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Lignocellulosic materials from the stems of annual plants

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Abstract: *Lignocellulosic materials from the stems of annual plants.* As part of the research, lignocellulosic materials were produced based on parallel gluing of whole (not crushed into small particles) stems of goldenrod, hemp, miscanthus and willow twigs using polyurethane glue. The stems of goldenrod, hemp and miscanthus were crushed before gluing in order to "open" the tubular structure. For the materials produced, the density, density profile, modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), thickness swelling (TS) and water absorption (WA) after 2 and 24 hours of soaking in water were tested. The produced materials had a density of 500 kg/m^3. The material made of willow twigs was characterized by the highest strength parameters. Materials made of goldenrod or hemp showed comparable strength parameters, but significantly higher than the strength parameters of the material made of miscanthus. The material made from miscanthus was characterized by the highest resistance to water.

Keywords: lignocellulosic materials from annual plants, goldenrod, hemp, willow twigs, miscanthus, strength parameters, physical properties

INTRODUCTION

In recent years, the quest for sustainable alternatives to traditional raw materials has led to a surge in research focusing on lignocellulosic materials derived from annual stem plants as a promising alternative to wood. With growing concerns over deforestation, climate change, and resource depletion, the exploration of renewable and abundant sources for various industrial applications has become imperative. While wood has historically been the main source of lignocellulosic materials, stalks of annual plants such as goldenrod, hemp, willow twigs, miscanthus and other fast-growing plants have gained significant attention due to their rapid growth cycle. It is worth noting that their use may concern materials for various purposes, both in furniture and construction (Hall 2022, Abobakr et al. 2024). Lipska and Ufnowski (2023) also pointed out that utilizing by-products from agri-food processing presents numerous chances to advance polymer-lignocellulosic composite technology. However, given the abundance of available raw materials, it's essential to carefully choose those that can produce composites with comparable quality to those made from wood.

The market for building biomaterials is diverse and has the potential to significantly replace conventional materials. Architects and designers should consider all crucial factors affecting the entire structure, especially the use of building biomaterials, throughout the construction and operation phases. Once the building's lifespan ends, these biomaterials can be repurposed and reused. Building biomaterials can have a neutral or even positive environmental impact. Their significant role in the circular economy, bioeconomy, and low-carbon economy is crucial during the climate crisis. To redefine traditional building methods, it is essential to increase the availability of building biomaterials and raise consumer awareness of their benefits (Wilk and Burawska 2022). By carefully considering fiber and resin composition as well as structural design, natural fiber composites could emerge as a feasible substitute for conventional building materials down the line. While the initial results regarding structural properties and design techniques are promising for residential and light commercial construction, further research is required to fully explore their potential (Bambach 2017). Change is necessary as the demand for wood intensifies, putting pressure on forest resources. It is inevitable that improved solutions will be sought. Research is increasingly focused on exploring sustainable and environmentally friendly alternatives to conventional building materials (Pelc and Kowaluk 2023).

As previously stated wood composite industry continually requires increasing amounts of wood raw material, even as forest resources are dwindling. This reduction in wood availability has prompted researchers to explore the use of non-wood lignocellulosic biomass in composite manufacturing, such as particleboard. Agricultural waste materials and annual plant fibers have emerged as alternative raw materials for producing particle or fiber composite materials (Guuntekin et al. 2009). Kalaycıoglu and Nemli (2006) indicate that availability and utilization of natural, renewable resources globally are influenced by numerous political, economic, social, geographic, and environmental factors. In developed countries, environmental movements, landfill regulations, recycling trends, and the green movement have contributed to a scarcity of wood. Developing countries already face limited wood resources for particleboard manufacturing. Consequently, non-wood fibers are increasingly important in balancing supply and demand.

This shift towards utilizing lignocellulosic materials from annual stem plants offers several advantages over traditional wood-based sources. Firstly, it reduces the pressure on natural forests, thereby mitigating deforestation and preserving biodiversity. Secondly, the cultivation of annual stem plants can be tailored to marginal lands, reducing competition with food crops and utilizing otherwise underutilized land resources. Additionally, the conversion of agricultural residues into value-added products provides farmers with alternative revenue streams and contributes to rural development. It is also important that wood-based panels with annual plants offer environmental benefits by promoting carbon sequestration and replacing energy-intensive materials sequestration and replacing energy-intensive materials (Costa et al. 2024). Wood-based panels with annual plants have been shown to have lower environmental impacts and better performance in various impact categories compared to traditional panels, particularly in terms of human health-related impacts and the absence of certain organic chemicals (Svobodová and Hlaváčková 2023, Sugahara et al. 2024).

The key advantage of lignocellulosic materials derived from non-woody and agricultural raw materials is their similarity to wood in chemical composition and fiber structure, facilitating their use in industrial wood panel production. However, several challenges hinder the industrial application of these alternative raw materials. Some need to be grown separately, leading to economic competition with food agriculture for land use. Using agricultural residues economically in wood-based panels is currently impractical due to the resulting low-quality panels. Additionally, the varied stalk types of harvest residues typically have shorter fibers and high extractive content, which negatively impact bonding quality and adhesive compatibility in the panels (Neitzel et al. 2022).

