WOOD RESEARCH doi.org/10.37763/wr.1336-4561/66.6.9951005
e-ISSN 2729-8906
66(6): 2021 995-1005 pp.

ANATOMICAL PROPERTIES OF STRAW OF VARIOUS ANNUAL PLANTS USED FOR THE PRODUCTION OF WOOD PANELS

RADOSŁAW MIRSKI, ALEKSANDRA BANASZAK, EWA FABISIAK, JOANNA SIUDA
POZNAŃ UNIVERSITY OF LIFE SCIENCES
POLAND

(RECEIVED APRIL 2021)

ABSTRACT

The aim of this study was to determine basic anatomical features of annual plant fibers used as wood substitutes for the production of wood-based panels. For this purpose rye, wheat, triticale, rape and corn straw were used. The determination of the morphological features of the fibers was conducted on the macerated material. Fiber lengths, fiber diameters and lumens were measured, and then the fiber wall thicknesses and slenderness ratios were calculated. The result clearly showed significant differences among all fiber characteristics of the tested plants. The strength and direction of the relationship between the anatomical properties determined in the study and the physicomechanical properties of the boards produced with straw from the tested annual plants were identified.

KEYWORDS: Straw of annual plants, anatomical properties, particleboards.

INTRODUCTION

The shortage of wood and its increasing prices lead to continuous work on re-placing the traditionally used particles in the production of particleboards (Mirski et al. 2020). Mainly trying to replace pine, spruce or birch chips with particles obtained from other lignocellulosic materials. One of the possibility is used straw of annual plants e.g. dried stalks of cereal crops, maize or rape. Term “straw” is commonly used in the case of cereals, legumes, flax and rape plants. In the EU countries, a significant amount of straw is observed as a residue from agriculture (Meyer et al. 2018). The straw of cereals, corn and rape is a by-product of agricultural production. In the case of rape, the demand to use straw results from the fact that rape is still the basic biocomponent in the production of biofuels (Markiewicz and Muślewski 2020). One of them is the use of straw as a lignocellulosic raw material in the broadly understood wood industry (for the production of large-size boards).

In Poland, in the years 1999–2018, the average annual surplus of straw harvested over agricultural consumption equaled 12.5 million tons (4.2 Mtoe) (Gradziuk et al. 2020). Cereal straw and other annual plants are different from wood, e.g. chemical composition. Depending on the species cereal straw contains 45-55% cellulose, 26-32% hemicellulose (pentosans) and 16-21% lignin (Paukszta 2006). Despite some technological difficulties, the incentives to use straw for the production of particleboards are its lower price, wide availability, its lower hygroscopicity, better thermal insulation and lower weight density (Dziurka and Mirski 2013). The concept of using these raw materials in the broadly understood wood industry is not new. The first at-tempts in this area were made in the 1960s. However, such boards have not been produced on an industrial scale. These limitations are partly due to incomplete knowledge about the properties of these raw materials, and thus the properties of the boards that can be produced under various technological conditions. The selection of wood substitutes should ensure compliance with the requirements, in terms of mechanical properties and water resistance, for boards used in the construction industry (Moriarty 2002).

The properties of oriented strand boards (OSB), in which the wood was partially or completely replaced with straw of cereals or rape, were investigated by e.g. Cheng et al. (2013), Mirski et al. (2016). Bekhta et al. (2013), Boquillon et al. (2004), Hafezi and Hosseini (2014) determined the properties of particle boards in which wheat straw was used as a substitute for wood. Dziurka and Mirski (2013), Huang et al. (2016) used rapeseed straw for the production of boards. Research also shows that white mustard can be used as a substitute for wood (Azizi et al. 2011, Bekhta et al. 2013, Boquillon et al. 2004, Dukarska et al. 2015, Grigoriou 2000, Mo et al. 2003). Moreover, Kurokochi and Sato (2015), Li et al. (2011) showed that rice straw can be use. Wu et al. (2015) conducted a study of the properties of boards produced with the use of corn straw, while Papadopoulos and Hague (2003) used flax and hemp. Papadopoulos et al. (2004), Xu et al. (2004) also applied bamboo and kenaf as a substitute for wood. Dukarska et al. (2012) for manufacture particleboards used evening primrose straw. An interesting option is also the replacement of wood particles with tomato and grape stalks, kiwi, coffee or tea waste (Bekalo and Reinhardt 2010, Guuntekin et al. 2009, Nemli et al. 2003). Medium-density fibreboards (MDF) enriched with corn or cotton stalk fibers were studied by Kargarfard and Latibari (2011). The cited studies carried out in various research centers show that not all lignocellulosic materials provide the boards produced with the physical and mechanical properties required in construction. This is the result of e.g. diversified anatomical structure, chemical composition and particle size of alternative raw materials.

