

Article

Management of Forest Residues as a Raw Material for the Production of Particleboards

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Abstract: Expanding the base of raw materials for use in the production of wood-based materials, researchers and panel manufacturers around the world are increasingly trying to produce panel prototypes from raw materials available in a given area and climate, or by managing waste from wood industry processing. The aim of the study was therefore to test the hypothesis that forest residues derived from Scots pine roundwood harvesting have the same suitability for the production of three-layer particleboard as the wood of the most valuable part of the Scots pine stem, by comparing selected properties of raw wood material and final product—particleboard. Characterization of both the raw material and the physical-mechanical and hygienic properties of the produced panels was carried out. For these panels from the tree trunk, MOR was 14.6 N/mm², MOE 1960 N/mm² and IB 0.46 N/mm². The MOR and IB values turned out to be higher for the panel from the branch and are 16.5 and 0.72 N/mm², respectively. Excessive swelling of the panels resulted in all manufactured particleboards meeting the standardized performance requirements of EN 312 for interior furnishing panels (including furniture) for use in dry conditions (type P2).

Keywords: wood-based materials properties; formaldehyde; alternative raw materials; forest residues



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1. Introduction

According to the Food and Agricultural Organization of the United Nations report [1], global roundwood production in 2020 (including wood fuel (WF) and industrial roundwood (IR)) was estimated at 3966 million m³ (WF—1945 million m³ and IR 2021 million m³). Compared to 2000 [2], global timber production has increased by about 24%. Available models and calculations show that if the world's human population reaches 10 billion, the demand for wood will be higher than the world's supply of this raw material, which may lead to increased wood prices and uncontrolled deforestation of protected forest areas for illegal wood trading. The importance of forests and the need to protect its resources is the reason to take steps toward environmental sustainability as one of the main parameters when selecting raw materials for industrial purposes. Therefore, to maintain stability in the production of wood and protect the most valuable wood resources, measures should be taken to increase the production of wood-based materials that can replace raw wood.

Forests residues (FR) represent a raw wood material which occurs during logging operations in both mature stands and thinning interventions [3,4]. Forest residues that are eligible for further use include branches, with needles and leaves, and tree tops, as well as undersized or damaged stem parts [5]. FR is usually left to decompose naturally or for the local population, for domestic heating purposes [5–7]. However, FR has the potential to be a suitable renewable source of energy also at the industrial scale [8]. While searching for

alternative uses of a given raw material, it is necessary to take into account the three pillars of sustainable development, which are environmental, social, and economic aspects [9]. According to estimates, the amount of forest residues available for further use in Polish forests ranges from a few to several million cubic meters [10,11]. The average share of FR in the total mass of harvested wood is about 11% and depends mainly on the fertility of the habitat [6,12]. The average wood volume of forest residues (mainly pine wood residues) in the total harvest was estimated at 37.7 m³/ha [6].

Besides utilizing FR for energy purposes [5,13–15], one of the possible alternative use of forest residues is to exploit them as material for wood-based boards, i.e., particleboards [16,17]. Currently, forest wood, lignocellulosic biomass [18,19], recycled wood [20,21], and industrial wood (residues in the form of cuttings and sawdust) [22–24] are processed for the production of wood-based materials including particleboards. Combinations of lignocellulosic raw materials, recycled wood and industrial particles [25], and even wood bark [26,27] can also be used. By expanding the base of raw materials for use in the production of wood materials, researchers and panels producers from all around the world are more and more often trying to produce prototypes of boards from raw materials available in a given area and climate, or using waste from the processing of the wood industry for added-value applications. The search for new alternative raw materials is one of the key issues in line with the bioeconomy approach, especially for particleboard production, which is in high demand [28].