Possible applications in the wood-based panel industry include agricultural industry residues such as: cereal straw (Mirski et al. 2021), cotton, hemp and jute stalks (Alma et al. 2005), rape straw (Dziurka and Mirski 2013), kenaf, miscanthus, and reed (Philippou and Karastergiou 2001, Kalaycioğlu and Nemli 2006), kiwi prunings (Nemli et al. al. 2003), date palm branches (Nemli et al. 2001), coffee husk and hulls (Bekalo and Reinhardt 2010), hazelnut husk (Kowaluk and Kądziela 2014), almond shell (Gürü et al. 2006), durian peel and coconut shells (Khedari et al. 2003), sunflower husk (Klimek et al. 2016), bagasse (Ghalehno et al. 2011), corn cobs (Banjo Akinyemi i in. 2016), tomato stalks (Taha et al. 2018), eggplant stalks (Guntekin and Karakus 2008), vine prunings (Ntalos and Grigoriou 2002), evening primrose waste (Dukarska et al., 2012) and apple wood (Auriga et al. 2019) or plum wood (Auriga et al. 2021).

As already indicated, wood is the primary lignocellulosic raw material used in the particleboard and fiberboard industries, but many countries also successfully use other agricultural materials. Annual plant waste like hemp shives or miscanthus grass are inexpensive and valuable resources for producing lignocellulosic boards (Kozlowski and Wladyka-Przybylak 2004). With the growing demand for sustainable insulating materials, products made from renewable flax, hemp, and coconut fibers are becoming increasingly available (Lyons 2010). Klimek et al. (2018) investigated miscanthus stalks as raw material for particleboards. He showed that particleboards made of miscanthus have lower mechanical properties than those made of spruce. In turn, Wronka and Kowaluk (2020) demonstrated that boards made from willow (Salix Viminalis L.) possess superior mechanical properties compared to those made from standard industrial particles. In turn, Zhou et al. (2024) and Abobakr et al. (2024) in his research indicates that straw-based panels exhibit excellent mechanical properties, including high flexural strength and Young's modulus, making them a viable alternative to traditional wood-based panels. Tichi et al. (2018) pointed out that the addition of rice straw to wood fiber in the production of medium density fiberboard enhanced the mechanical and physical properties of the composite. Zhou et al. (2024), examining the effect of reed straw on the properties of particle boards, showed higher mechanical strength than most straw-based and even wood-based panels, meeting heavy-duty load-bearing requirements in dry conditions

In many instances, particleboards made from alternative raw materials demonstrate mechanical properties that are comparable to or superior to those of traditional wood-based particleboards. As a result, using agricultural biomass and recycled wood waste for board production can promote sustainable development, encompassing economic growth, social inclusion, and environmental protection. Additionally, this approach can reduce the strain on forest resources and create new employment opportunities (Lee et al. 2022). It is worth noting, however, that in most research works, agricultural raw materials are crushed into small particles similar to wood particles or wood fibers. As part of this research, an attempt was made to use whole plant stems (without dividing them into smaller particles) to produce parallel-fiber composites.

MATERIALS AND METHODS

Materials

The stems or twigs of the following plants were used as a raw material for research (https://atlas.roslin.pl/):

- **Goldenrod** (Solidago) is a genus of plants from the Asteraceae family, which includes about 100-120 species. It is commonly found in North America, and some species have been introduced to Europe and other parts of the world. Goldenrod is known for its bright yellow flowers that bloom in late summer and fall, adding color to the landscape. In folk medicine, goldenrod was used as an anti-inflammatory, diuretic and wound healing agent. It contains numerous active compounds, such as saponins, flavonoids and tannins, which contribute to its health-promoting properties.
- **Hemp** is grown all over the world and has a variety of uses, from industrial to medicinal. The hemp family (Cannabaceae) includes several species and subspecies, including the most famous Cannabis sativa and Cannabis indica. Hemp (Cannabis sativa L. var. sativa) is used to produce fabrics, ropes, paper and even building materials. Hemp fibers are strong and durable. Hemp oil is rich in omega-3 and omega-6 fatty acids and can be used in the production of cosmetics, food and as a dietary supplement. Hemp is an organic plant because it grows quickly, requires few pesticides and can be grown in a variety of soils. Their root system helps prevent soil erosion and the entire plant can be used, minimizing waste.

- **Willow** (Salix) is a genus of woody and shrub plants from the willow family (Salicaceae), including about 400 species. It occurs mainly in the northern hemisphere, and the most famous species are the white willow (Salix alba), the weeping willow (Salix babylonica) and the willow (Salix caprea). Willows are characterized by long, narrow leaves and flexible branches. Some species, such as the weeping willow, have characteristic hanging branches. They prefer moist areas such as the banks of rivers, lakes and wetlands. They are also often planted in parks and gardens due to their decorative appearance. Willow wood is light and pliable, used in the production of tools, toys and some musical instruments. Young willow shoots, known as tendrils, are used to weave baskets, furniture and other utilitarian and decorative items.
- **Miscanthus** is a genus of grass plants from the Poaceae family, including about 20 species. These perennial grasses are mainly native to Asia, although they are also grown in other parts of the world for their many uses and ornamental values. Miscanthus are tall, tufted grasses with wide, lanceolate leaves and characteristic flower panicles that appear in late summer and autumn. Some species can reach a height of up to 3-4 meters. It grows best in fertile, moist soil, but is a plant quite resistant to various environmental conditions. Miscanthus x giganteus is cultivated on a large scale as an energy plant. Due to its rapid growth rate and high biomass efficiency, it is used for the production of biofuels, including pellets and briquettes, as well as for the production of bioenergy through combustion.

