or burned in the field (Papadopoulos et al., 2019;

Sun et al., 2013). Such waste is a renewable resource and can be used successfully as a raw material for particleboard manufacturing. Over the past few decades, many studies have been conducted on a wide range of agricultural waste from many different regions of the world: wheat straw (Bekhta et al., 2013), rape straw (Dziurka and Mirski, 2013), rice straw (Hussein et al., 2019), cotton stalks (Guler and Ozen, 2004), hemp shives (Auriga et al., 2022; Réh and Vrtielka, 2013; Sam-Brew and Smith, 2017; Zvirgzds et al., 2022), flax shives (Sam-Brew and Smith, 2017), tea leaf waste (Yalinkilic et al., 1998), reed stalks (Kord et al., 2015), vine prunings (Yeniocak et al., 2014), cup plant (Klímek et al., 2021), hay (Pipiska et al., 2023) and sunflower stalks (Khristova et al., 1996). Sunflower stalks are one of the most common sources of waste lignocellulosic biomass and their use as a raw material in the wood industry could lead to environmental (Vaňová, 2021) and economic benefits (Klimek et al., 2016). Sunflower stalks are usually burned, causing environmental damage and economic loss to the country. Sunflower is the fourth largest source of oilseeds worldwide with over 25 million hectares under cultivation (Diaz et al., 2011). It is estimated that 3-7 tonnes of dry biomass can be obtained from each hectare of harvested sunflower, including plant heads (10%) and stems. The volume of cultivation increased annually by 10-20% to meet increasing demand for vegetable oil, which has led to a significant increase in the availability of waste sunflower stalks (Pilanee et al., 2009).

The use of sunflower stalks in particleboard manufacture has been the subject of several studies (Bektas et al., 2005; Gertjejansen et al., 1972; Gertjejansen, 1977; Güler et al., 2006; Khristova et al., 1996) and the material has been found technically suitable for this application. Gertjejansen et al. (1972, 1977) demonstrated that adding sunflower hulls to aspen phenol-formaldehyde (PF)-bonded particleboards (with densities of 670 and 770 kg/m^3) had a deleterious effect on the strength properties, dimensional stability and decay resistance of the board. However, the removal of the pith and increase in board density increased MOR and IB. Kristova et al. (1996) used sunflower stalks as a basic raw material to make particleboards with densities of 509-731 kg/m^3 with PF resin as the binder. They found that the higher the density of the board the better its physical and mechanical properties. In another study by Kristova et al. (1998), particleboards using sunflower stalks with superior properties were prepared with a tannin-to-urea formaldehyde resin ratio of 1:9 (or 10%) in the density range of 550-650 kg/m^3. Balducci et al. (2008) showed that the internal bond (IB) strength of one-layer lightweight PMDI-bonded boards with a density of 400 kg/m^3 made from sunflower stalks met the requirements of EN 312 (type P2). In another study, Dix et al. (2009) found that lightweight particleboards made from hemp shives, sunflower stalks and topinambur with low densities (400-500 kg/m^3) met the minimum requirements of EN 312 for IB strength. In both of these studies, it was found that lightweight boards failed to meet the requirements for modulus of elasticity (MOE) and bending strength (MOR). Lenormand et al. (2017) made binderless particleboards with target densities ranging from 50 to 100 kg/m^3, suggesting that sunflower pith is a very good candidate for insulation application. Taghiyari et al. (2017) studied the properties of low-density insulating particleboards (450 kg/m^3) made from wood particles and waste sunflower stalks. The study conducted by Mahieu et al. (2019) demonstrated the possibility of using flax shives and sunflower bark in particleboards with two target densities: 350 and 500 kg/m^3. Other researchers (Güler et al., 2006) used sunflower stalks in combination with pine particles to make UF-bonded particleboards with a density of 700 kg/m^3. They reported an improvement in physical and mechanical properties; in addition, the boards met the requirements of general-purpose particleboards (Güler et al., 2006). The same conclusion was reached in a study using sunflower stalks combined with poplar particles for the manufacture of UF-bonded particleboards with a density of 700 kg/m^3 (Bektas et al., 2005). The effects of adding titanium oxide nanoparticles to a mixture of sunflower stalk particles and apple tree prunings on the properties of particleboards were also studied (Ghofrani et al., 2015). The addition of titanium oxide allowed the thickness swelling (TS) of the boards to be reduced slightly. A significant improvement in the TS values of boards occurred after modifying the sunflower stalks with acetylation, but this had a negative effect on the internal bond strength (IB) (Papadopoulos et al., 2019). Other scientists have studied particleboards with a density of 600 kg/m^3 using sunflower, topinambur and cup-plant stalks with methylene diphenyl diisocyanate (MDI) and urea-formaldehyde (UF) resins (Klimek et al., 2016). They found that the resulting particleboards, made from agricultural waste bonded with MDI resins, fully complied with the European standard EN 312 class P1 and were suitable for use in furniture production.

Thus, the combination of wood raw materials and agricultural fibres for the manufacture of particleboards is one of the trends that allows boards to be made with low densities and the consumption of wood raw materials to be reduced. However, most studies are related to the properties of particleboards with a density greater than 500 kg/m^3 and the use of more expansive adhesives than UF. The literature concerning the manufacture of low-density particleboards using sunflower stalks is more limited. Therefore, we aimed to assess the technical feasibility of manufacturing UF-bonded lightweight particleboards with a density range of 350-550 kg/m^3 using sunflower stalk particles and to determine their properties. The results were compared with the relevant standards for lightweight particleboards and studies by other researchers.

2. Materials and methods

2.1. Materials

Industrially produced wood particles from coniferous (75%) and hardwood (25%) species (origin: from the Ukrainian Carpathians, Ivano-Frankivsk region, Ukraine) were obtained from a particleboard factory. The moisture content (MC) of the particles was approximately 8%.

Sunflower (*Helianthus annuus* L.) stalks were collected from the Lviv region, Ukraine. Sunflower stalk particles (Fig. 1) were made by processing the stalks first with a straw cutter, and then by chipping in a hammer mill. A fine fraction was separated from the resultant particles by sieving.

The fractional composition and appearance of the wood and sunflower stalk particles used for the outer and core layers of our experimental boards are shown in Fig. 2 and are given in Table 1. The wood and sunflower stalk particles were dried in a laboratory dryer to approximately 3% MC at a temperature of 85 °C. After drying, the bulk density of each particle type was determined.