In addition, it is possible to produce boards from raw materials of other origins, such as annual plant residues, e.g., straws and grasses [28,29], crop residues [30,31], post-production residues from the food industry, e.g., seed husks [32,33], or residues from garden tree pruning [34,35], sugarcane bagasse [29] and other lignocellulosic wastes [18,19]. When cereal straw is used, to obtain a satisfactory board quality, binders other than those used commonly are often employed to improve the adhesion of straw particles [36,37]. When using alternative raw materials other than wood, it is most advantageous to use mixtures of wood and non-wood raw materials, as this allows to control of the strength parameters of the manufactured boards and reduces the radicality of adjusting technological parameters. At the same time, the use of alternative raw materials additives contributes to the reduction of significant amounts of waste (of various origins) and also reduces the costs of purchasing raw materials, which has positive environmental and economic aspects.

Several studies have focused on the evaluation of FR for particleboard production. Iwakiri et al. 2017 reported that it is possible to produce particleboards based on 50% of forest residues from branches, tree tops, stumps, and roots in a mixture with industrial pine particles highlighting that the obtained panels meet the requirements of EN 312 standard [38]. Panels produced from a mixture of industrial particles and forest residues in a 50/50% ratio were considered the maximum possible, as they showed a statistically equal average to panels produced with a predominance of industrial particles and tree tops and branches (in a 75/25% ratio) and also a mixture of three other types of materials. Wronka and Kowaluk (2022) proved that there is a possibility to use different content (up to 50%) of Scots pine (*Pinus sylvestris* L.) branches to produce three-layer particleboard. Their results indicate that the higher bulk density of branch particles than the industrial material, along with an increase in the content of branch particles, results in a significant increase in internal bonding. On the other hand, the values of flexural strength and modulus of elasticity decreased with an increase in the content of branch particles up to 100%. Therefore, a 50% content in the panel of branch particles characterized by a maximum diameter of 40 mm was also considered maximum [39]. Nurek et al. 2019 showed that the mean density of unfractionated forest residues was app. 800 kg/m³ [8]. They also noticed the correlation between density and particle size—the smaller the fraction the greater the density. Rahman et al. (2013) showed that a practical board from stem wood has better properties than particleboard made from branches and twigs of surian tree (*Toona sinensis* Roem) [40]. In addition, wood from garden resources (citrus branches) and beech twigs (*Fagus orientalis* Lipsky) and poplar wood trunks (*Populus alba* L.) can be

successfully used to produce particleboards with good mechanical properties [41]. On the other hand, Nemli et al. 2004 identified the presence of branch wood as a parameter which is negatively influencing the mechanical properties of particleboards produced from black locust biomass [42]. The same phenomenon was observed by Kowaluk et al. (2011). Therefore, further research is needed to test the possibility of applying FR in the sustainable production of particleboards and converting them into value-added products [43]. Most of the published studies are focusing on the properties of wood-based boards produced from mixing wood and branches wood [30,39] or other materials [19,33,35,41]. Moreover, in particular, knowledge about the properties of particleboards produced from FR derived from logging interventions in Scots pine (*Pinus sylvestris* L.) stands is still limited.

The aim of the study was therefore to test the hypothesis that forest residues derived from Scots pine roundwood harvesting have the same suitability for the production of three-layer particleboard as the wood of the most valuable part of the Scots pine stem, by comparing selected properties of raw wood material and the final product—particleboard.

2. Materials and Methods

2.1. Raw Wood Material

The wood used in the study was harvested as part of a clearcut in a 94-year-old Scots pine stand in the State Forests in Poland. Wood raw material from 3 trees was taken and debarked for laboratory analyses and particular board preparation. Figure 1 presents graphically the elements of the raw material obtained at individual stages.