Raw materials for testing were made available by the Research & Development Center for Wood-Based Panels Ltd. in Czarna Woda. The first step in the production of lignocellulosic materials was the preparation of stems. All stems and twigs were cut to the appropriate length (400 mm) and then the miscanthus, hemp and goldenrod stems were crushed in a hydraulic press to split the tubular structure into strands of raw material for the better penetration of glue inside the stems.

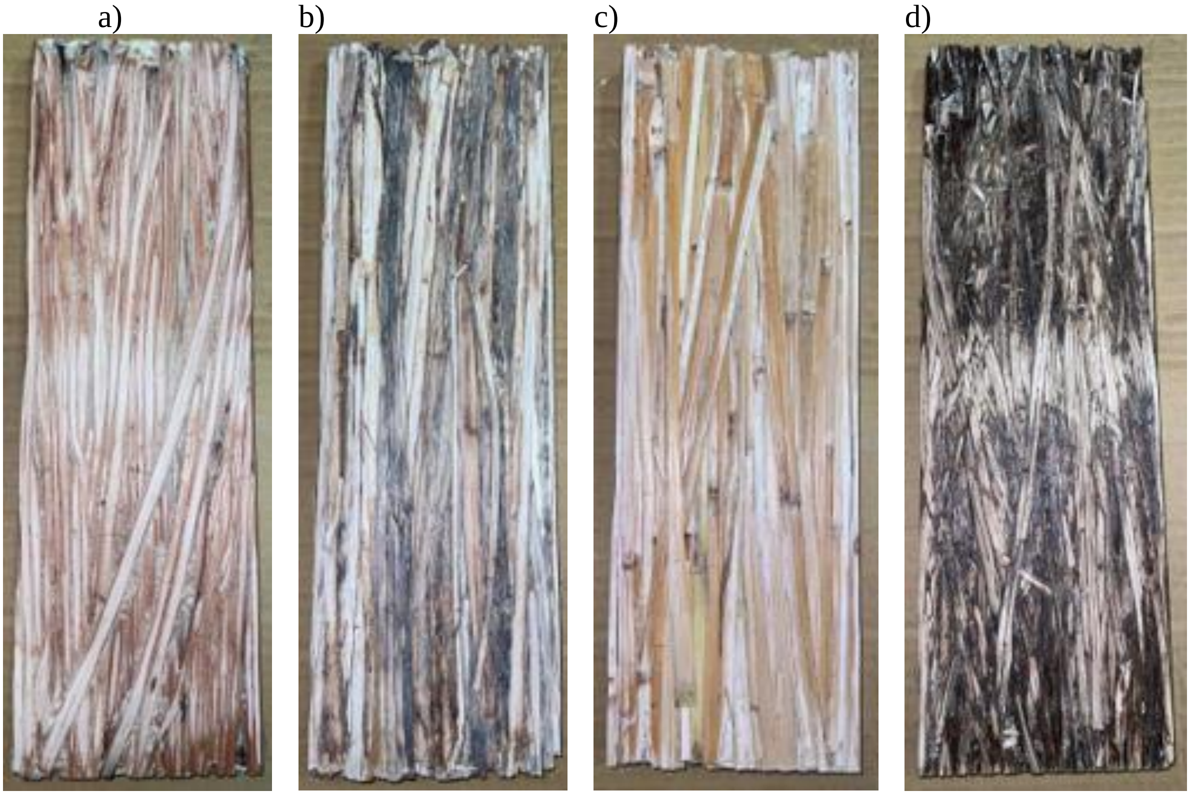

Figure.1 Lignocellulosic materials made of willow twigs (a), hemp (b), miscanthus (c) and goldenrod (d)

The moisture content of the raw materials was 8% - 10%. In the second step raw materials was covered with solvent-free, one-component polyurethane adhesive D4 Chemolan B45 (Interchemol sp. z o. o., Oborniki Śląskie, Poland). Glue was applied to the raw material manually using a brush and the glue content was 15%. In the third step raw materials were cold pressed (20 oC) in a mold with dimensions: 18x125x400mm, using a hydraulic press (AB AK Eriksson, Mariannelund, Sweden). Pressing time was 40 minutes. The pressing pressure was each time selected so that the mold was fully closed. The assumed density of the materials was 500 kg/m3. Three repetitions were made for each type of raw materials (fig. 1).

After pressing, the materials were air-conditioned in laboratory conditions (t = 20 oC, φ = 65%) for 7 days. The mechanical and physical properties of the manufactured materials were tested.

Density and density profile test

The density of the material was tested in accordance with the PN-EN 323:1999 standard. For each variant, 10 samples were tested. The density profile was examined using the Laboratory Density Analyser DAX GreCon. Density measurement was made every 0.02 mm at the measurement speed of 0.05 mm/s. For each variant, 3 samples were tested.