Moreover, various technological conditions for the production of boards, as well as the types of adhesives used, make it difficult to compare the properties of the produced boards and to select the most appropriate substitutes for wood. In the case of gluing straw particles of annual plants, the presence of waxy substances on their surface hinders the gluing of the particles, which make worse the strength and water resistance of the boards. This problem can be solved by using iso-cyanate-based pMDI resins (Grigoriou 2000, Mo et al. 2003). For replace currently using materials, knowledge a specification of straw and their influence on particleboards properties is necessary.

Until now, research related to alternative materials instead of wood, especially straw from annual plants used in the production of particle boards or fiberboards, has focused mainly on determining the physical and mechanical proper-ties of boards made of these materials. One of the factors determining the possibilities of using straw from annual plants for the production of panels is the varied anatomical structure of these materials. The comparison of the properties of boards in which straw is the substitute for wood from different annual plants is possible if they were produced under the same technological conditions. Therefore, the aim of these studies was to determine the morphological features of straw fibers of annual plants and to determine the strength and direction of the relationship between the microstructure features and the physicomechanical properties of the boards, determined in previous studies on the same experimental material and produced according to the same methodology (Mirski et al. 2018).

MATERIAL AND METHODS

Material

In this research rape straw (*Brassica napus* L. var. Napus) (Ra), triticale straw (*Triticosecale* Witt.) (Tr), rye straw (*Secale* L.) (Ry), corn straw (*Zea mays* L.) (Co), wheat straw (*Triticum* L.) (Wh) were used. This material was obtained from the harvest in the same year, in Wielkopolska province (Poland), in the form of bales. It has been crushed and stripped of mineral impurities.

Methods

The morphological features of the straw anatomical elements were marked on the macerated material. Maceration was carried out with a mixture of acetic acid and hydrogen peroxide (30%) in the proportion 1:1, at the temperature of 60°C for 20 h. From the obtained macerates, microscopic preparations were made. Length and diameter of the fibers as well as the diameter of the lumens were measured. From each tested raw material, 30 fibers were measured, and their diameters were determined at the widest points of the tested cells. Based on the performed measurements, the thickness of the fiber walls and the slenderness ratio, which is the ratio of the length to the diameter of the fibers, were calculated. Measurements were performed using a Primo Star light microscope (Carl Zeiss Microscopy, Germany) coupled with a computer image analyzer (Motic Images Plus 4.0, Motic In-corporation Ltd, Hong Kong, China). The macrostructure of the longitudinal surfaces of the tested lignocellulosic materials was observed using a stereoscopic microscope made by Olympus (Olympus Poland) coupled with a computer image analyzer using the Motic Images Plus 2.0 program (Motic Incorporation, Ltd., Hong Kong, China).

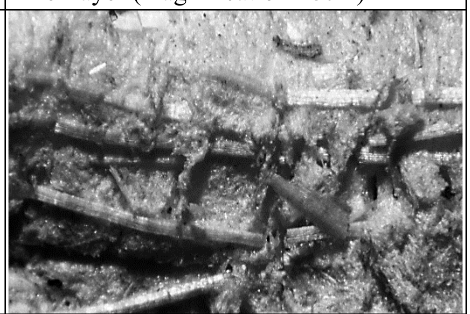
Statistical analysis was performed using Statistica 13.0 software (Dell, Round Rock, TX, USA). The descriptive statistics and one-way analysis of variance (ANOVA) were applied. All tests were performed at the significance level of $p < 0.05$.