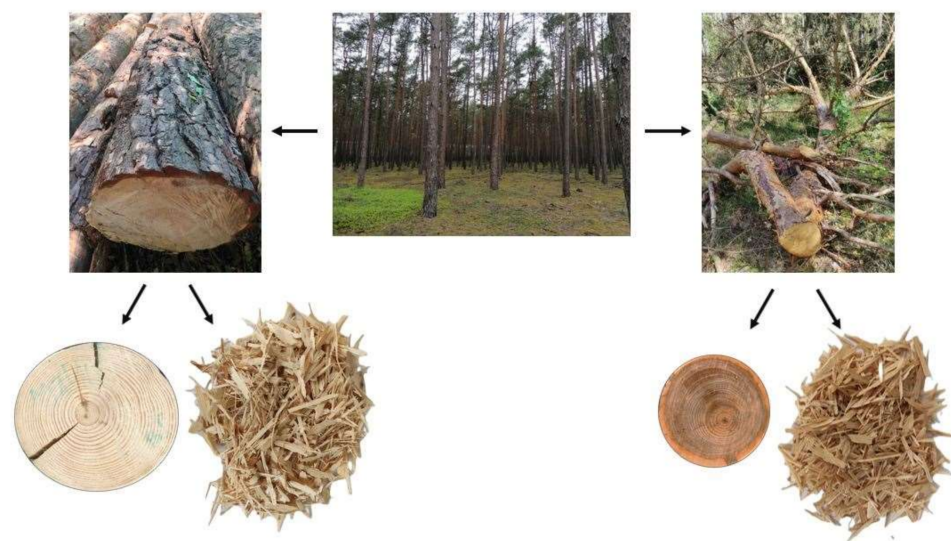


Figure 1. The process of obtaining individual elements of raw materials.

A 1.0 m long log was taken from each tree, measured from the base of the trunk, and pieces of branches were cut from each crown. Immediately after the tree was cut, approximately 4 cm thick discs were cut at the breast height from each tree for green (GD) and basic (BD) density estimation. Respectively the same was done with branches. Each disc was weighed with an accuracy of 0.001 g using a Steinberg laboratory scale (Steinberg Systems SBS-LW-200A, Berlin, Germany). After weighing, the thickness of each sample was measured to an accuracy of 0.01 mm using a certified Vogel calliper in five different places, and the diameter of each disc was measured by using the cross-over method according to the minimum and maximum size of the sample (Vogel Germany GmbH & Co. KG, Kevelaer, Germany). Then, the volume of each disc was calculated by Equation (1) according to Pérez-Harguindeguy et al. dimensional methodology [44]:

$$V = \pi \times (0.5r)^2 \times h \quad (\text{m}^3) \quad (1)$$

where V is the volume of disc, r is the average diameter of the disc, and h is the average height of each sample.

In the next stage, discs were transported to the laboratory where were dried for 48 h at 105 °C in a laboratory oven. After drying the samples were placed in a desiccator until cooled. Next, each sample was weighed and measured by the same procedure that had been used for samples in fresh condition. The green density was calculated using Equation (2), while basic density was calculated using Equation (3):

$$GD = \frac{m_f}{v_m} \quad (\text{kg/m}^3) \quad (2)$$

$$BD = \frac{m_s}{v_m} \quad (\text{kg/m}^3) \quad (3)$$

where m_f is the mass of fresh felled wood, m_s is the mass of an oven-dried sample and v_m is the volume of the fresh sample.

The remaining parts of both raw materials were first cut into smaller elements on a format saw (Felder, Hall in Tirol, Austria) and then shredded in a cutting mill Condux (Mankato, MN, United States). Obtained particles were divided into fractions on a vibrating sorter (Allgaier, Uhingen, Germany) equipped with sieves with mesh sizes: 8.0, 2.0, 1.0, and 0.5 mm. The core layer fraction consisted of particles retained on a 2.0 mm sieve, and the surface layers were particles from a sieve 1.0 mm in diameter and smaller. The fractional composition of the tree stem and branches stem intended for core layers are determined on a laboratory vibrating screen AS 200 tap (Fritsch, Idar-Oberstein, Germany) with the following sets of mesh sieves: 8.0, 4.0, 2.0, 1.0, 0.50, 0.25, and <0.25 mm. Their bulk density (ρ) was also determined according to Equation (4):

$$\rho = \frac{m_c - m_n}{V} \quad (\text{kg/m}^3) \quad (4)$$

where m_c is the weight of the measuring vessel with the raw material (kg), m_n is the mass of the measuring vessel (kg) and V is the capacity measuring vessel (m^3).