Modulus of rupture (MOR) and Modulus of elasticity (MOE) test

The MOR and MOE test was carried out in accordance with the PN-EN 310:1994 standard using a strength apparatus (OBRPPD, Czarna Woda).. The spacing of the supports during the test was 360 mm, and the pressure speed was 10 mm/min. For each variant, 10 samples were tested.

Internal bond (IB) test

The IB test (fig. 2) was carried out in accordance with PN-EN 319:1999 standard using a strength apparatus (OBRPPD, Czarna Woda). For each variant, 10 samples were tested.

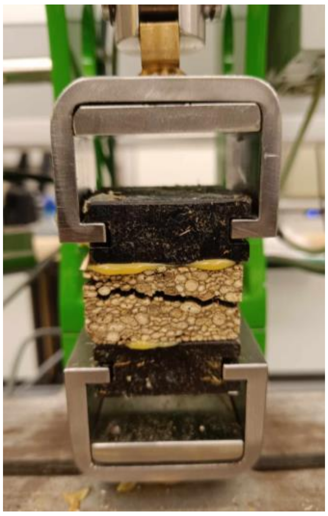

Figure 2. Internal bond (IB)

Thickness swelling (TS) and water absorption (WA) test

TS and WA testing was carried out in accordance with PN-EN 317:1999 standard. The tests were carried out after soaking the samples in water for 2 hours and 24 hours. For each variant, 10 samples were tested.

Water absorption was calculated using the formula:

$$N_{(2,24)} = \frac{m_{2(2,24)} - m_1}{m_1} \times 100\ [\%]$$

Where:

$N_{(2,24)}$- water absorption after 2 or 24h soaking in water [%],

$m_{2(2,24)}$- mass of the sample after 2 or 24h soaking in water [g],

m_1- mass of the sample before immersion in water [g].

Statistical analysis

Statistica 13 was used to conduct a statistical examination of the results obtained. This examination involved performing a one-way analysis of variance (ANOVA) to analyze the data. Additionally, Tukey's honestly significant difference test was employed to assess the significance of discrepancies among individual values.

RESULTS

The results of density testing of individual material variants are shown in Fig. 3. The highest density value of 511 kg/m^3 was observed in the variant made of hemp. while the lowest density value of 480kg/m^3 was observed in the variant made of miscanthus. The recorded difference in density values between these variants, although small - 31 kg/m^3, was statistically significant (different homogeneous groups A and B). The remaining variants were characterized by similar density values, and the differences between them were statistically insignificant (the same homogeneous groups). It is worth noting that the manufactured variants of materials with a density close to 500 kg/m^3 are in line with the current trend of obtaining low-density materials (Thoemen et al. 2010). It should be noted that the percentage influence of the type of raw material on the density of the material, although statistically significant, was relatively small, as it amounted to only 10.7% (Table 1). In turn, factors not analyzed in this research had a decisive percentage impact on the density of the material: Error = 89.3% (Table 1). These include, among others, the evenness of glue application, the degree of compression of the raw material and the redeformation of the material after pressing, and changes in moisture content.

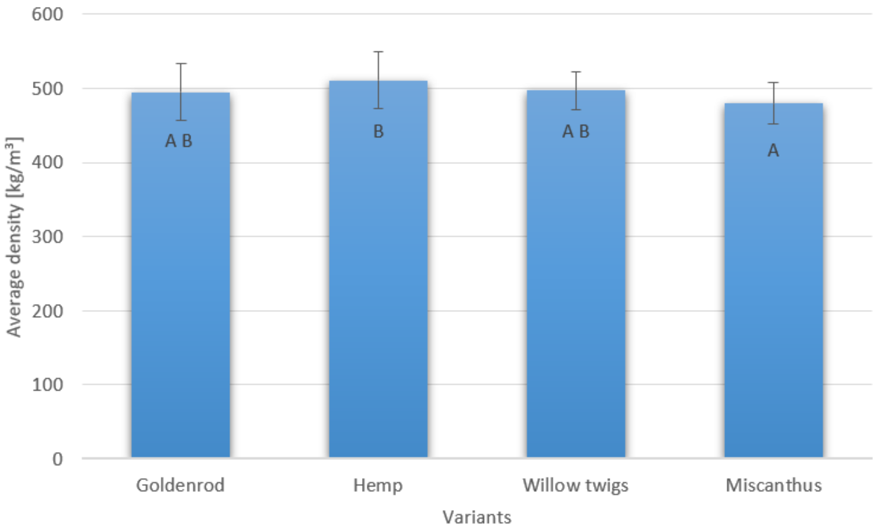

Figure 3. Average density of tested materials; A, B, C - homogeneous groups determined using the Tukey test.

The results of density profile test are presented on fig. 4. In general, it can be said that all density profiles are relatively uniform. It is worth noting, however, that the density profile of material made from willow twigs has the smallest differences. This material has the most uniform structure in cross-section (fig. 5). The greatest variation in the density profile (approx. 200 kg/m^3) was observed in the variant made of goldenrod. It should be emphasized that, unlike willow twigs, the stems of goldenrod, hemp or miscanthus have been crushed, which makes the structure of the material much more diverse (fig. 5).