In order to numerically determine the relationship between the anatomical properties determined in the study and the physicomechanical properties of the boards (made with the use of straw from the studied annual plants) taken from authors previous research, a correlation matrix was used.

RESULTS AND DISCUSSION

The straws of the examined annual plants differ in their macro- and microscopic structure. Rye, wheat, triticale and corn belong to the grasses, and rape is a variety of cabbage. The most important part of the straw is the tube-shaped stalk, separated by elbows into segments called internodes (Liu et al. 2018). Straw from annual plants is characterized by high morphological heterogeneity. They consist of fibers and other structural elements such as vessels and parenchymal cells. The straw walls consist of three layers. The outer layer is made of a covering tissue whose cells are characterized by serrated edges. The middle layer is made of slender, pointed bast fibers with thick walls. Apart from them, in this layer there are slightly shorter and less slender sclerenchymatic strengthening cells, concentrated mainly in the nodes forming the so-called elbows. The inner layer consists mainly of parenchymal cells, vessels and bast fibers. During the growth of these plants, their parenchyma quickly disappears and the stalk, except for the nodes, be-comes empty inside. The exception is maize, in which the nodes and internodes are filled with parenchyma (spongy core). Rapeseed, on the other hand, is a plant of the type of cabbage, hence its straw has a structure different from that of other plants and is not suitable for fodder or bedding. The parenchyma is undesirable from the point of view of adhesion and mechanical properties. From the point of view of suitability for the wood-based panels industry, the bast fibers are the most valuable cells in the straw composition. In the structure of the stem, the fiber is its most durable structural element. In addition, they have a favorable strength to density ratio and have good thermal and acoustic insulation properties.

The macrostructure images of the longitudinal sections are presented in Fig. 1. The tested lignocellulosic raw materials differ in the structure of external and internal longitudinal surfaces. The outer surfaces of the straw are smoother. On the other hand, the inner surfaces are rough due to the presence of parenchymal cells. The surface roughness is desirable as it contributes to better adhesion with the binder matrix (glue) for greater strength. It should also be noted that the particles of different straws show the presence of contaminants from the storage environment. Similar results were observed by Bouasker et al. (2014).

Material	Inner layer (magnification 60 x)	Inner layer (magnification 180 x)
Corn straw		
Triticale	Outer layer (magnification 130 x)	Inner layer (magnification 130 x)

