ORIGINAL ARTICLE

Selected physical and mechanical properties of particleboards manufactured with addition of *Betula* bark post-extraction residues

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Abstract

As awareness grows regarding the necessity for sustainable technologies across various industries, including wood-based composites, there's a heightened demand for ecological solutions. One of the proposed solutions is the partial replacement of wood raw materials in composites with forestry and agricultural waste, thus contributing to the circular economy. Suberin, which is a natural polyester present in tree bark, after depolymerization can be converted into suberinic acids, and after this process, post-extraction solid residues (SAR suberinic acid residues) remain, which include suberin monomers, lignin, cellulose and esters. In this study, it was decided to use this waste in the form of a powder with dimensions of 0.250 mesh as a filler for particleboards. Three-layer boards were prepared in four variants of SAR share in all layers (0%, 5%, 10%, 15%). The physical and mechanical properties of the manufactured boards were tested—modulus of rupture, modulus of elasticity, internal bond strength, screw withdrawal resistance, thickness swelling, water absorption, density profile, contact angle. The formaldehyde and total volatile compounds emissions of the boards were also determined. As a result of the research, it was shown that the addition of SAR has a positive effect on the properties of the panels, but only up to the level of 10%, whereas for boards with a SAR content of 15%, a statistically significant decrease in mechanical and physical properties was noted. The values obtained, however, were still within the required assumptions of the European Standards. Only the IB value obtained for the SAR 15% variant did not meet the requirements of the EU Standards. As shown, SAR addition significantly minimizes the emissions from boards, however, it decreases also the hydrophobicity. This study shows a great potential in applying post-extraction residues from bark as a filler material for wood-based panels.

1 Introduction

Contemporary industry generates significant amounts of forest (Top et al. 2018; Şahin 2020; Pandey 2022) and agricultural (Sołowiej; Skonecki et al. 2011; Sugahara et al. 2019; Mensah et al. 2020) waste, posing unique challenges for effective and sustainable management. One promising avenue for processing this waste is its utilization in the production of particleboards. A large portion of these wastes is disposed by combustion or for the production of biofuels (Gochev and Stoilov 2008; Eker 2011; Top et al. 2018; Moskalik and Gendek 2019; Moretti et al. 2021; Roman et al. 2021). However, there is increasing attention towards valorizing these wastes to add higher value to them, as incineration is not perceived as a sustainable disposal method (Jeżo and Kowaluk 2023a; Wronka and Kowaluk 2023; Silva et al. 2024).

An example of adding value to commonly recognized waste materials is their integration into wood-derived material technologies. In the technology of particleboards,

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successful utilization has been observed with forest residues from *Pinus* wood harvesting (Pędzik et al. 2022b), as well as waste from *Teobroma cacao* and *Ceiba* species, which were used in particleboards with enhanced resistance to fungal attack (Mensah et al. 2020). Apart from wood waste, the potential use of other lignocellulosic waste materials has been explored, including cones (Sahin and Arslan 2011), nuts (Pędzik et al. 2022a), chestnuts (Liang et al. 2021), corn husks (Prasetiyo et al. 2020), wheat straw (Wang and Sun 2002), and residual grass clippings (Gökay et al. 2009). The combination of cement and agricultural waste has also been investigated in particleboards (Davies and Davies 2017).

One of the most significant forest residues is tree bark. The quantity of bark remaining after debarking of wood logs is best exemplified by specific species. In vast landscapes of the Northern hemisphere, *Betula pendula* Roth. and *Betula pubescens* Ehrh. are the primary *Betula* species, playing a crucial role beyond mere canopy presence (Bergelin and Holmbom 2008). These *Betula* species, widely recognized for their role in pulp and plywood production, significantly shape the industrial landscape. Interestingly, *Betula* bark, comprising about 12.5% of the tree's mass, emerges as a valuable by-product, with the outer bark of logs constituting 2.0–3.4% of their total composition (Pinto et al. 2009). The impact of *Betula* extends further, as pulp production boasting an annual output of 400,000 tons and a plywood factory with an annual production of 252,000 m^3 significantly contribute to the by-product stream. In particular, these facilities generate approximately 28,000 and 16,000 tons of outer bark, respectively. It is worth noting that the calorific value of this outer bark exceeds 30 MJ/kg, making it a potent energy source. Besides other residual materials like veneer chips and sawdust, the outer bark finds applications in power plants, pulp mills, and plywood factories, where it is efficiently incinerated (Rizhikovs et al. 2015).