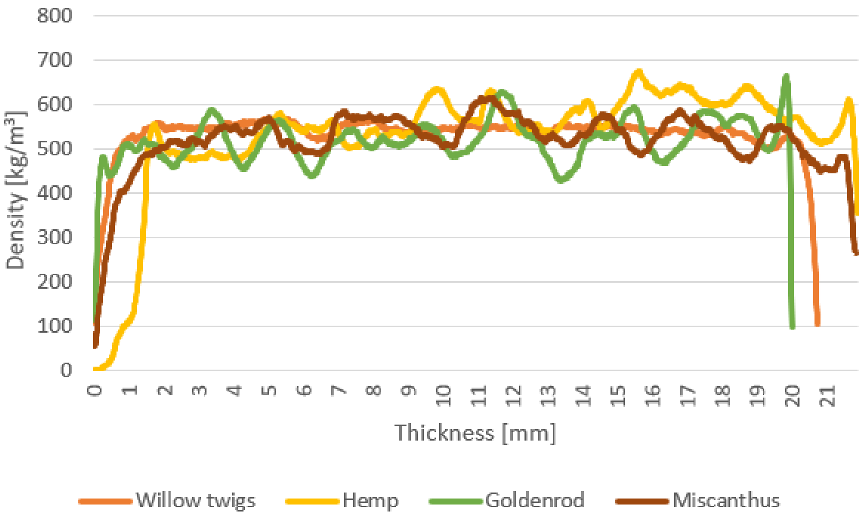

Figure 4. Density profiles of tested materials

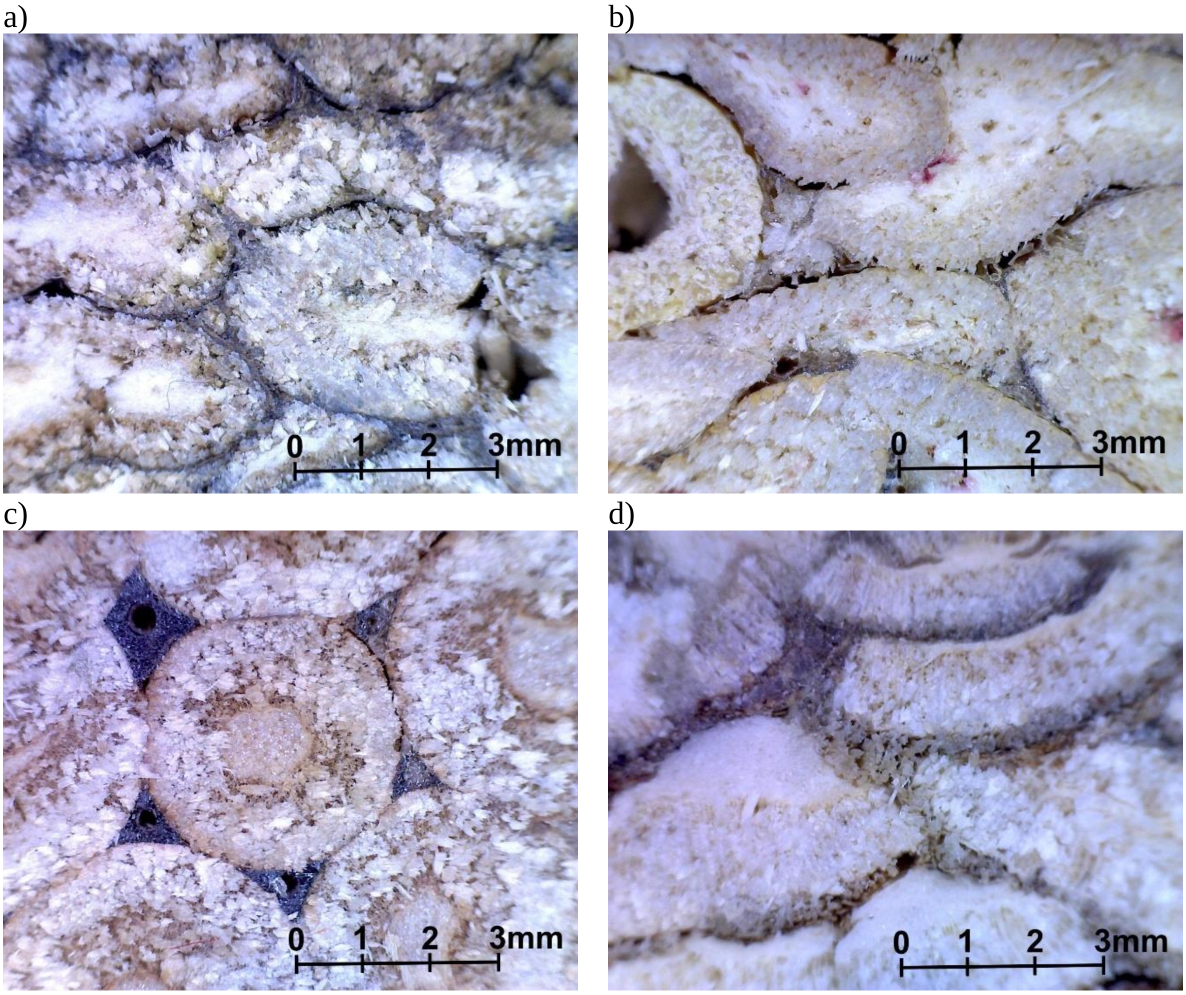

Figure 1. Cross-section of material made from: a) goldenrod, b) miscanthus, c) willow twigs, d) hemp (40x magnification)