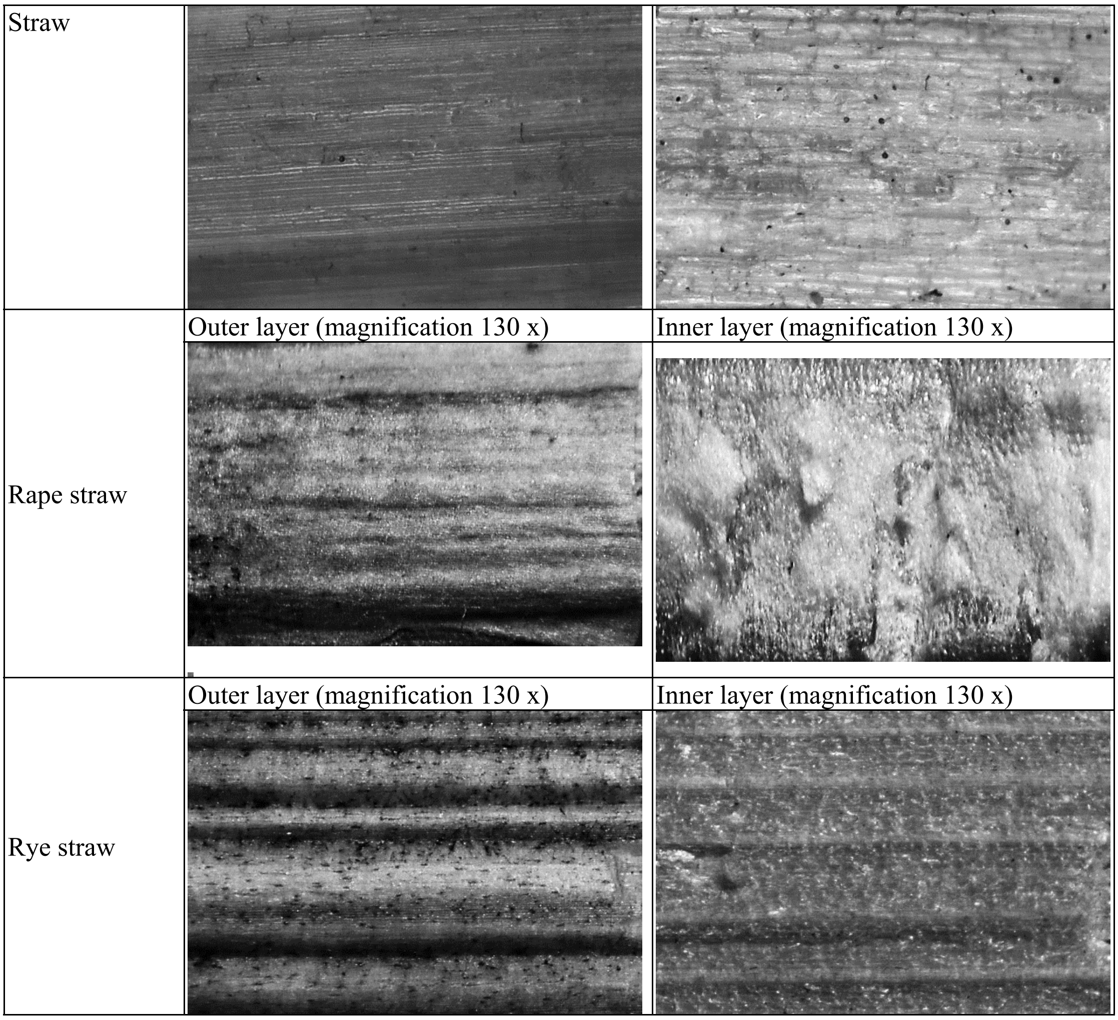


Fig. 1: Macrostructure of longitudinal sections of external and internal layers of the investigated straws of annual plants.

The results of the determination of the anatomical properties of the fibers of the tested lignocellulosic raw materials are presented in Fig. 2. The first stage of the straw morphological analysis was started with the comparison of the fiber length. Wheat has the longest fibers, the average length of these cells is 1820 µm. Literature data indicate that wheat straw fiber length was smaller (970 µm) in comparison with results of presented research (Ferdous et al. 2020). In turn, the shortest fibers were recorded for rape, as their average length was 800 µm. In the case of corn, the fibers from the inner zones of the cross-section were about 40% shorter (their average length was approximately 985 µm) compared to the outer zones. Rape had the largest diameter fibers (21.9 µm). According to these dimensions, these fibers showed the smallest slenderness, which did not exceed the value of 40. The diameters of the fibers of the tested plants were more even than their length.

The thickness of the fiber walls is also an important dimension influencing the physical and mechanical properties of the boards. Triticale and wheat fibers (about 5.6 µm) were characterized by very similar and at the same time the thickest walls. According to Ferdous et al. (2020) fiber wall thickness of wheat straw was 1.99 µm. The wall thicknesses of rye and rape fibers were about 20% smaller, and that of maize about 36%, compared to the average thickness of triticale and wheat. In the case of maize, the thickness of the fiber walls (outer and inner part) was practically the same (3.7 μm). Comparing the coefficients of variation of the measured values, it can be concluded that the highest values occurred for the fiber length and they ranged from 19% for wheat to 42% for rape. For the fiber diameter and wall thickness, the coefficients of variation were smaller and amounted to, respectively, from 21% to 30% and from 23% to 32%.