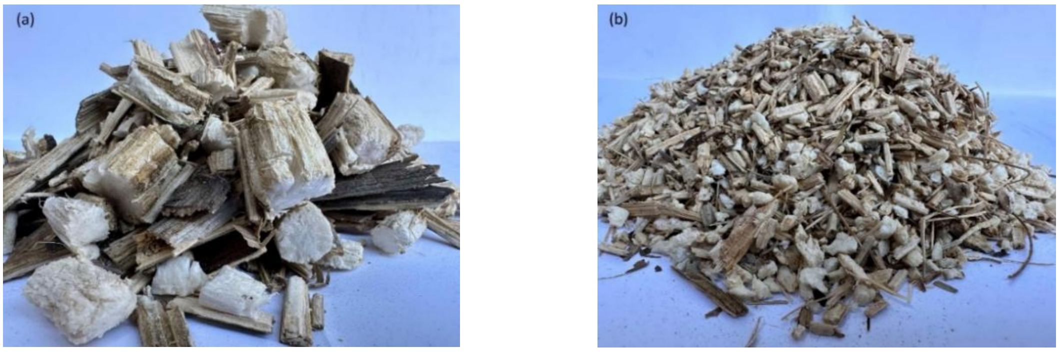

Fig. 1. Sunflower stalk particles: (a) after cutting in a straw cutter; (b) after chipping in a hammer mill.

Fig. 2. Particles used in the manufacture of lightweight particleboards: (a) wood particles for the outer layers; (b) wood particles for the core layer; (c) sunflower stalk particles for the core layer.

Table 1
Fraction analysis (% by weight) of particles used in the study.

Outer layer		Core layer		
Screen hole size (mm)	Content of wood particles (%)	Screen hole size (mm)	Content of sunflower particles (%)	Content of wood particles (%)
1.25	8.8	5.00	1.0	12.0
1.00	1.2	3.15	13.3	25.6
0.80	9.4	2.00	63.4	31.4
0.63	12.2	1.25	12.7	10.6
0.40	26.4	0.63	8.7	8.4
0.20	17.6	0.32	0.6	1.4
Dust	14.5	Dust	0.2	0.6
Total	100.0	Total	100.0	100.0

Urea-formaldehyde (UF) resin grade A (producer Karpatsmoly LLC, Kalush, Ukraine), paraffin emulsion, urea (43% solution) and ammonium sulphate [$(NH_4)_2SO_4$] (33% solution) were used to manufacture the particleboards. UF resin had the following characteristics: density 1.28 g/cm^3, solid content 66%, Ford cup (4 mm, 20 °C) viscosity 98 s, pH = 8.05 and gel time 50 s.

2.2. Determining the bulk density of particles

The bulk density of the particles was established by determining their mass and bulk volume. The volume of the glass container in which the particles were examined was determined. For this, the glass container was set on a scale, weighed with an accuracy of 0.01 g, and filled with water to the top at room temperature. The excess surface tension of water was removed from the edges of the glass with a glass rod. The container of water was weighed. The volume of the container (V in m^3) was calculated according to the formula

$$V = \frac{m_1 - m_0}{\rho_w} \times 10^{-3}, \quad (1)$$

where m_0 = mass of empty container, g; m_1 = mass of container with water, g; ρ_w = density of water, kg/m^3.

The bulk volume and mass of the particles were determined by filling a glass container of known volume with particles. The container was weighed and filled with particles to the top. Excess particles were removed by running a glass rod along the edges of the container. The container with particles was weighed (Fig. 3).

Fig. 3. Weighing of the container with particles.

The bulk density of particles of the set moisture content (ρ_{pw} in kg/m^3) was calculated using the formula

$$\rho_{pw} = \frac{m_2 - m_0}{V} \times 10^{-3}, \quad (2)$$

where m_2 = mass of container with particles, g.

The bulk density of absolutely dry particles (ρ_p in kg/m^3) was calculated using the formula

$$\rho_p = \frac{100 \times \rho_{pw}}{100 + W}, \tag{3}$$

where W = moisture content of particles, %.

2.3. Manufacturing the particleboards

Three-layer particleboards measuring 290 mm × 290 mm × 16 mm (length × width × thickness) with target densities of 350, 450 and 550 kg/m^3 were prepared under laboratory conditions. The outer layer consisted of 100% wood particles. Sunflower particles were not added to the outer layer because of the presence of a soft core in the stalk, which could have created uneven hardness in the surface of the boards and possible difficulty during lamination. Therefore, sunflower particles were added only to the core layer. The proportions of wood-to-sunflower particles in core layer were 100:0%, 75:25%, 50:50%, 25:75% and 0:100% (Table 2). Thus, the first specification was for 100% wood particles in both the outer layers and the core layer (the reference boards), while the last specification was for 100% wood particles in the outer layer and 100% sunflower stalk particles in the core layer; the other three specifications were intermediate between these extremes. The shelling ratio (outers : core) for all board samples was 33 : 67%. The amounts of UF resin, urea, hardener and paraffin emulsion required for the blending process were different for the core layer and the outer layers. This is due to the temperature difference between the surface and the core layers of the board caused by heat transfer from the surface to the core of the board. In addition, the different amount of resin and additives used is due to the difference in the surface area of the particles used in the core and outer layers of the board. The amount of solid UF resin was 14 wt.% and 9 wt.% based on the weight of dry wood particles for the outer and core layers, respectively. During resin mixing, 2.3% and 0.5% of urea solution and 0.2% and 0.6% of ammonium sulphate solution were added based on the weight of dry particles for the outer and core layers, respectively. Paraffin emulsion (0.8%) based on the weight of dry particles was added to the resin. Particles were blended with the prepared adhesive by hand. After blending, the resinated particles were evenly distributed by hand in a rectangular wooden mould, which was the basis for forming the mat. The hand-formed mat was compacted manually in the mould (Fig. 4). Next, the pre-pressed mat (Fig. 5) was subjected to hot pressing in an automatically controlled hydraulic laboratory press at a pressure of 2.5 MPa, temperature of 190 °C and pressing time of 0.37 min/mm. During the last 30 s of the pressing cycle, the pressure was gradually reduced to 0 MPa.

Table 2
Manufacturing parameters of particleboards produced in this study

Code of boards	Target density of board (kg/m^3)	Proportion of particles in the core layer (%)	
		wood	sunflower
A0		100	0
A25		75	25
A50	350	50	50
A75		25	75
A100		0	100
B0		100	0
B25		75	25
B50	450	50	50
B75		25	75
B100		0	100
C0		100	0
C25		75	25
C50	550	50	50
C75		25	75
C100		0	100

Note: Surface layers consisted of 100% wood particles.

Fig. 4. Pre-pressing the mat.

Fig. 5. The formed mat.