An approach involving the use of tree bark for production of wood-based composites has been undertaken by adding bark to wood particles in the production of particleboards. Single-layer (Jiang et al. 2020) and three-layer (Jiang et al. 2023) particleboards were manufactured by partially replacing primary wood particles with liquefied bark (PLB) in internal or surface layers. Similar solutions were demonstrated for bark flour, however in this case as a filler in binders, obtained from *Pinus* bark (Antov et al. 2020) and *Fagus* (Bekhta et al. 2021), *Acer*, and *Betula* bark (Walkiewicz et al. 2022).

Utilization of bark in the production of particleboards has been tested mostly in the core layer of a board (Pedieu et al. 2008). In order to reduce emissions of harmful substances such as formaldehyde (Medved et al. 2019), a binder-free board with the addition of *Melaleuca viridiflora* Sol. Ex Gaertn. bark was produced (Manufacture and Bark 2020). Additionally, Blanchet et al. (2000) produced a particleboard

with ground *Picea* bark, meeting the American National Standard Institute indoor requirement for wood particleboard under certain conditions. Particleboards with the addition of *Abies* and *Larix* bark, without any other additives, were also produced (Burrows 1960). Utilizing chips, sawdust, and bark for particleboard production is a good way to reduce material losses (Dziurka et al. 2022). However, as investigated by Arabi et al. (2011), the smallest particle sizes (such as wood or bark flour, sawdust) have a larger total special surface area than other classes and, at the same weight, they need more resin to cover the surface of all the fine particles. In this case, the amount of resin is the same for all treatments, which means less adhesion and, therefore, less durability. Although increasing the share of binder in the board has a positive effect on its properties, reducing resin content may result in a significant decrease in total particleboard production cost. In addition, the formaldehyde released during production and use of wood-based composites is carcinogenic. Therefore, increasing the proportion of binders to compensate for property losses caused by for example particle size is not a good strategy when developing new technologies for producing wood-based boards.

Above mentioned *Betula* outer bark contains up to 45% suberin, being a natural, bioprotective polyester. After the extraction of triterpenes, the remaining biomass can still be used for the production of other high-value-added products. Suberinic acids (SA) are obtained by the depolymerization of suberin through alkaline hydrolysis or transesterification, where SA residue (SAR) remains after the extraction of suberinic acid, containing small amounts of suberinic acids and other suberin components, including betulin, lupeol, and glycerol derivatives. This *Betula* outer bark component opens the door to producing various high-value-added materials, using the remaining bark biomass, including SA as a substitute for synthetic adhesives and polymers (Makars et al. 2023). SA have been used as an adhesive for the production of particleboards, offering excellent properties of obtained panels (Rižikovs et al. 2014; Makars et al. 2022b, a; Rizikovs et al. 2023).

In the wood industry, applications of SAR have also been explored, focusing on the analysis of the strength of particleboard and plywood. It has been demonstrated that SAR can serve as both a filler and a hardener in the adhesive of plywood (Gumowska and Kowaluk 2022; Jeżo et al. 2023). Studies have shown that by using post-extraction *Betula* bark residues, with adhesive application at 10% and 20%, the requirements of EN312:2010 were met only for the bending modulus of elasticity for boards produced with the largest wood particles used in the research. The degree of adhesion and the size of wood particles influenced the properties of the tested boards (Jeżo and Wronka 2022). The addition of SAR to poly(lactide) - PLA and polycaprolactone - PCL polymers was investigated, with a 20% and 50% ratio. It was

demonstrated that the mechanical properties of such coatings increased with the SAR content, and additionally, the emissions of formaldehyde and volatile organic compounds (VOC) were reduced (Jeżo and Kowaluk 2023a).

Based on the current state of knowledge the authors decided to conduct this study, aiming to investigate the impact of SAR as a filler material in particleboards on their physical and mechanical properties. The novelty of the study lays in an underestimated character of suberinic acids and their residues. It is a waste material, making this study a perfect fit for the circular economy model and the idea of upcycling. The innovation of this study lies in the use of waste material that has never before been considered as a feedstock in particle boards.