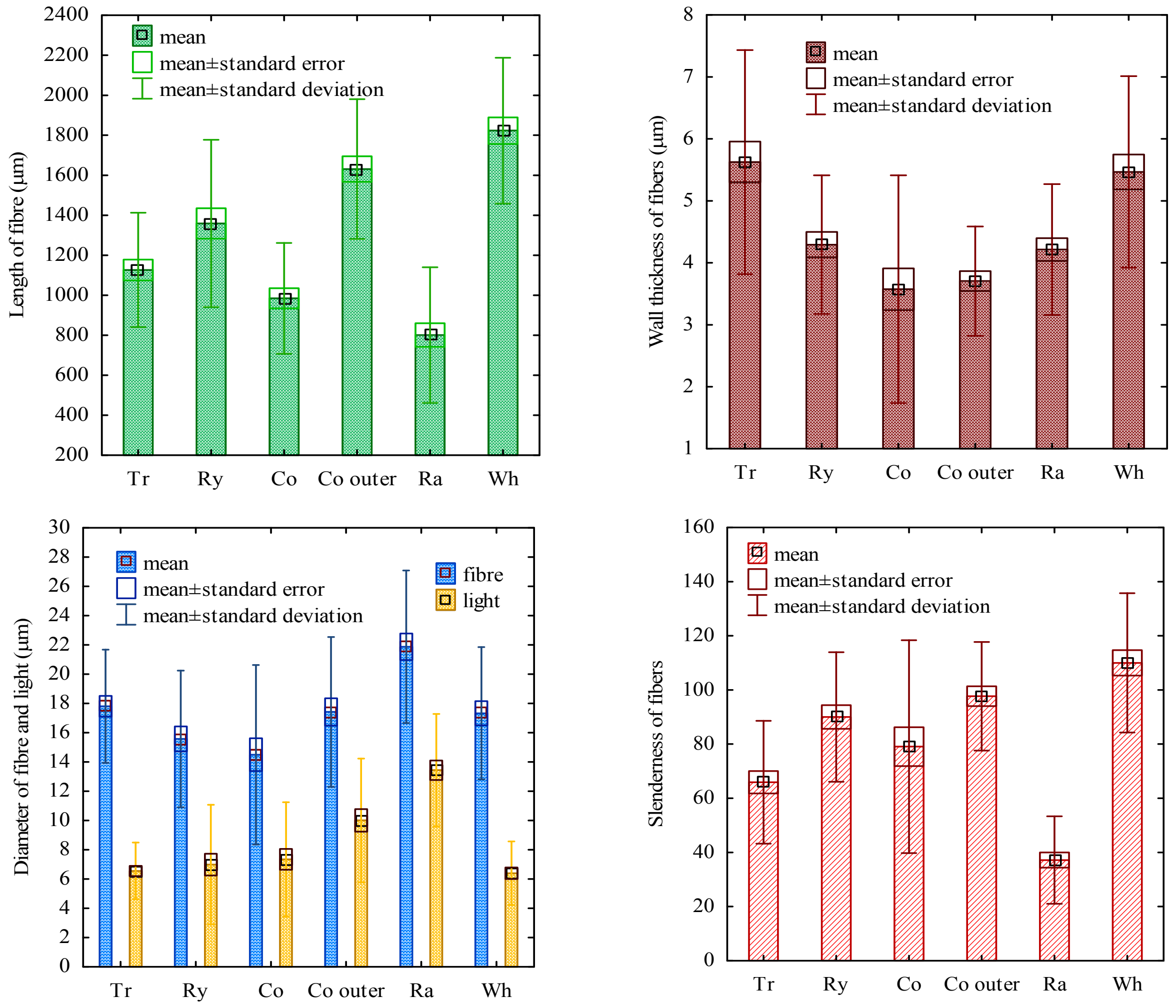


Fig. 2: Length, diameter of fibers and lumens, thickness and slenderness of fibers of tested lignocellulosic materials (Tr – triticale; Ry - rye; Co - corn; Ra - rape; Wh – wheat).

The Anova analysis of variance showed that at the significance level of 0.05, the differences in all measured fiber dimensions and the slenderness ratio of the tested plants are statistically significant. The values of the calculated Fisher F test statistics are greater than the table statistics (Tab. 1).

Tab. 1: Analysis of variance (ANOVA) of selected properties anatomical of the examined fibrous materials.