2.4. Testing the particleboards

After pressing, the boards were stabilised in the air until they reached room temperature. The boards were then conditioned for one week in a conditioning room where a relative humidity of 65 ± 5% and temperature of 20 °C were maintained before evaluating their properties. Three replicate boards were manufactured for each type of board, a total of 45 boards. The conditioned boards were cut to the required test sizes according to the relevant standards. The samples of each board were tested according to European standards for density EN 323 (1993), bending strength (MOR) EN 310 (1993), modulus of elasticity (MOE) EN 310 (1993), internal bond strength (IB) EN 319 (1993), and thickness swelling (TS) and water absorption (WA) EN 317 (1993). For each batch, one board was also randomly selected for analysis of formaldehyde content (FC) based on EN ISO 12460-5 (perforator method) (2015). The effects of the presence of sunflower stalk particles on the WA and TS of boards were determined on 50 mm × 50 mm samples according to EN 317 (1993) by submerging the test pieces oriented vertically in water at room temperature for 2 and 24 hours. After each submersion period, test pieces were drained of excess water and measured for change in thickness and amount of water absorbed.

Density profiles were obtained at a linear resolution of 0.01 mm across the sample thickness by using a DPX300-LTE X-ray density profile analyser (IMAL, Italy) and the average density profile was calculated.

Microscopic analysis of the inner structure of the lightweight particleboards was carried out with a Leica S6D stereo microscope equipped with a Leica DFC295 digital camera and a 0.63x c-mount adapter. Prior to the analysis the cross section was smoothed using a drum sander (the final grit was 600) and cleaned with compressed air.

2.5. Statistical analysis

The effect of the proportion of sunflower particles on the properties of the lightweight particleboards was evaluated by analysis of variance (ANOVA) at the 0.05 level of significance. Duncan's range tests were conducted to determine significant differences between mean values.

3. Results

3.1. Chemical analysis of sunflower stalk particles

The chemical composition of sunflower stalks harvested in Ukraine, in comparison with deciduous and coniferous wood species, analysed according to Trembus (2016) is presented in Table 3. As can be seen, the lignin and cellulose content of the sunflower stalks is close to that of deciduous wood and lower than that of wood from coniferous species. The presence of resins, fats, waxes and pentosans in sunflower stalks is similar to deciduous and coniferous wood species, as indicated. The holocellulose content (cellulose and hemicellulose) in sunflower stalks was higher (61.9%) than in coniferous wood (50.8-60.8%) and lower than in hardwood (59.0-77.0%). It is well known that hemicelluloses contain a large number of hydroxyl groups (Pirayesh and Khazaeian, 2012), which are predominantly responsible for the bonding with polar adhesive polymers (Ayrilmis et al., 2009) on the one hand and water uptake (Gwon et al., 2010; Nourbakhsh et al., 2011) on the other. A lower lignin content was found in the sunflower stalks than in deciduous and coniferous wood species. Since lignin is more hygroscopic than other wood constituents, this makes sunflower stalk particles easily accessible to water (Achyuthan et al., 2010); adding sunflower stalks could cause the board to take in more water (Nourbakhsh et al., 2011). At the same time, sunflower stalks contain several times more minerals (ash content) and NaOH-soluble components (starch, pectins, inorganic salts, cyclic alcohols, dyes, tannins, hemicelluloses and low-molecular cellulose fractions) than wood. If a high ash content is unfavourable for lignocellulosic composites (Khristova et al., 1996), then a high extractives content could reduce the TS and WA of particleboards (Nasser, 2012). Therefore, the chemical composition of particles can affect the physical and mechanical properties of boards made from them. However, it is very difficult to isolate a single chemical constituent as a key point of influence on the properties of boards as the chemical composition of sunflower stalks is very complex and any single constituent shows both separate and combined action with other constituents.

Table 3
Chemical composition of sunflower stalks and other raw materials (%) (Trembus 2016)

Raw materials	Soluble			Lignin	Cellulose	Pentosans	Ash
	in water	in NaOH	in alcohol-benzene				
Sunflower stalks	5.6	36.6	2.3	20.1	40.6	21.3	3.0
Coniferous wood	2.1-2.5	11.0-11.6	0.9-7.5	28-30	40-50	10.8	1.0-0.7
Deciduous wood	1.8-2.4	10.9-11.3	0.4-3.0	18-25	31-49	28.0	0.1-0.5

3.2. Bulk density of particles

The bulk density of sunflower stalk particles for the core layer was found to be about half that of the wood particles used for the outer layers (Table 4), but about 30% lower than that of the wood particles for the core layer. For board manufacturers, this means that a greater weight of sunflower particles is required than of wood particles to produce a particleboard of similar thickness. The low bulk density of sunflower stalk particles is affected by the presence of pith which is very lightweight, with a texture comparable to expanded polystyrene and a bulk density of about 35 kg/m^3 (Marechal & Rigal 1999). Since sunflower particles have a lower bulk density than wood particles, increasing their proportion in the mixture means more particles and therefore fewer voids between particles, a larger contact area between them and less space for water molecules to bond. The addition of sunflower particles creates fewer surfaces for the potential engagement of water, thus yielding lower WA. Additionally, lower bulk density of particles usually improves the IB strength because they have the tendency to pack together better during mat formation, creating a larger contact area between them. This can yield a faster heat transfer rate to the core than with wood particles.

Table 4
Bulk density of sunflower stalks and wood particles. The values shown are means from three samples. Standard deviations are in parentheses.

Raw materials	Bulk density (kg/m^3)
Industrial wood particles for the outer layer	172.4 (1.6)
Industrial wood particles for the core layer	134.3 (1.5)
Sunflower stalk particles for the core layer	95.2 (1.7)

3.3. Microstructural analysis of boards

Figure 6 shows the microscopic structure of the core layer of boards with a density of 350 and 550 kg/m^3 made of 100% wood particles (Fig. 6, A0 and Fig. 6, C0, respectively) and 100% sunflower particles (Fig. 6, A100 and Fig. 6, C100, respectively) in this layer. The microscopic images of the cross section show a clear difference between the structure of the core layers made of wood and sunflower particles. In the boards made with 100% wood particles in the core layer, the structure of this layer was less compact. The heterogeneous distribution of wood particles and a loose connection between them is observed, which leads to more voids in the layer structure (Fig. 6, A0, C0). This can be explained by the higher bulk density of wood particles compared to sunflower particles (Table 4). In addition, wood particles are more difficult to compress than sunflower particles due to their higher density. More compact structures with fewer cavities (voids) between the particles and uniform distributions of particles were observed in boards made with 100% sunflower particles in the core layer (Fig. 6, A100, C100). This is especially noticeable in samples with a density of 550 kg/m^3 where the white pith particles are highly deformed.