The MOR results of lignocellulosic materials are presented in the Fig.6. The highest bending strength value of 57.6 N/mm² was observed in the variant made of willow twigs. The lowest bending strength value of 17.5 N/mm² was observed in the variant made of miscanthus. Referring to literature (Tröger et al. 1998) it was noted that particleboards made of miscanthus had similar bending strength values to boards made of wood. In turn, Balducci et al. (2008) in their research, they demonstrated that particleboards made of hemp had higher bending strength values that particleboards made of miscanthus. The highest difference of 40.1 N/mm² was observed between variants made of willow twigs and miscanthus. Taking into account the homogeneous groups determined using the Tukey test, it can be concluded that the difference in bending strength between variants made of willow twigs and miscanthus is statistically significant (the different homogeneous groups A and C). The smallest difference in bending strength of 2.6 N/mm² was observed between variants made of hemp and goldenrod. It is worth noting here that the same homogeneous groups (A) indicate that these difference is not statistically significant.

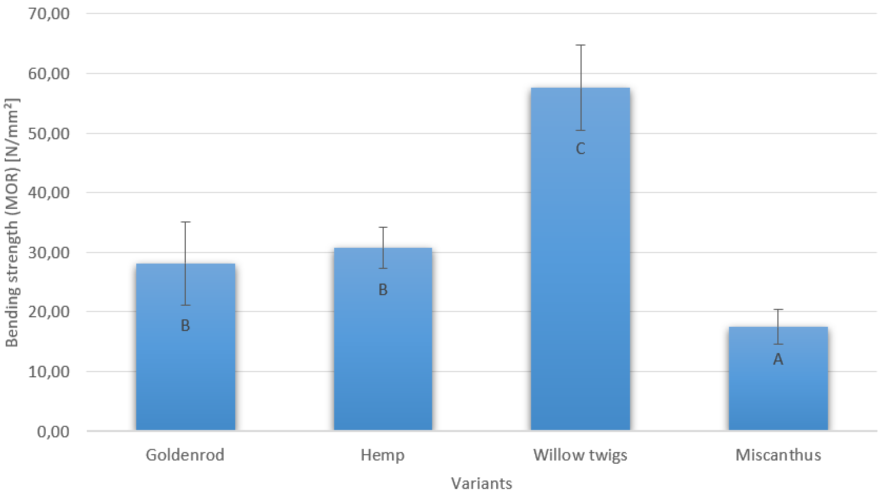

Figure 6. Average MOR values of the tested materials; A, B, C - homogeneous groups determined using the Tukey test.

The MOE results of lignocellulosic materials are presented in the Fig.7. Similarly to the case of MOR, the highest modulus of elasticity value of 6010 N/mm² was observed in the variant made of willow twigs. In turn, the lowest modulus of elasticity value of 2983N/mm² was observed in the variant made of miscanthus. It is worth noting here that Tröger et al. (1998) in their research they demonstrated that particleboards made of miscanthus had almost identical MOE values as particleboards made of wood.

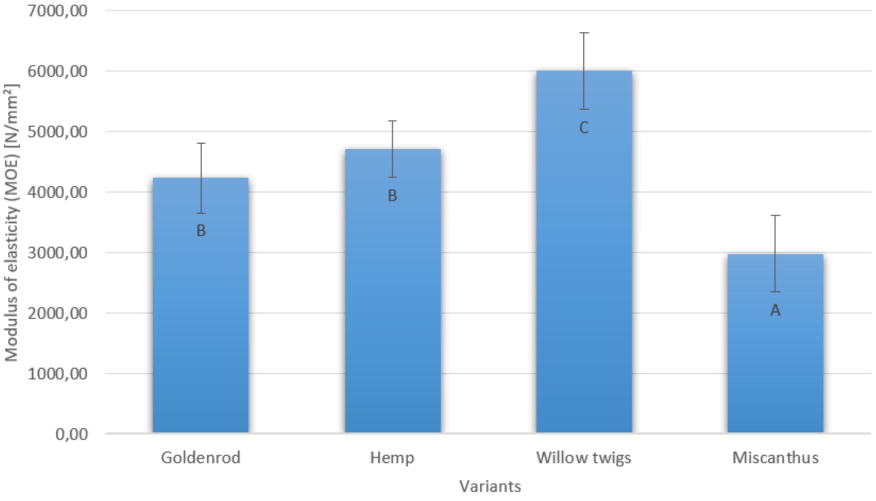

Figure 7. Average MOE values of the tested materials; A, B, C - homogeneous groups determined using the Tukey test

The highest difference of 3026 N/mm² was observed between variants made of willow twigs and miscanthus. It is worth noting that this difference, as in the case of MOR, is statistically significant (the different homogeneous groups A and C). The smallest difference in modulus of elasticity of 483 N/mm² was observed between variants made of hemp and goldenrod. These differences are statistically insignificant (the same homogeneous groups A). The IB results of lignocellulosic materials are presented in the Fig.8. Also in this case, the highest IB value of 1.61 N/mm² was observed in the variant made of willow twigs. Materials made of goldenrod, hemp and miscanthus were characterized by much lower IB values, respectively: 0.38 N/mm², 0.20 N/mm² and 0.16 N/mm². It is worth emphasizing that the differences between these values are statistically insignificant (the same homogeneous group A). In turn, the differences between the IB values for materials made of willow twigs and materials made of goldenrod, hemp or miscanthus are statistically significant (different homogeneous groups A and B). In their research Balducci et al. (2008) they demonstrated that particleboards made of hemp had higher IB value that particleboards made of miscanthus.