Source of variation	$F_{estimated}$ $F_{(5;177;0.05)}$	$F_{tabular}$ $F_{(5;177;0.05)}$	p
Fiber lengths (µm)	40.339	2.265	0.000
Fiber diameters (µm)	8.215		0.000
Thickness of wall of fibres (µm)	11.381		0.000
Slenders ratio	32.455		0.000

Note: df- degrees of freedom, F- value of test Fisher, p- level of significance.

In previous studies, Mirski et al. 2018 determined the physicomechanical proper-ties of three-layer boards, in which the middle layer was made of industrial pine chips and the outer layers were straw particles of the annual plants studied in this study. Physical and mechanical properties of the boards were different for the individual plants. In order to demonstrate which anatomical features of the fibers of the studied plants have an impact on the physicomechanical properties and to determine the strength of this correlation, a correlation matrix was prepared based on their mean values (Tab. 2).

Tab. 2: Density correlation matrix (ρ), modulus of rigidity (MOR), modulus of elasticity (MOE), thickness swelling (TS24) and water absorption (WA24h), fiber lengths (L), fiber diameters (Dw), lumen diameters (Dl), slenderness fibers (S) and wall thickness fibers (T) of the annual plants tested.

Correlation coefficients (p < 0.05)										
	ρ	MOR	MOE	TS24h	WA24h	L	D_w	D_l	S	T
ρ	1.000	**0.7015**	**0.7588**	-0.4335	-0.6512	0.5065	-0.0402	-0.5425	0.1686	**0.9554**
MOR		1.0000	**0.9476**	**-0.8109**	**-0.9374**	**0.9571**	-0.4248	-0.6910	0.6680	0.5224
MOE			1.0000	**-0.9043**	**-0.9884**	**0.9271**	-0.5962	**-0.8744**	**0.7559**	0.5430
TS24h				1.0000	**0.9545**	**-0.9165**	**0.8725**	**0.9426**	**-0.9613**	-0.1504
WA24h					1.0000	**-0.9600**	0.6903	**0.8970**	**-0.8436**	-0.4091
L						1.0000	-0.6349	**-0.7677**	**0.8437**	0.2721
D_w							1.0000	**0.8603**	**-0.9453**	0.2513
D_l								1.0000	**-0.8682**	-0.2771
S									1.0000	-0.1279
T										1.0000

The obtained high values of correlation coefficients indicated that the increase in fiber length resulted in an increase in modulus of rigidity (MOR) and modulus of elasticity (MOE) and a decrease in both thickness swelling (TS) and water absorption (WA) after 24 h of soaking the tested boards in water. These correlations were statistically significant at the level of 0.05 with respect to the stiffness and water absorption modulus of the boards. The increase in fiber lumen diameter facilitates access and increases the possibility of water penetration into their interior, which influenced water absorption and swelling after 24 hours of soaking the boards in water and reduced the modulus of elasticity. It should be noted, however, that these correlations are strong, as these coefficients range from 0.8744 to 0.9426, but are statistically insignificant. On the other hand, the increase in the slenderness of the fibers significantly reduces the swelling of the boards after 24 hours of soaking in water. A strong and positive, although statistically insignificant, relationship was found between slenderness and modulus of elasticity, and a strong and negative correlation was found between slenderness and water ab-sorption after 24 h of soaking. On the other hand, the correlation coefficient between the thickness of the fiber walls and the density of the boards indicates that this relationship is strong and statistically significant, as it reaches the value of 0.9554.

CONCLUSIONS

(1) The tested straws of annual plants show statistically significant differences at the level of 0.05 for all analyzed anatomical features of the fibers. *(2)* The longest fibers were recorded for wheat and these values were over two times higher than those of rape, where these cells were the shortest. Due to small differences in fiber diameters in the analyzed plants, the slenderness ratio was determined by the fiber length. The differentiation of the mean values of this coefficient was almost threefold. *(3)* The thickness of the fiber walls was similar for wheat and triticale (approx. 5.5 µm) as well as rye and rape (approx. 4.5 µm) and they were respectively approx. 35% and approx. 15% higher than corn fibers. *(4)* A strong positive correlation was demonstrated between fiber length and modulus of rigidity (MOR) and modulus of elasticity (MOE) and a strong but negative correlation between fiber length and swelling and water absorption after 24 h of soaking the panels. *(5)* A strong, positive correlation was also obtained for the relationship between the diameter of the lumen of the fibers and the thickness swelling and water absorption after 24 h of soaking the panels. On the other hand, high, but negative correlation coefficients were established between the slenderness of the fibers and the analyzed physical properties of the boards. Slightly smaller, positive values of the correlation coefficients were obtained between the slenderness of the fibers and the modulus of rigidity (MOR) and modulus of elasticity (MOE).