2 Materials and methods

2.1 Preparation of particleboards

Three-layer particleboards with a nominal density of 680 kg/m^3 were produced. The resination of all the panels equaled 12% for the outer layers and 8% for the inner layer, based on wood oven-dry weight. The thickness of the panels produced equaled 16 mm. To ensure the thickness of 16 mm, spacers were used during the whole process of pressing. As binder, an industrial urea–formaldehyde (UF) resin Silekol S-123 (Silekol Sp. z o. o., Kędzierzyn- Koźle, Poland) of about 66% dry content was used. The hardener for UF adhesive mass was a 40 wt% water solution of ammonium nitrate. The UF bonding mass composition had a weight ratio of 100:8:8 (resin, water, hardener solution, respectively) to reach the curing time of the adhesive mass at 100 °C for about 86 s. The viscosity of the used binder before application was about 420–450 mPa·s. No hydrophobic agents were added.

The wood raw material used for particle production was mainly *Pinus sylvestris* L., reinforced with SAR in dimensions of 0.250 mm. Industrially obtained wood particles were utilized in two fractions (0.5 mm for face layers and 2 mm for the core layer). The moisture content of both fractions before resination equaled 6%. The particles of both fractions were evenly substituted with SAR. The SAR was kindly provided by the Latvian State Institute of Wood Chemistry, Riga, Latvia, and has been made from the residues resulting from the isolation of SA acid, under the process described by Makars et al. (2022a). The residues resulting from the depolymerization of suberin contained 9.0 wt% cellulose, 21.4 wt% of suberin + lignin, 17.5 wt% of ω-hydroxy acids and 11.9 wt% of α,ω-diacids (Makars et al. 2022a). Industrial wood particles and SAR particles, priorly mixed by hand, were put together into the mechanical mixer and then the binder was sprayed by a pneumatic pistol into the mixer. The panels were pressed in a hot press (AKE,

Mariannelund, Sweden) at a pressing temperature of 180 °C, and a pressing time factor 20 s·mm^{-1} of the nominal thickness of the panel, with a specific maximum unit pressure of 2.5 MPa. The boards were conditioned in a climatic chamber (Research and Development Centre for Wood-Based Panels Sp. z o.o. in Czarna Woda, Poland) at 20 °C and 65% air humidity until a constant mass was obtained. No sanding of the panels after pressing has been performed.

The panels were manufactured in four variants, regarding the mass share of SAR contained:

- SAR 0%—panels containing no SAR feedstock, control sample;
- SAR 5%—panels with SAR share equaling 5% of particles mass;
- SAR 10%—panels with SAR share equaling 10% of particles mass;
- SAR 15%—panels with SAR share equaling 15% of particles mass.

There was an attempt to produce variants with more than 15% of SAR, however, by increasing the amount of SAR to 20%, the dust absorbed too much binder, making it unable to bind the particles.

The manufactured panels can be seen in Fig. 1. Two boards of the size 350mm x 350mm of each variant were prepared. Each board has been cut into samples of 320mm x 50mm, resulting in 12 samples for MOE and MOR tests. Samples destroyed during the tests were then cut into samples of dimensions of 50mm x 50mm, giving samples for all of the other tests.

2.2 Mechanical and physical properties testing

Density profile was performed with the use of the Grecon DA-X unit, with a sampling step of 0.02 mm and measuring speed of 0.1 mm/s (3 samples of every panel type used; the most representative profile was then presented in the plot). The following mechanical parameters of produced panels were investigated: modulus of rupture (MOR) and modulus of elasticity (MOE) during bending, according to EN 310:1994 (European Committee for Standarization, Brussels 1994), tensile strength perpendicular to the plane of the board or internal bond strength (IB) according to EN 319:1993 (European Committee for Standarization, Brussels 1996a), screw withdrawal resistance (SWR) according to EN 320:2011 (European Committee for Standarization, Brussels 2011). A number of 10 samples of every panel type were used for mentioned tests; 12 for MOE and MOR testing. The following physical properties of produced panels were investigated: swelling in thickness (TS) and water absorption (WA) after immersion in water according to EN 317:1993 (European Committee for Standarization, Brussels