2.2. Adhesives

A melamine-urea-formaldehyde (MUF) adhesive (Swiss Krono Sp. z o.o., Żary, Poland) was used for the production of particleboards. Table 1 presents the selected properties of the adhesive. The resination was 11% for the surface layers and 9% for the core layer particles of dry resin content referred to dry particles (w/w). The hardener is a 40% water solution of NH_4NO_3 which was used in an amount of 2 wt.% for a core layer and 3 wt.% for the surface layers. A paraffin emulsion (0.8 wt.% for the core layer and 0.2 wt.% for the surface layers) was also added to the resin to protect the manufactured boards from exposure to water.

Table 1. Properties of MUF adhesive.

Properties	Value
Dry mass	67.5%
Relative density	1.27 g/cm ³
pH	8.4
Dynamic viscosity	326 mPa s
Gel time	95 s

2.3. Particleboard Production

Two three-layer particleboards with a nominal density of 670 kg/m³ and dimensions 500 × 700 × 16 mm were produced the share of surface layers in the panels was 35 wt.%. The raw materials were dried at 100 °C to a moisture content of 2–3% in a chamber dryer

with forced air circulation (Ashaki Kagaku Co., Ltd., Tokyo, Japan) and then glued in a rotary laboratory sealer with pneumatic spraying (Lodge, Paderborn, Germany).

The boards were pressed on a hydraulic single-level press (Simpelkamp, Krefeld, Germany) using the pressing parameters: unit pressure 2.5 MPa, temperature 200 °C, pressing factor 7 s per one mm of nominal board thickness. After manufacturing, respectively, the boards were conditioned in an air-conditioning chamber at a relative humidity of $65 \pm 5\%$ and a temperature of 20 ± 2 °C. Then parameters were determined, such as density, modulus of elasticity in bending (MOE), modulus of rupture (MOR), internal bond (IB), thickness swelling (TS) after 24 h water immersion, and water absorption (WA), formaldehyde content by perforator method and formaldehyde emission by the chamber method according to procedures defined in the European standards: EN 120 [45], EN 310 [46], EN 317 [47], EN 319 [48], EN 323 [49], EN 717-1 [47].

2.4. Statistical Analysis

In the first step, the Shapiro–Wilk test was performed to verify the normal distribution of data. The result of the test rejected the normal distribution hypothesis. To compare data between samples the non-parametric Mann–Whitney U test was performed. Statistical inference was performed at significance level $\alpha = 0.05$. The program Statistica 13.1 (TIBCO Software Inc., Palo Alto, CA, USA) and RStudio and the R package (R Core Team 2022) were used for the calculations.

3. Results

3.1. Characteristics of Raw Material

Wood discs collected from branches were characterized by a greater green density of wood than wood collected from tree stems. The difference between these two wood locations was app. 11 kg/m³. The maximum GD of branches was over 1000 kg/m³ and was higher than the maximum stem wood GD by 61.83 kg/m³ (Table 2).

Table 2. Basic statistics of green density (kg/m³) of raw wood material collected from tree stems and branches of wood.

Raw Wood Material	Mean	Sd. Dev.	Minimum	Maximum	Median	U-W Test
Tree stem	982.26	6.69	976.21	989.44	981.13	Ns *
Tree branches	993.20	40.18	938.75	1051.27	995.52	

* Ns—no significant differences.

When in the case of basic density wood from branches was characterized by lower density. The differences between obtained results from the stems and branches were app. 160 kg/m³ and was statistically significant (Table 3).

Table 3. Basic statistics of basic density (kg/m³) of raw wood material collected from tree stems and branches wood.

Raw Wood Material	Mean	Sd. Dev.	Minimum	Maximum	Median	U-W Test
Tree stem	555.07	14.02	545.95	571.22	548.05	0.03
Tree branches	395.41	35.54	340.40	436.53	393.88	

The bulk density of the material is closely related to the density of the raw material from which it was obtained. Already shredded to particle form, the material from the tree trunk showed a bulk density of about 90 kg/m³, while that from tree branches was about 70 kg/m³.