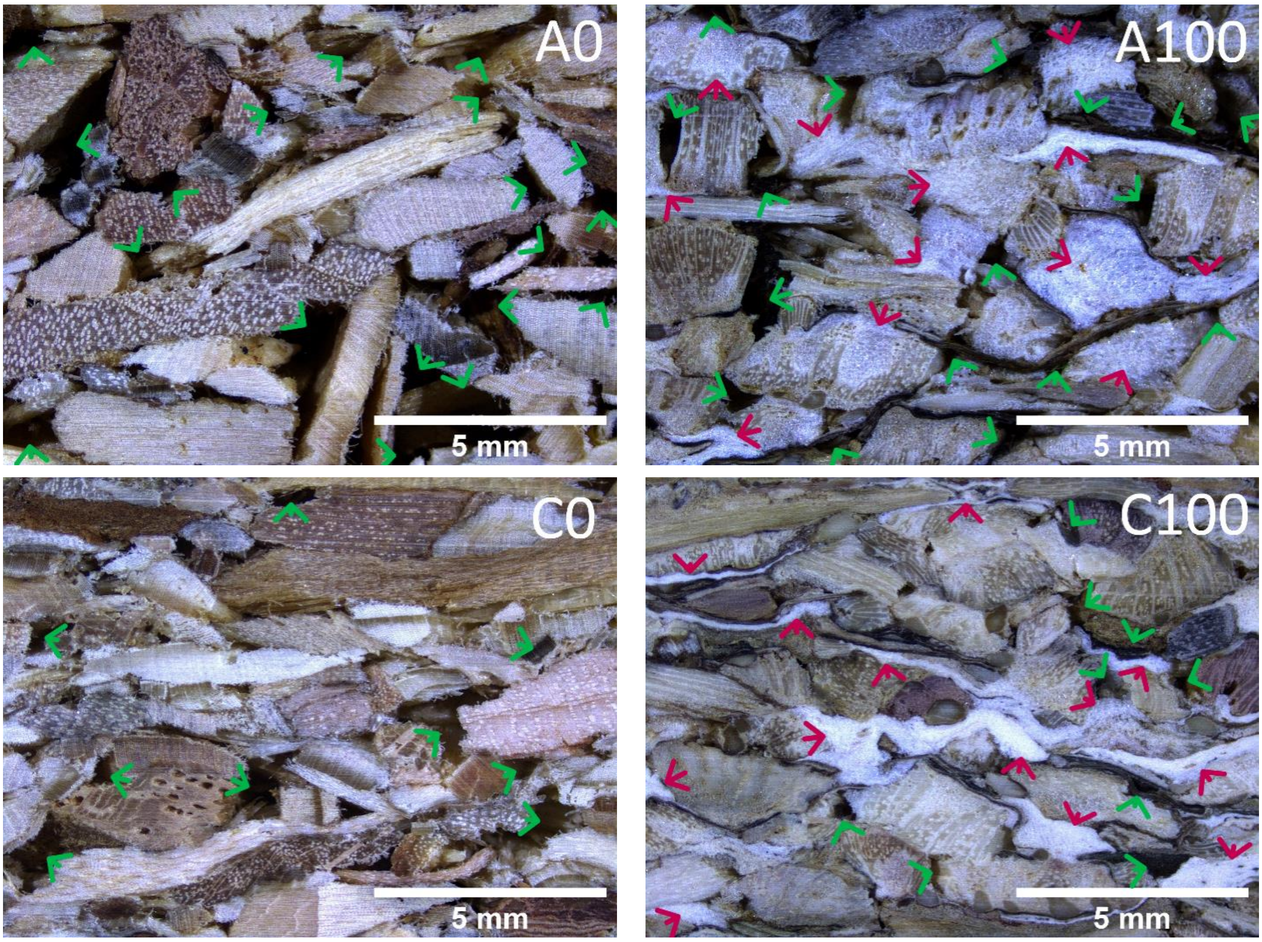

Fig. 6. Microscopic images of the structure of core layer boards made with 100% wood particles (A0, C0) and 100% sunflower particles (A100, C100) where the higher densities are labeled with C: green arrows – voids between particles; red arrows – soft parenchymatic pith tissue of sunflower stalk.

The presence of wax in sunflower particles prevents the penetration of UF adhesive, thus allowing better coating of their surface with resin (Liu et al., 2004). Thus, in the boards made with 100% sunflower stalk particles, the adhesive was uniformly distributed over the surface of the particles and filled the voids between the particles with the formation of effective bonds to provide adequate adhesion among the particles. This fact, combined with the higher plasticity of sunflower particles and their lower bulk density compared to wood particles, resulted in a better contact area between particles in the core layer (Fig. 6, A100, C100), which could undoubtedly improve their adhesion. The situation was different in the case of wood particles. Their structure is more porous than sunflower particles and they are not covered with wax. The UF adhesive penetrated them, thereby weakening the adhesive bond between the particles.

3.4. Physical properties of particleboards

Table 5 presents the average values of density, TS and WA after 2 and 24 hours for boards made with different proportions of sunflower stalk particles in the core layer. The MC of the boards was within 6%.

Table 5

Physical properties of boards (The numbers in parentheses are standard deviations. Means followed by the same letter are not significant at $p \leq 0.05$.).

Code of boards	Density of board (kg/m^3)	WA 2 h soaking (%)	WA 24 h soaking (%)	TS 2 h soaking (%)	TS 24 h soaking (%)
A0	343 (13) A	143.2 (3.1) C	153.5 (2.1) B	14.5 (0.7) C	15.8 (0.6) B
A25	334 (23) A	138.2 (6.7) C	153.1 (4.0) B	12.8 (1.0) B	14.8 (1.8) AB
A50	344 (10) A	130.1 (4.8) B	146.3 (3.0) A	12.4 (0.5) B	14.9 (0.8) AB
A75	339 (18) A	125.3 (5.6) AB	144.1 (7.1) A	11.2 (0.9) A	13.6 (1.6) A
A100	345 (14) A	118.7 (5.2) A	140.9 (6.4) A	11.1 (0.6) A	13.8 (0.7) A
B0	435 (14) A	116.4 (4.4) C	132.1 (5.1) B	16.7 (0.7) D	19.4 (0.7) B
B25	434 (20) A	114.9 (7.5) C	130.4 (5.1) B	16.0 (0.7) CD	19.0 (0.9) AB
B50	455 (15) A	105.0 (3.6) B	123.8 (4.6) A	15.7 (0.7) BC	19.1 (1.3) AB
B75	432 (11) A	103.8 (3.9) B	126.4 (3.0) AB	14.9 (0.6) AB	19.0 (0.6) AB
B100	453 (7) A	94.6 (4.1) A	122.7 (2.2) A	14.1 (0.6) A	17.8 (0.8) A
C0	551 (16) B	91.7 (2.2) A	107.8 (2.1) A	20.3 (0.8) C	25.1 (1.0) D
C25	544 (22) B	87.3 (3.3) A	107.8 (3.0) A	19.3 (1.0) C	23.9 (1.4) CD
C50	529 (27) AB	87.8 (7.9) A	108.9 (5.3) A	17.9 (1.0) B	22.8 (1.4) BC
C75	527 (27) AB	85.2 (6.0) A	107.8 (6.3) A	17.0 (0.7) B	21.4 (1.3) AB
C100	545 (26) B	85.0 (5.8) A	106.3 (6.9) A	15.9 (0.9) A	20.8 (1.2) A

The average values of the densities of the boards differed slightly but differences among these values were statistically insignificant ($p \geq 0.05$). Most likely, these small deviations of the average values of board densities from the target values were caused by the loss of material during the manual formation of the mat.