Fig. 1 Visual representation of the manufactured panels
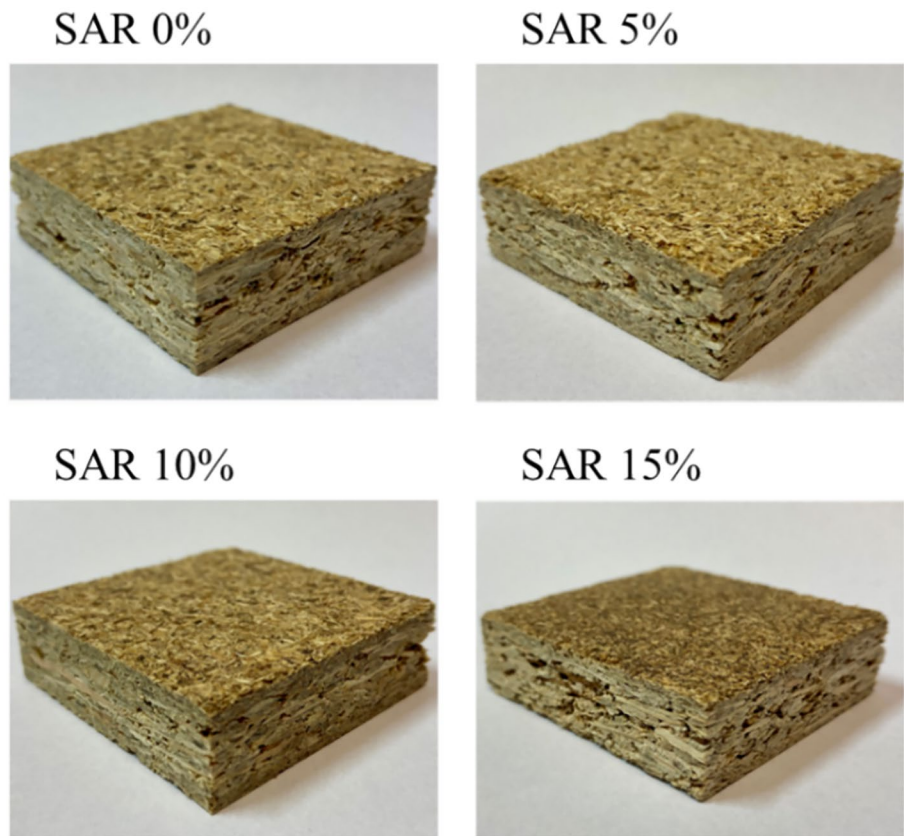
1996b) standard (no less than 5 samples of every panel type used). Contact angle measurements were conducted using the contact angle analyzer PHOENIX300 (SEO—Surface & Electro Optics Co., Gyeonggi-do, Ltd., Suwon City, Republic of Korea) equipment while using the method of distilled water sessile drop in 3 repetitions per variant. The contact angle was measured directly after drop deposition, as well as 60 s after drop deposition for the same drop. The total VOC (TVOC) and formaldehyde emission tests were completed in the emission test chamber at a temperature of 23 °C +/− 0.5 °C and relative air humidity of 44% +/− 1%. Other parameters of sample conditioning were carried out following the EN 717-1 standard (European Committee for Standarization, Brussels 1993). The TVOC and formaldehyde emission tests were carried out after 24 h of conditioning of the samples by analyzing the chamber air over three repetitions after 20 min each using a JD-3002 Air Quality Tester (Dongguan Jinlide Electronic Technology Co., Ltd., Dongguan City, Guangdong Province, China). We adhered to the standards regarding air conditioning conditions for samples during the emission test. The sample size for the MOR and MOE testing was 350 mm x 50 mm and for all the rest of the tests it was 50mm x 50 mm. All the tested panels were conditioned prior to the tests at 20°C/65% RH to a constant weight. The obtained results were examined through the analysis of variance (ANOVA). The Student's test was carried out ($\alpha = 0.05$) to determine the statistical significance of differences between the factors. The results presented in the graphs (where applicable) show mean values, standard deviations and Tukey's significance groups.

3 Results and discussion

3.1 Vertical density profile

The vertical density profiles of the examined panels are illustrated in Fig. 2.