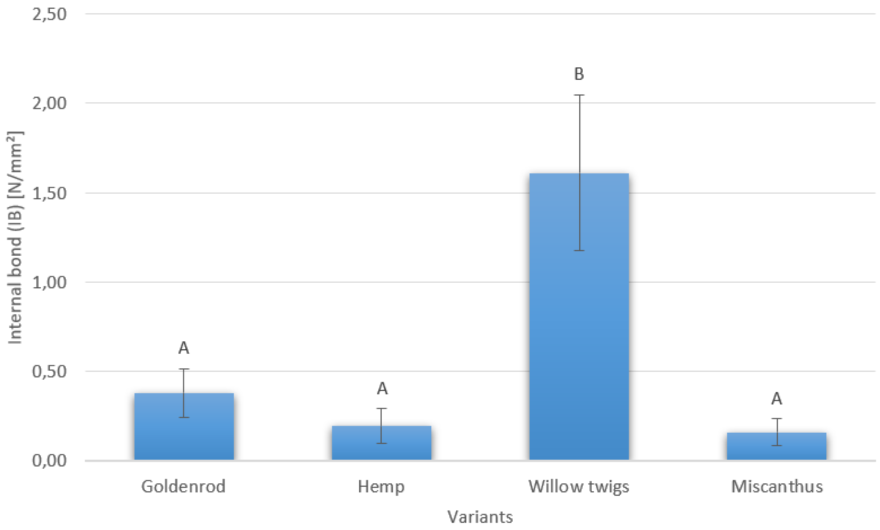

Figure 8. Average IB values of the tested materials; A, B, C - homogeneous groups determined using the Tukey test

Table 1. Analysis of variance in the results of strength tests of manufactured materials.

	Density		MOR		MOE		IB	
	p	X	p	X	p	X	p	X
type of raw material	0.033643	10.7	0.000000	89.6	0.000003	74.9	0.000000	90.5
Error		89.3		10.4		25.1		9.5

p – significant with α=0.05; X – percentage of contribution

Analyzing the produced lignocellulosic materials, it can be concluded that the type of raw material had a statistically significant impact on the values of their strength properties: MOR, MOE and IB (Table 1). The percentage influence of the type of raw material was 89.6%, 74.9% and 90.5%, respectively. It is worth emphasizing that the influence of factors not analyzed in the study was significant (Error = 10.4%, 25.1% and 9.5%, respectively).

The results of the thickness swelling test after 2 and 24 hours of soaking lignocellulosic materials in water are shown in Fig 9.. The highest thickness swelling after 2 and 24 hours values of 36.20% and 42.88% respectively were observed in variant made of hemp. It is worth noting here that Zvirgzds et al. (2022) they demonstrated that smaller particles of hemp swell 20% more in size than larger particles. In turn, the lowest thickness swelling after 2 and 24 hours values of 13.42% and 17.26% respectively were observed in variant made of miscanthus. It is worth noting that in each case (after 2 and 24 hours), the differences recorded between the values of thickness specification for material made of hemp and material made of miscanthus were statistically significant (different homogeneous groups a, c and A, C). In turn, materials made of goldenord and willow twigs are characterized by similar thickness swelling values. The differences observed both after 2 and 24 hours of soaking were statistically insignificant (the same homogeneous groups).

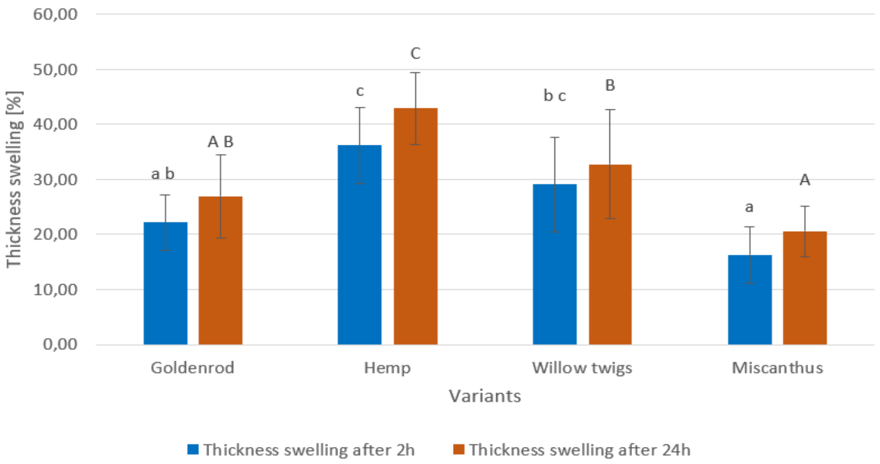

Figure 9. Average thickness swelling values after 2 and 24 hours of the tested lignocellulosic materials; a, b, c, A, B, C - homogeneous groups determined using the Tukey test

The results of the water absorption test after soaking the tested lignocellulosic materials in water for 2 and 24 hours are presented in Fig. 10. In general, it should be stated that higher water absorption values were recorded for the variants made of goldenord or hemp. The differences between these two variants after both 2 and 24 h of soaking in water are statistically insignificant (the same homogeneous geups b, B, respectively). In turn, variants made from willow twigs or miscanthus were characterized by lower water absorption values by about 30% after 2 hours and about 25% after 24 hours of soaking. It should be added, however, that also in these cases the differences between the variants were statistically insignificant (the same homogeneous geups a, A, respectively).