The WA and TS values were significantly different depending on the board type, proportion of sunflower stalk particles in the core layer, and time immersed in water (Table 5). The measured WA 2 h/24 h values were within the limits 118.7-143.2%/140.9-153.5% (350 kg/m^3), 94.6-116.4%/122.7-132.1% (450 kg/m^3) and 85.0-91.7%/106.3-108.9% (550 kg/m^3). The TS 2 h/24 h values were within the limits 11.1-14.5%/13.6-15.8% (350 kg/m^3), 14.1-16.7%/17.8-19.4% (450 kg/m^3) and 15.9-20.3%/20.8-25.1% (550 kg/m^3). The results of this study are compatible with previous results reported in the literature (Bektas et al., 2005; Klimek et al., 2018). Klimek et al. (2018); we found lower TS values for particleboards made from *Miscanthus* stalks than for boards made from spruce wood. Bektas et al. (2005) reported WA 2 h/24 h and TS 2 h/24 h values of 65.4%/82.2% and 19.2%/25.1% for particleboards with a 700 kg/m^3 density produced with 100% sunflower stalks.

Despite the high pith content, sunflower stalk particles affected the WA and TS properties positively. In general, it was observed that the higher the target density of the boards, the lower the WA values after 2 and 24 hours of immersion. This dependence was observed in all types of board investigated. In C100 boards containing 100% sunflower stalk particles with a density of 550 kg/m^3, the WA after 2 and 24 hours was 28.3% and 24.6% lower, respectively, than in A100 boards with a density of 350 kg/m^3. It is obvious that water penetrates into the structure of lightweight boards with a low density and a large number of pores more freely than into the less porous structure of boards with a higher density. The low porosity provides difficult diffusion in boards with high density. A similar tendency in decreasing the WA and TS values of boards with an increase in density using sunflower stalks was observed by other authors (Khristova et al. 1996; Khristova et al. 1998). WA decreased considerably with an increase in board density (Khristova et al. 1998).

With the increasing content of sunflower stalk particles in lightweight boards, their WA decreases after 2 and 24 hours of immersion in water. WA 2 h and 24 h for A100, B100 and C100 boards with target densities of 350, 450 and 550 kg/m^3, respectively, from sunflower stalk particles in the core layer were lower than for A0, B0 and C0 boards with the same densities from wood particles in the core layer. These differences in WA values for densities 350 and 450 kg/m^3 are significant ($p \leq 0.05$). The WA values after 2 and 24 hours in C100 boards with 100% sunflower stalk particles in the core layer and a target density of 550 kg/m^3 were 7.3% and 1.4% lower, respectively, than C0 boards made only of wood particles. The positive effect of the content of sunflower stalk particles in the boards on their WA is due to the lower porosity of such boards (Fig.6, A100, C100) and due to the lower bulk density of these particles, compared to wood particles (Fig.6, A0, C0). The more compact structure of the core layer from sunflower stalk particles and, accordingly, fewer cavities (voids) between particles prevent water penetration into the board. The presence of wax in sunflower stalk particles also prevents water penetration.

The content of sunflower stalk particles in the core layer also had a positive effect on the TS of the board. TS 2 h and 24 h for A100, B100 and C100 boards with target densities of 350, 450 and 550 kg/m^3, respectively, made with 100% sunflower stalk particles in the core layer were lower than for A0, B0, and C0 boards with the same densities made with 100% wood particles in the core layer. These differences in TS values for all target densities 350, 450 and 550 kg/m^3 were significant ($p \leq 0.05$). The TS values after 2 h and 24 h soaking in water for boards with a density of 550 kg/m^3 made with 100% sunflower stalk particles in the core layer were lower by 14.9% and 9.6%, respectively, than those values for boards made with 100% wood particles in the core layer. In our opinion, this effect is caused by the elasticity and non-swelling in the water of particles from the inner part of sunflower stalks. It can be assumed that the lowest TS values observed in the boards made from 100% sunflower stalks is due to the presence of pith particles. Pith is almost entirely composed of parenchyma cells, which have soft and spongy structures. Therefore, the dry pith particles in the board, due to the spongy nature of this tissue, absorb water without swelling.

TS values increased as the density of boards increased. Boards with a density of 550 kg/m^3 containing 100% sunflower stalk particles in the core layer showed 52.3% and 60.8% higher TS after 2 and 24 hours of immersion in water, respectively, than boards with a density of 350 kg/m^3.

The destruction of the adhesive joints by water causes the destruction of the board structure. Reversible strains occur in the particles after compression. Such deformations are greater in denser boards.

Other authors have reported contradictory findings (Bektas et al., 2002; Guler et al., 2006; Khristova et al., 1996). They state that the increase in the number of sunflower stalks in the mixture with wood particles leads to increasing WA and TS values of particleboards. The reason for this finding could be the high porosity of stalks, the presence of pith (parenchyma cells) and the high content of hygroscopic hemicelluloses. Papadopoulos et al. (2019) showed that acetylation of sunflower stalks greatly improves the dimensional stability but adversely affects the IB strength.

3.5. Density profile of particleboards

Vertical density profiles (VDP) show density distribution through the thickness of the board sample. These were recorded to reveal any correspondence between density and the mechanical properties, especially MOR, MOE and IB. It is known that IB depends on the bonding of the core layer (Balea et al., 2022; Pham Van et al., 2021) and that the MOR and MOE are most influenced by the strength of the face layers (Martins et al., 2021), although the MOE depends also on the material itself. Figure 7 shows the VDP of lightweight particleboards made with the addition of sunflower particles to the core layer. These VDPs did not differ significantly from the VDP of particleboards made of wood particles in the core layer (Fig. 7). In general, a usual U-shaped VDP with two symmetrical maximum peaks arranged a few millimeters from the faces as well as a minimum located in the middle area was observed for all types of board. Higher densities at the face layers are associated with higher compaction in external regions due to direct contact with the hot plates, as well as with the smaller particle size and higher adhesive content (Maloney 1993). The average densities of the outer layers were 464 kg/m^3, 689 kg/m^3 and 817 kg/m^3 in the boards with 100% wood particles in the core layer and 543 kg/m^3, 663 kg/m^3 and 766 kg/m^3 in the boards with 100% sunflower particles in the core layer for boards with a target density of 350, 450 and 550 kg/m^3, respectively.