All of the examined variants have a U-shaped density, following the standard shape of a three-layers particleboard's density. In the middle of the thickness, all boards had a density below 600 kg/m³, and these densities were very close to each other. The density profiles did not show absolute symmetry, one of the outer layers was characterized by a higher density than the other outer layer. The SAR 0% sample showed a density of the outer layers of approximately 1100 kg/m³, the SAR 5% variant achieved a similar value, but only on one side, while the other showed a density of close to 900 kg/m³. The 10% SAR variant can be considered the most symmetrical, with both outer layers having a density of approximately 900 kg/m³. The last variant—SAR 15%—achieved density values for the outer

Fig. 2 Vertical density profiles of the examined panels (sample dimensions: 50 mm × 50 mm, repetitions per variant: 3)
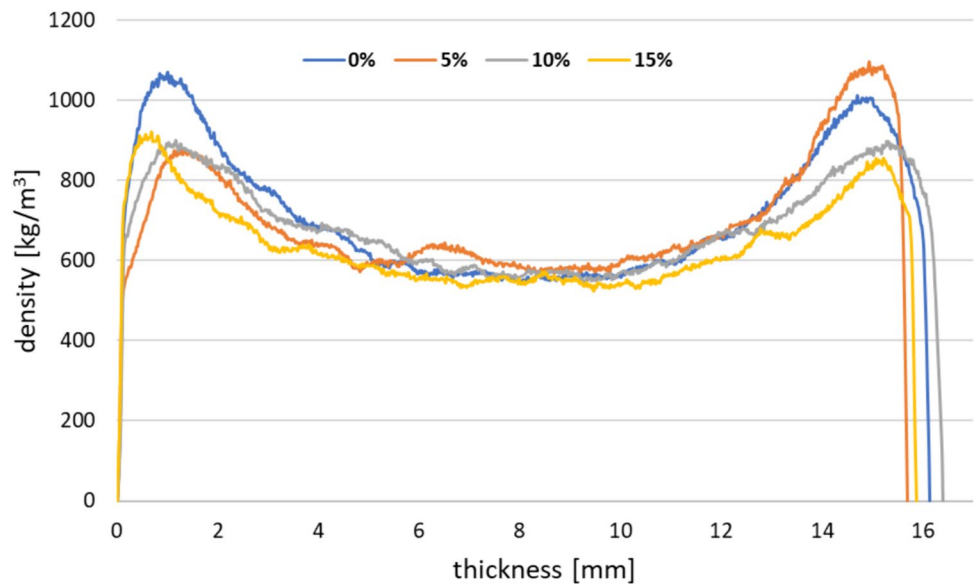
layers of approximately 850 and 900 kg/m³. The reason for the decrease in density in the outer layers in the SAR 15% variant can be found in a weaker gluing—fine SAR particles absorbed a large amount of binder during gluing, which is why, in general observation, the boards in this variant were drier to the touch. The density profiles indeed vary and the addition of SAR did decrease the densities, due to the worse quality of gluing. Therefore, the densities vary from the nominal one. As investigated by Farrokhpayam et al. (2016), the particles in the fine class have the smallest size, therefore the total special surface area is larger than other classes and with the same weight they need more resin to cover the surface of all the fine particles. In this case, the amount of resin is the same for all treatments, which means less adhesion and, therefore, less durability. There is a strong correlation between density and mechanical properties of boards: as the board density increases, the mechanical properties improve. This relationship, confirmed by Arabi et al. (2011), will also influence the further presented results.

3.2 *Modulus* of rupture (MOR) and *modulus* of elasticity (MOE)