REFERENCES

1. Azizi, K., Tabarsa, T., Ashori, A., 2011: Performance characterizations of particleboards made with wheat straw and waste veneer splinters. Composites Part B: Engineering 42(7): 2085–2089.
2. Bekalo, S.A., Reinhardt, H.-W., 2010: Fibers of coffee husk and hulls for the production of particleboard. Materials and structures 43: 1049–1060.
3. Bekhta, P., Korkut, S., Hiziroglu, S., 2013: Effect of pretreatment of raw material on properties of particleboard panels made from wheat straw. BioResources 8(3): 4766–4774.
4. Boquillon, N., Elbez, G., SchÖnfeld, U., 2004: Properties of wheat straw particleboards bonded with different types of resin. Journal of Wood Sciences 50: 230–235.
5. Bouasker, M., Belayachi, N., Hoxha, D., Al-Mukhtar, M., 2014: Physical characterization of natural straw fibers as aggregates for construction materials applications. Materials 7(4): 3034–3048.

6. Cheng, W., Han, G., Fang, D., 2013: Oriented structural boards from split wheat straw: effects of straw length, panel density, and resin content. BioResources 8(3): 4497–4504.
7. Dukarska, D., Bartkowiak, M., Stachowiak- Wencek, A., 2015: White mustard straw as an alternative raw materials in the manufacture of particleboards resonated with different amounts of urea-formaldehyde resin. Drewno 58(194): 49–63.
8. Dukarska, D., Łęcka, J., Czarnecki, R., 2015: The effect of wood chip substitution with evening primrose waste on properties of particleboards depending on the type of binding agent. Electronic Journal of Polish Agricultural Universities: 15(2): 5.
9. Dziurka, D., Mirski, R., 2013: Lightweight boards from wood and rape straw particles. Drewno 56(190): 19-31.
10. Ferdous, T., Quaiyyum, M.A., Bashar, S., Jahan, M.S., 2020: Anatomical, morphological and chemical characteristics of kaun straw (*Seetaria italika*). Nordic Pulp & Paper Research Journal 35(2): 288–298.
11. Gradziuk, P., Gradziuk, B., Trocewicz, A., Jendrzejewski, B., 2020: Potential of straw for energy purposes in Poland. Forecasts based on trend and causal models. Energies 13: 5054.
12. Grigoriou, A.H., 2000: Straw-wood composites bonded with various adhesive systems. Wood Science and Technology 34: 355–365.
13. Guuntekin, E., Uner, B., Karakus, B., 2009: Chemical composition of tomato (*Solanum lycopersicum*) stalk and suitability in the particleboard production. Journal of environmental biology 30(5): 731-734.
14. Hafezi, S.M., Hosseini, K.D., 2014: Surface characteristics and physical properties of wheat straw particleboard with UF resin. Journal of the Indian Academy of Wood 11: 168–173.
15. Huang, L., Xia, P., Liu, Y., Fu, Y., Jiang, Y., Liu, S., Wang, X., 2016: Production of biodegradable board using rape straw and analysis of mechanical properties. BioResources 11(1): 772–785.
16. Kargarfard, A., Latibari, A.J., 2011: The performance of corn and cotton stalks for medium density fiberboard production. BioResources 6(2): 1147–1157.
17. Kurokochi, Y., Sato, M., 2015: Effect of surface structure, wax and silica on the properties of binderless board made from rice straw. Industrial Crops and Products 77: 949–953.
18. Li, X., Cai, Z., Winandy, J.E., Basta, A.H., 2011: Effect of oxalic acid and steam pretreatment on the primary properties of UF-bonded rice straw particleboards. Industrial Crops and Products 33(3): 665–669.
19. Liu, Z., Wang, H., Hui, L., 2018: Pulping and papermaking of non-wood fibers. Pulp and Paper Processing 1: 4–31.
20. Madej, A., 2016: Bilans słomy w Polsce w latach 2010-2014 oraz prognoza do 2030 roku (Straw balance in Poland in the years 2010-2014 and forecast to the year 2030). Roczniki Naukowe Stowarzyszenia Ekonomistów Rolnictwa i Agrobiznesu 18: 163–168.
21. Markiewicz, M., Muślewski, Ł., 2020: Survey performance and emission parameters of diesel engine powered by diesel oil and fatty acid methyl esters using fuzzy logic techniques. Fuel 277: 118179.