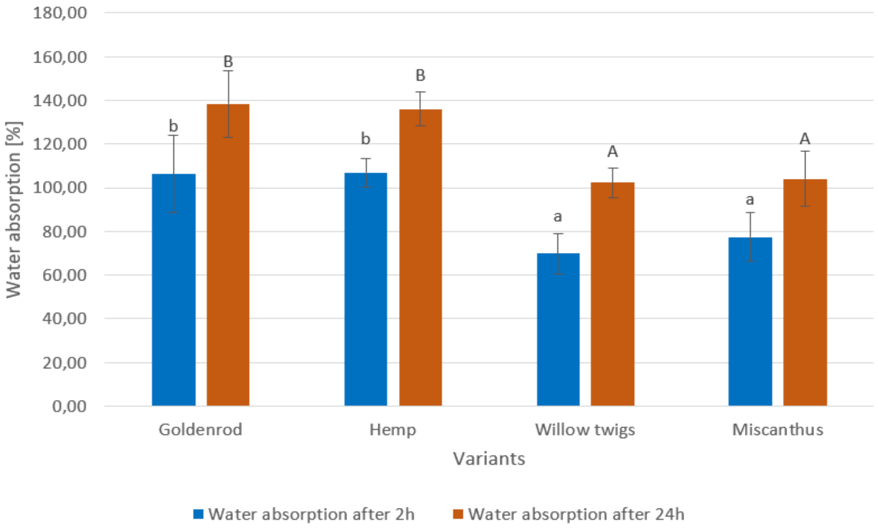

Figure 10. Average water absorption values after 2 and 24 hours of the tested lignocellulosic materials; a, b, A, B - homogeneous groups determined using the Tukey test

The analysis of variance (Table 2) showed that the type of raw material has a statistically significant impact on the resistance of the produced lignocellulosic materials to water ($p<0.05$). In each of the tested characteristics, the percentage influence of the type of raw material was significant (from 59.3% to 72.4%, respectively). The influence of factors not analyzed in this study (Error) was smaller and ranged from 27.6% to 40.7%, respectively (Table 2).

Table 2. Analysis of variance in the results of testing the physical properties of manufactured materials.

	Thickness swelling				Water absorption			
	2h		24h		2h		24h	
	p	X	p	X	p	X	p	X
type of raw material	0.000007	62.0	0.000005	59.3	0.000000	68.8	0.000000	72.4
Error		38.0		40.7		31.2		27.6

p – significant with $\alpha=0.05$; X – percentage of contribution

CONCLUSIONS

Based on the tests carried out on four variants of materials made of goldenrod, hemp, willow twigs or miscanthus, glued with polyurethane adhesive, the following conclusions can be drawn:

1. The stalks of annual plants serve as a rich and renewable source of lignocellulosic raw materials, offering a sustainable alternative to traditional raw materials in the production of materials dedicated to low-density beam elements.
2. The material made of willow twigs is characterized by the highest strength parameters (MOR, MOE, IB).
3. Materials made from goldenrod or hemp are characterized by comparable strength parameters (MOR, MOE, IB) and at the same time statistically significantly higher than the strength parameters of material made from miscanthus.
4. The material made from miscanthus has the highest resistance to water (lowest TS and WA), and the material made from willow twigs also has similar parameters.

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Streszczenie: *Materiały lignocelulozowe z łodyg roślin jednorocznych*. W ramach badań wytworzono materiały lignocelulozowe na bazie równoległego sklejania całych (nierozdrobnionych do postaci drobnych cząstek) łodyg nawłoci, konopi, miskantusa oraz witkek wierzbowych przy zastosowaniu kleju poliuretanowego. Łodygi nawłoci, konopi, miskantusa przed klejeniem były miażdżone w celu „otwarica" struktury rurkowej. Dla wytworzonych materiałów zbadano gęstość, profil gęstości, wytrzymałość na zginanie statyczne (MOR), modył sprężystości przy zginaniu (MOE), wytrzymałość na rozciąganie prostopadłe (IB), spęcznienia na grubość (TS) oraz nasiakliwość (WA) po 2 i 24h moczenia w wodzie. Wytworzone materiały charakteryzowały się gęstością 500 kg/m^3. Najwyższymi parametrami wytrzymałościowymi charakteryzował się materiał wykonany z witek wierzby. Materiały wykonane z nawłoci lub konopi wykazywały porównywalne parametry wytrzymałościowe, jednakże istotnie wyższe od parametrów wytrzymałościowych materiału wykonanego z miskantusa. Materiał wytworzony z miskantusa charakteryzował się największą odpornością na działanie wody.

Słowa kluczowe: materiały lignocelulozowe z roślin jednorocznych, nawłoć, konopie, witki wierzby, miskantus, właściwości wytrzymałościowe, właściwości fizyczne

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