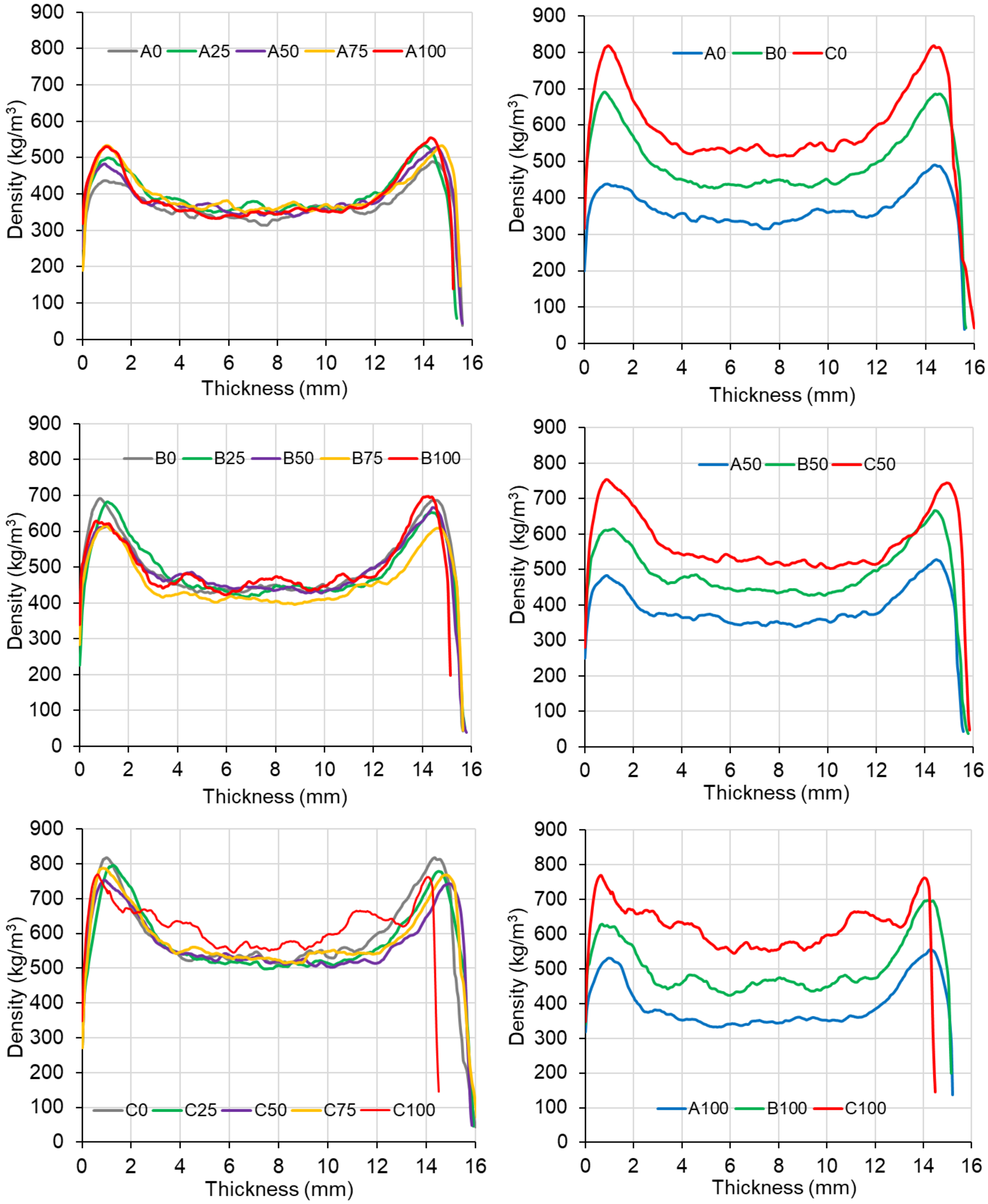

Fig. 7. The vertical density profile of particleboard samples.

The average density value in the surface layers of boards made using the two raw materials for the core layer (sunflower stalk and wood) did not differ significantly from each other for a given target board density. That is because the density of the surface layers is formed (provided) by the particles of this layer. In this study, only wood particles were used for the surface layers. A significant difference was observed only for the density values of outer layers in the lightest boards with a target density of 350 kg/m^3. Differences were observed only for the boards with different target densities, which was natural.

The average density of the core layer for boards made from sunflower and wood particles did not differ significantly with target board density. The average densities of the core layer were 344 kg/m^3, 445 kg/m^3 and 538 kg/m^3 for boards with 100% wood particles in the core layer and 351 kg/m^3, 457 kg/m^3 and 590 kg/m^3 for boards with 100% sunflower particles in the core layer and a target density of 350, 450 and 550 kg/m^3, respectively. As can be seen from Fig. 7, the largest density fluctuations along the board thickness were observed in the core layer of the A100, B100, C100 boards, which were made with 100% sunflower particles. This can be explained by the greater presence of pith, which was not separated from the particles.

The data obtained indicate that the VDP and average values of the density of the core layer did not affect the MOR and MOE, but may have been responsible for the differences in the physical characteristics and bonding strength of the boards. They also show that the compaction factor for the core layer was slightly higher for the boards using sunflower particles, due to the lower bulk density of these particles and the presence of a soft pith (parenchyma cells) that densifies easily. In addition, sunflower stalks have a lower basic density than wood (Khristova et al., 1996).

3.6. Mechanical properties of particleboards

A graphic illustration of the effect of sunflower stalk particles on the mechanical properties of lightweight particleboards is shown in Figures 8-10. In general, it was observed that increasing the target density of boards and the proportion of sunflower stalk particles in the core layer affects the board's mechanical properties positively.

The values of MOR for boards with 100% sunflower stalk particles in the core layer and a target density of 450 kg/m^3 and 550 kg/m^3 increased by 170.0% and 340.0%, respectively, compared to those values for boards with a density of 350 kg/m^3. This is because the number of adhesive contacts between the particles increases as the density of the boards increases (Fig.6, A100, C100).

In addition, for the target densities 450 kg/m^3 and 550 kg/m^3, the values of MOR (Fig. 8) were higher than the minimum lower value of 3.5 MPa established by standard EN 16368 (2014). However, the MOR values for boards with a target density of 350 kg/m^3 with sunflower stalk particles in the core layer as well as without them did not meet the requirements of this standard.