22. Meyer, A.K.P, Ehimen, E.A., Holm-Nielsen J.B., 2018: Future European biogas: Animal manure, straw and grass potentials for a sustainable European biogas production. Biomass and Bioenergy 111: 154-164.
23. Mirski, R., Dziurka, D., Banaszak, A., 2018: Properties of particleboards produced from various lignocellulosic particles. BioResources 13(4): 7758–7765.
24. Mirski, R., Dziurka, D., Czarnecki, R. 2016: The possibility of replacing strands in the core layer of oriented strand board by particles from the stems of rape (*Brassica napus* L. Var. Napus). BioResources 11(4): 9273–9279.
25. Mirski, R., Kawalerczyk, J., Dziurka, D., Wieruszewski, M., Trociński, A., 2020: Effects of using bark particles with various dimensions as a filler for urea-formaldehyde resin in plywood. BioResources 15(1): 1692–1701.
26. Mo, X., Cheng, E., Wang, D., Sun, X.S., 2003: Physical properties of medium-density wheat straw particleboard using different adhesives. Industrial Crops and Products 18: 47–53.
27. Moriarty, C.J., 2002: The effect of lab-made flakes on physical and mechanical property variability of laboratory flakeboard. Forest Products Journal 52: 69–73.
28. Nemli, G., Kırcı, H., Serdar, B., Ay, N., 2003: Suitability of kiwi (*Actinidia sinensis* Planch.) prunings for particleboard manufacturing. Industrial Crops and Products 17: 39–46.
29. Paukszta, D., 2006: Skład Chemiczny Zdrewniałej Części Łodygi Słomy Rzepakowej (Chemical composition of wooden parts of rape stem). Rośliny Oleiste – Oilseed Crops XXVII: 143–150.
30. Papadopoulos, A.N., Hague, J.R., 2003: The potential for using flax (*Linum usitatissimum* L.) shiv as a lignocellulosic raw material for particleboard. Industrial Crops and Products 17: 143–147.
31. Papadopoulos, A.N., Hill, C.A.S., Gkaraveli, A., Ntalos, G.A., Karastergiou, S.P., 2004: Bamboo chips (*Bambusa vulgaris*) as an alternative lignocellulosic raw material for particleboard manufacture. Holz als Roh-und Werkstoff 62(1): 36–39.
32. van Duren, I., Voinov, A., Arodudu, O., Firrisa, M.T., 2015: Where to produce rapeseed biodiesel and why? Mapping European Rapeseed Energy Efficiency. Renewable Energy 74: 49–59.
33. Wu, T., Wang, X., Kito, K., 2015: Effects of pressures on the mechanical properties of corn straw bio-board. Engineering in Agriculture, Environment and Food 8(3): 123–129.
34. Xu, J., Sugawara, R., Widyorini, R., Han, G., Kawai, S., 2004: Manufacture and properties of low-density binderless particleboard from kenaf core. Journal of Wood Science 50: 62–67.

RADOSŁAW MIRSKI*, ALEKSANDRA BANASZAK, EWA FABISIAK,
JOANNA SIUDA
POZNAŃ UNIVERSITY OF LIFE SCIENCES
DEPARTMENT OF WOOD BASED MATERIAL
28 WOJSKA POLSKIEGO STR., 60-637
POZNAŃ, POLAND
*Corresponding author: radoslaw.mirski@up.poznan.pl