Figure 2 presents the fractional composition of particles from tree stems and branches. The analysis shows that the fractions with the size of 4.0, 2.0, and 1.0 mm represent the largest mass share of particles obtained from the tree stem, respectively 30, 36, and 28%. In turn, for the particles from the branches, the largest fraction came from the 2.0 and 1.0 mm sieves—a total of 72% of the entire particle mixture. Very small amounts of fine particles from the sieve with a mesh smaller than 1.0 mm were observed for the trunk particles it is approx. 7% and for the branches particles approx. 4%.

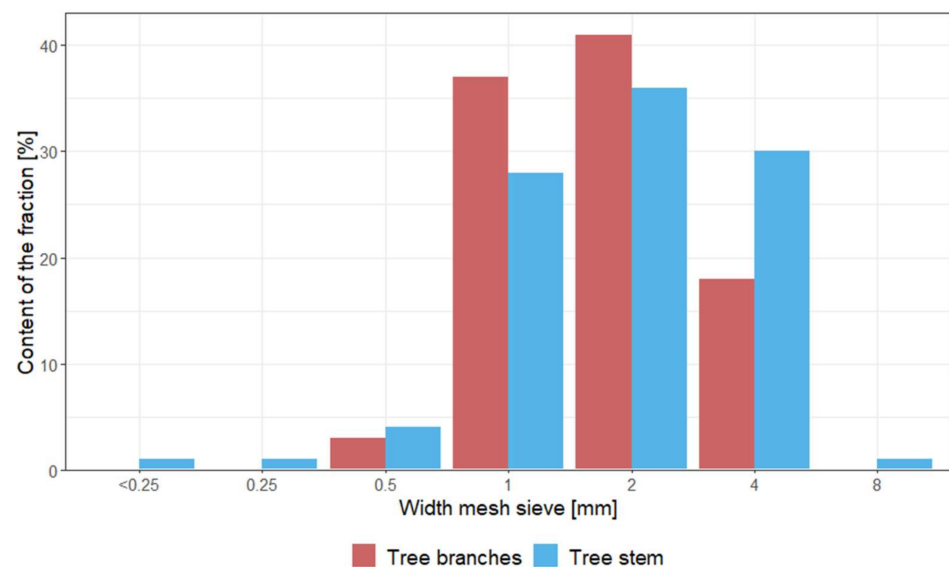


Figure 2. Fractional composition of particles from tree stem and branches.

3.2. Properties of Particleboards Depending on Raw Wood Material

Physical-mechanical properties of the investigated particleboards are reported in Table 4 and the hygienic properties are given in Table 5. No statistically significant differences were found regarding MOR. All the mechanical properties of the manufactured boards have met the requirements of P3 type 16 mm thick boards—non-load-bearing boards for use in humid conditions. For these panels, MOR 14.6 N/mm², MOE 1960 N/mm², and IB 0.46 N/mm² were obtained. On the other hand, the MOR and IB values turned out to be higher for the branch panel and are respectively 16.5 and 0.72 N/mm². Such high values made it possible to qualify the board to the P5 type—load-bearing boards for use in humid conditions. Comparing the achieved results of internal bond tests to the EN 312 standard requirements it should be noted, that the IB values of tree branches panels exceed the minimal requirements for P7 type—heavy duty load-bearing boards for use in humid conditions, which is 0.70 N/mm². In the case of TS and WA, the stem panels showed better performance, but were still insufficient to achieve adequate water resistance.

Table 4. The mean value and standard deviation of examined properties of 3-layer particleboards from tree stem and branches wood.

Raw Wood Material	MOR	MOE [N/mm ²]	IB	TS [%]	WA [%]
Tree stem	14.6 ± 1.9	2960 ± 190	0.46 ± 0.08	31.2 ± 1.49	78.4 ± 3
Tree branches	16.5 ± 0.9	2640 ± 120	0.72 ± 0.04	37.6 ± 2.07	97.7 ± 1
U-W test result	Ns *	0.0031	0.0009	0.0006	0.0008

* Ns—no significant differences.

Table 5. Hygienic properties of 3-layer particleboards from tree stems and branches of wood.