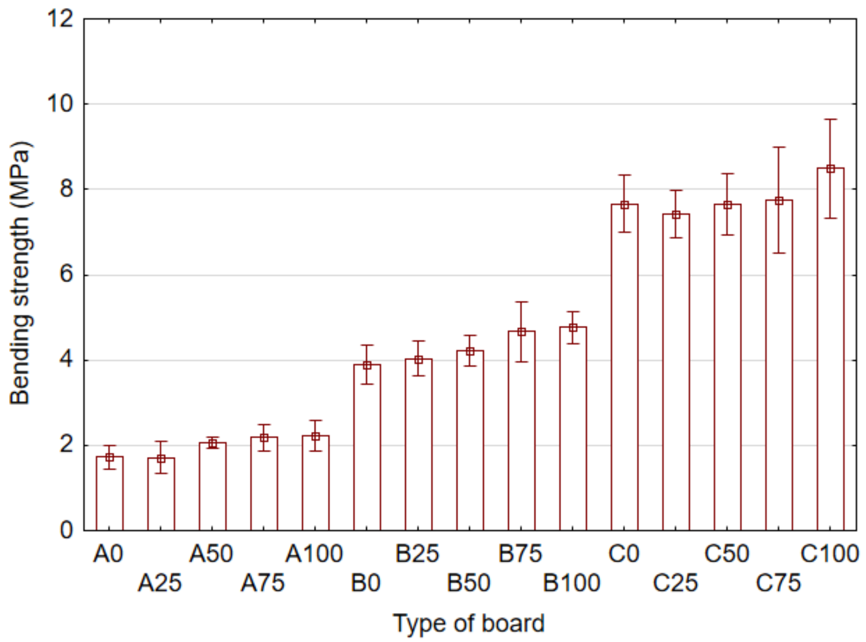

Fig. 8. Bending strength of lightweight particleboards as a function of the board's density and content of sunflower stalk particles in the core layer (error bars represent 95% confidence intervals).

The values of MOR (2.2, 4.8 and 8.5 MPa) for A100, B100 and C100 lightweight boards containing 100% sunflower stalk particles in the core layer were higher than the values of MOR (1.7, 3.9 and 7.7 MPa) for A0, B0 and C0 boards with 100% wood particles in the core layer (Fig. 8). The differences in the bending strength values between A100 and A0 boards and B100 and B0 boards are significant ($p \leq 0.05$). With increasing content of sunflower stalk particles in the core layer from 25% to 100% the MOR increased from 9.9% to 19.4%, from 3.9% to 16.9% and from 2.6% to 16.3% for a board's target density of 350 kg/m^3, 450 kg/m^3 and 550 kg/m^3, respectively. Because the sunflower stalk particles are lighter than wood particles, their volume in the board with the same density is greater than that of wood particles. This causes lower porosity of boards with sunflower stalk particles and a greater number of adhesive contacts between the particles (Fig. 6, A100, C100).

The MOE of lightweight particleboards increased with increasing density and the amount of sunflower stalks particles in the core layer (Fig. 9). The MOE values increased by 160.0% and 320.1% for boards with 100% sunflower stalk particles in the core layer and a target density of 450 kg/m^3 and 550 kg/m^3, respectively, compared to those values for boards with a target density of 350 kg/m^3. Similarly to the MOR, this is because with increasing board density, the number of adhesive contacts between the particles increases. The MOE values for the target densities of 350 kg/m^3 (only A100 boards), 450 kg/m^3 and 550 kg/m^3 are higher than the lower limit value of 500 MPa established by EN 16368 (2014). However, the values of MOE for A0, A25, A50 and A75 boards with a target density of 350 kg/m^3 did not meet the requirements of this standard.

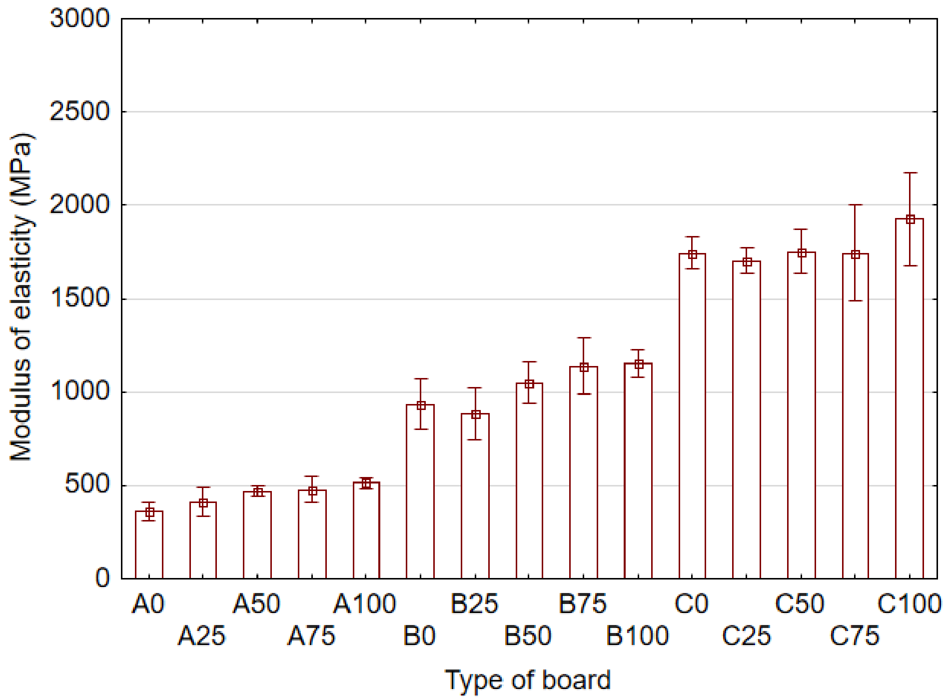

Fig. 9. Modulus of elasticity of lightweight particleboards as a function of the board's density and content of sunflower stalk particles in the core layer (error bars represent 95% confidence intervals).

The MOE values (511.7, 1153.0 and 1926.7 MPa) for A100, B100, and C100 boards containing 100% sunflower stalk particles in the core layer were higher than those values (359.0, 936.1 and 1742.6 MPa) for A0, B0, and C0 boards with 100% wood particles in the core layer. The differences in the MOE values between A100 and A0 boards and B100 and B0 boards are significant ($p \leq 0.05$). With increasing content of sunflower stalk particles in the core layer from

25% to 100% the MOE increased from 13.0% to 28.1%, from 3.6 % to 18.6% and from 1.5% to 16.6% for a board's target density of 350 kg/m^3, 450 kg/m^3 and 550 kg/m^3, respectively.

We assume that the increase in the MOE of the boards, both due to the increase in their density and the amount of sunflower stalk particles in the core layer, occurred due to a decrease in the porosity of the board and an increase in the number of adhesive contacts (Fig. 6, A100, C100). The positive influence of increasing board density on mechanical properties has been mentioned in similar work (Maloney 1993). In contrast to this study, many other scientists (Balducci et al., 2008; Bektas et al., 2002; Guler et al., 2006; Khristova et al., 1996; Klimek et al., 2016) have concluded that the mechanical properties (MOR and MOE) of particleboards made from sunflower stalks are inferior to those made from wood particles. According to them, the reason is that the excessive presence of parenchymatic pith tissue in sunflower stalks has a reducing effect on MOE and MOR. However, in this study, the sunflower stalks were used only for the core layer, and this did not adversely affect the MOR and MOE of the boards.

An increase in the density of lightweight particleboards and the amount of sunflower stalk particles in the core layer affects the IB strength positively (Fig. 10). However, not all types of board tested met the requirements of the EN 16368 (2014) standard. It was found that the values of IB strength for the boards with 75% and 100% sunflower stalk particles in the core layer and density of 450 kg/m^3 and for the boards with 25%, 50%, 75% and 100% sunflower stalk particles in the core layer and density of 550 kg/m^3 were higher than the lower limit value of 0.24 MPa established by the EN 16368 (2014) standard. The values of IB strength for boards of all investigated densities and with 100% wood particles in the core layer did not meet the specified requirements. Evidently, an adequate number of adhesive joints in porous boards of low density are not enough for the strong bonding of wood particles (Fig. 6, A0, C0).

The values of IB strength increased by 52.3% and 104.6% for boards with 100% sunflower stalk particles in the core layer and target densities of 450 kg/m^3 and 550 kg/m^3, respectively, compared to the density of 350 kg /m^3. A remarkable outcome was that A100 boards with a lower density 350 kg/m^3 with 100% sunflower particles in the core layer were characterised by insignificantly ($p \geq$ 0.05) higher IB strength (0.17 MPa) than B0 boards with 100% wood particles in the core layer, but with a higher density of 450 kg/m^3 (0.16 MPa); whereas B100 boards with a lower density of 450 kg/m^3 with 100% sunflower particles in the core layer were characterised by significantly ($p \leq 0.05$) higher IB strength (0.28 MPa) than C0 boards with 100% wood particles in the core layer, but with a higher density of 550 kg/m^3 (0.23 MPa). A possible contributory factor to the relatively low bonding properties of the wood particles in the core layer could be the higher proportion of longer and thicker particles in the mixture (Table 1), their greater stiffness and poor compressibility, which leads to an increase in space (voids, cavities) and reduces the contact area between them (Fig. 6, A0, C0).

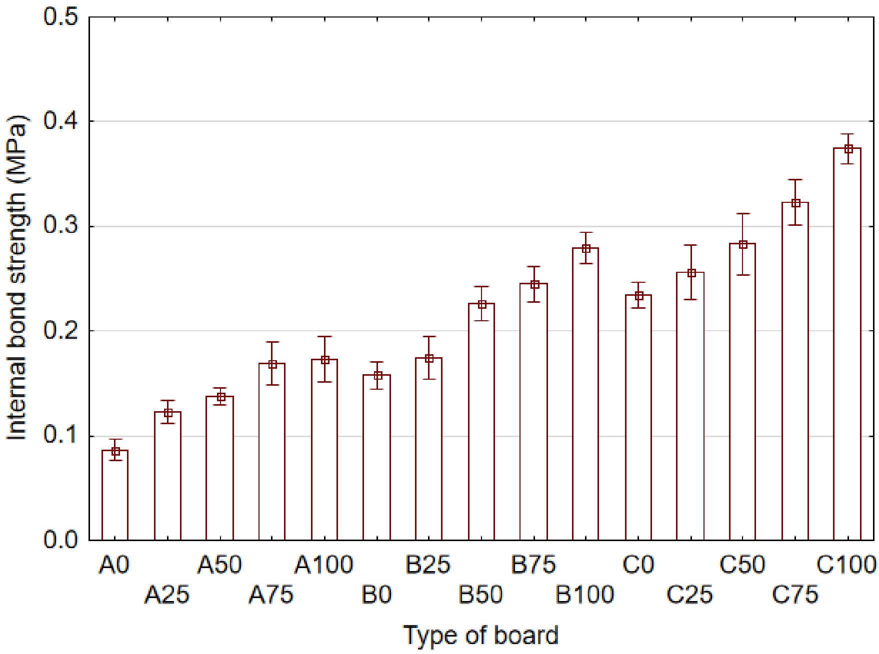

Fig. 10. Internal bond strength of lightweight particleboards as a function of the board's density and content of sunflower stalk particles in the core layer (error bars represent 95% confidence intervals).

With increasing sunflower stalk particles in the core layer from 25% to 100%, the values of IB strength increased by 36.7% and 129.8%, 17.0% and 80.0% and 10.2% and 62.7% for boards with a target density of 350 kg/m^3, 450 kg/m^3 and 550 kg/m^3, respectively. Such increasing IB strength values are facilitated by the insignificant weight of sunflower stalk particles, which occupy the core layer of the board in a larger volume than wood particles. This reduces the porosity of this layer and increases the number of adhesive contacts. Similar results were obtained by other scientists (Taghiyari et al., 2017), who produced low-density insulating particleboards (450 kg/m^3) from wood particles and waste sunflower stalks. They also found the highest internal bonds (IB) in boards made from 100% sunflower stalks and attributed this to the higher compression ratio of the sunflower stalk in the core layer. In another study, authors using hazelnut husk and European black pine particles to produce particleboards with a target density of 700 kg/m^3 observed the highest IB value in the board produced using 100% husk (Güler et al., 2009); while Guler et al. (2006), making particleboards with a target density of 700 kg/m^3 using sunflower stalks and Calabrian pine wood, found that boards produced from sunflower stalks had the lowest IB. However, they also concluded that the mechanical properties of boards made entirely from sunflower stalks, although slightly inferior, were not statistically different from those of boards made entirely from pine. Bektas et al. (2005) produced three-layer particleboards with a density of 700 kg/m^3 from a mixture of sunflower stalks and poplar wood and found that the IB of the boards was reduced with the increasing sunflower stalk concentration in the board matrix, despite the fact that all the boards still met the requirements of 0.35 MPa in the EN 312-3 (1999) standards.

In summary, it can be stated that the properties of boards manufactured entirely from sunflower stalk particles in the core layer were usually superior to those of boards manufactured entirely from wood particles. Moreover, no difference was found between the values of formaldehyde content in the boards made of sunflower particles and wood particles. The values of the formaldehyde content were less than 3.5 mg/100 g, and all tested boards met the requirements of the formaldehyde emission class E1 (≤ 8.0 mg/100 g).

Conclusions

This study confirmed the possibility of producing lightweight particleboards (450-550 kg/m^3) using sunflower stalk particles. Based on our findings, it is evident that the addition of 100% of sunflower stalk particles to the core layer significantly improves internal bond strength and decreases water affinity without worsening the bending strength and modulus of elasticity of the lightweight UF-bonded particleboard. Therefore, in order to overcome the adverse effect of the pith and some of the chemical components of sunflower stalks on the properties of lightweight particleboards, it is recommended to make the outer layers entirely from wood particles and the core layer entirely from sunflower stalk particles. Finally, the most important finding of this study is that sunflower stalks, otherwise considered agricultural waste materials, whose disposal causes environmental pollution, could be successfully used to manufacture lightweight particleboards saving wood raw materials, and the resulting boards could be used for making indoor furniture.

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