Raw Wood Material	Perforator Value [mg/100 g Oven Dry Board]	Formaldehyde Emission [ppm]
Tree stem	1.2	0.025
Tree branches	1.5	0.021

The formaldehyde content was determined using the EN 120 perforator method, and it was found that boards manufactured with formaldehyde-containing resin achieved very low formaldehyde content. Many factors can affect the formaldehyde content of particleboard, and certainly, these are the pressing parameters, the raw material, the type and amount of hardener, and the properties of the resin itself: the type of resin and the molar ratio (of urea and formaldehyde) and the formaldehyde content in the resin [28]. A lower formaldehyde content was observed in panels made from the stem portion of 1.2 mg/100 g oven dry board. The obtained formaldehyde emission level is also satisfactorily low. For the E1 emission class, acceptable values for raw wood-based boards are ≤ 8 mg/100 g oven dry board content and release ≤ 0.124 mg/m³ air.

4. Discussion

The main aim of this study was to estimate the suitability of forest residues (pine branches) for the production of three-layer particleboard. Moreover, particleboards from the stems of trees from which the forest residues were collected, were produced for comparison.

Raw wood material collected from pine stems was characterized by a mean green density of around 982 kg/m³ when the basic density of the same material was 555 kg/m³. Obtained green mean values results were similar to results noticed on freshly felled pine logs by Tomczak et al. (2020) and Tomczak et al. (2016) [50,51]. The wood of branches is characterized by a different anatomical structure and structure than stem wood [52]. Mainly due to the high occurrence of reaction wood, which, among other things, has an impact on wood density [53,54]. The mean value of wood branches green density was 993 kg/m³ when the basic density was 395 kg/m³. Findings about branches basic density concerning mostly tropical species [55–57]. When studies about wood branches properties of European species are very limited. The basic density of branches of wood was significantly lower than the density of samples collected from the stem. This result is not comparable with a study carried out by Dibdiakova and Vadla (2012) [58] and Gryc et al. (2011) [59], who compared the basic density of branches and wood basic density of the stem of spruce from different sites. In both presented studies obtained branch wood density was higher than in our study.

Currently, alternative lignocellulosic raw materials are high in high demand [19] which will be able to compete with other industries due to the lack of wood, such as the paper industry, or for energy purposes. Forest residues also could be a good alternative for high quality as a raw material for board production. Alamsyah et al. (2020) produced OSB and particleboard from branches and twigs of surian tree (*Toona sinensis* Roem) [60], Rahman et al. (2013) manufactured boards from branches and stem wood in three types: only from stem wood, only from branch wood and stem-branch mix of bahdi (*Lannea coromandelica* Merr.) [40]. According to the comparison they presented, stem particles were characterized by the highest mechanical properties, then branch-stem particles, and the lowest quality were obtained in branch particles. In the study by Jahan-Latibari and Roohnia (2010), two types of forest residues were used to make particleboard, they were poplar branches, small-diameter poplar wood (3–8 cm), and beech wood [61]. Their results showed that the characteristics of particleboard made from poplar branches and small-diameter wood were comparable to that made from mature beech wood. In our study panels made of branch particles were characterized by significantly higher quality than stem ones. Which led to classified branch panels as P7 type—heavy-duty load-bearing boards for use in humid conditions according to EN 312. Such differences between our and

presented studies can be explained by species' wood properties. At the stage of production of wood-based materials, it is important to increase the durability of products, which extends their life cycle, thus influencing the extension of the period of carbon sequestration in the wood contained in them, which is a beneficial environmental aspect. The use of a board with such good mechanical parameters for the manufacture of furniture from them can allow reducing the amount of waste wood-based materials created by slower consumption of products and replacement with new ones. Due to the non-emissivity of wood-based panels, the control of free formaldehyde content and emissions is important. Sustainable production of low-emission materials raises ecological issues that are extremely important for the environment and subsequent use, without polluting the air and disposing of products.

In our study, the bulk density of raw material obtained from stem wood was higher than the bulk density of the wood from branches. The research of Kowaluk et al. 2019 used a mixture of industrial wood chips only with an admixture of coniferous wood (mainly *Pinus sylvestris* L.), thanks to which it obtained a bulk density of approx. 164 kg/m³ [62]. In the same study, applewood particles (classified as moderately heavy species) were used, the density of which was approx. 245 kg/m³. The higher the bulk density of the lignocellulosic material, the smaller the thickness of the mat prepared to be pressed to form a particleboard. Knowledge of the material density is especially important when preparing mats from alternative lignocellulosic raw materials, which are characterized by a much lower density than pine wood particles. An example is straw particles obtained from alternative lignocellulosic raw materials, such as rapeseed—approx. 42 kg/m³ and rye approx. 25 kg/m³ [36]. The lower bulk density of materials may cause some technical limitations in the industrial-scale manufacturing process. In addition, there may be some logistical problems in developing an optimal and sustainable transportation mechanism [28]. Due to the high volume of logged timber—around 40 mln m³ per year, State Forests (SF) in Poland are a huge source of forest residues [63]. The exact amount of FR production is difficult to estimate. Due to many environmental factors that affect the amount of waste [6,12]. Gendek et al. [6], in reference to estimates in a paper by Zajaczkowski (2013) [64], estimated that forest residues in Poland in 2031 could amount to 2.34 million m³, an increase of 12.5% over the 2021 estimate. In recent years SF in Poland offer to sell FR for energy purposes as M2E assortments [65]. The starting price of the auction starts around 4–5 EUR/m³ (accessed on 1 September 2022). According to the results of our study, this raw material is also relevant and sustainable for high-value particleboard production. Due to the relatively low price, high accessibility, and quality of the final product. Unfortunately, the destabilization of the timber market in Poland, caused among others energy problems and war in Ukraine (stopped wood import). Moreover, EU sanctions have stopped the import of forest residues from Belarus. Therefore currently the final auction price of wood biomass sells by State Forest significantly increased even to over 100 EUR/m³.

From an environmental and economic point of view, particleboard production could be based on the idea of using less valuable wood waste and residues. For example, those generated in the woodworking process like particles and residues from the production of wood-based panels, constitute a significant waste [66]. This would create a value-added product that contributes to improved waste management. Moreover, additions of other materials such as waste from the leather industry [67,68], tetrapak packaging [69,70], and construction materials [71,72] can be used. When material innovations are used to make panels, the hygienic properties of the panels made from them must be controlled, the standards of which must be strictly observed. When using wood material, the likelihood of high emission values and formaldehyde is much lower than for alternative raw materials. There are many additives to amine resins that are designed to reduce formaldehyde content in the board, but often their mechanical and physical properties are adversely affected. An example of the use of formaldehyde (FS) Scavenger Solution described in Basbog 2022, which was synthesized using a mixture of monoethanolamine (MEA), ammonium chloride (AC), and distilled water (DW) [73]. Adhesives that are considered biobased on a mixture

of citric acid and glycerin [74], waste melamine impregnated paper [75], protein-based [76], and cornstarch and tannin-based wood adhesives [42,77] can be used.

5. Conclusions

One possible alternative use of forest residues is their use as an alternative material for wood-based panels, namely particleboard. Based on the research, it can be concluded that forest biomass in the form of pine branches can replace roundwood. The results obtained clearly show that the use of wood material in the form of forest biomass residues improves MOR, which is worth noting, and significantly increases the IB value from 0.46 N/mm² for boards made of stem wood particles to 0.72 N/mm². Mechanically, the obtained panels meet the minimum requirements for P5-type boards, but nevertheless, the TS value is insufficient. All of the particleboards produced met standardized performance requirements, making them suitable for use as a board for interior fitments (including furniture) for use in dry conditions (type P2).

Future research should be directed toward improving the quality of particleboard produced from raw materials that are alternatives to roundwood. Consideration should be given to raw materials with lower market prices and the use of additives in the form of alternative adhesives, including those that increase water resistance. In addition, further research is needed to reduce competition for raw materials in the energy sector, which is currently a major obstacle to the cultivation of many industrial crops.

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