The results of the MOR test for the analyzed panels are presented in Fig. 3. The highest results were achieved for samples with a SAR content of 5% (13.04 N/mm²), followed by reference samples and those with a SAR of 10%, achieving 12.03 N/mm² and 11.58 N/mm², respectively. The lowest values of the MOR index, which did not meet the standard set by EN 310 for P2 particleboard type (11 N/mm²), were recorded for samples containing SAR at the level of 15%—they amounted to 8.54 N/mm². The statistical analysis showed a significant difference only for samples with a SAR of 15% (marked as group b in the chart), while the remaining
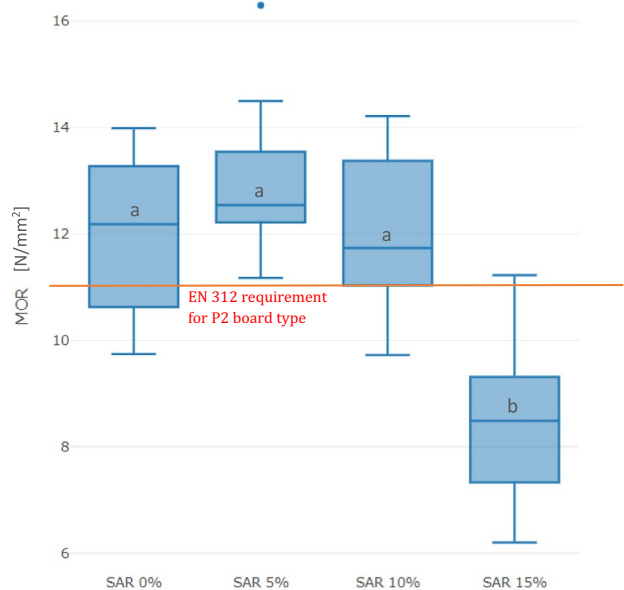

Fig. 3 Modulus of rupture results for the examined panels (sample dimensions: 50 mm × 320 mm, repetitions per variant: 12) with significance groups marked on the boxplots, according to the Tukey's test (letters a and b)

samples belonged to the same significance group (marked as group a in the chart).

Figure 4 illustrates the results of testing the MOE of the considered panels. The highest values were obtained for the reference samples (2411.61 N/mm²), followed by SAR10% and SAR 5%, 2369.50 N/mm² and 2347.90 N/mm², respectively. The lowest MOE values were obtained for SAR15% samples—1637.98 N/mm². All of the variants met the
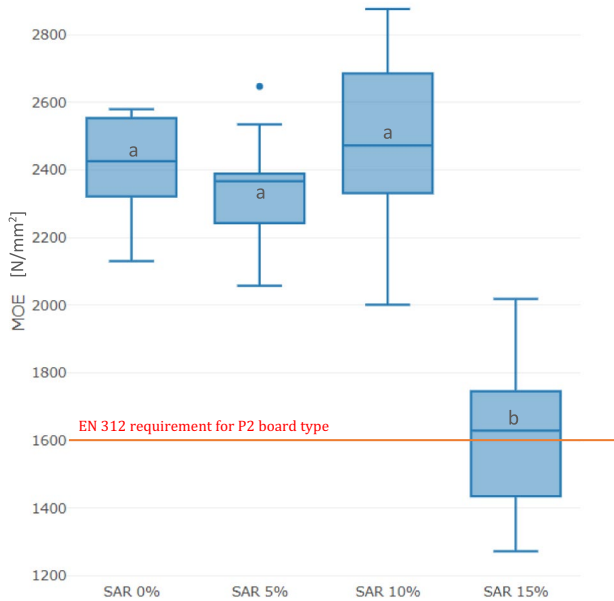
Fig. 4 Modulus of elasticity results for the examined panels (sample dimensions: 50 mm×320 mm, repetitions per variant: 12) with significance groups marked on the boxplots, according to the Tukey's test (letters a and b)

requirements set by EN 310 for P2 type of particleboards. Statistical analysis showed that the only variant significantly different from the others was SAR 15% (marked as group b on the chart). The remaining samples belong to the same significance group (in the graph marked as a).

Since this is the first study to use post-extraction waste from suberin depolymerization, it is not possible to compare the results for this material with other studies. However, since SAR is a derivative of bark, containing some of its main components, the authors decided to compare the obtained results with the results obtained for the addition of bark as feedstock material in particleboards. As Yemele et al. (2008) showed, three-layer particleboards with a target density of 800 kg/m³ made with aspen bark content of 50% had an MOE in the range of 2323–2519 N/mm², while returning the bark share to 100% resulted in a significant decrease in the MOE. For the same panels the MOR values equaled 11.1–13.0 N/mm² (with the values increasing by the decrease of bark particles size). The authors noticed a similar tendency for boards using spruce bark. The MOE and MOR values obtained for the boards with 50% of spruce bark content were respectively 12 and 37% lower than that of the control, what, according to the authors, can be explained by the low cellulose content of bark as compared to wood. Taking into account this difference in cellulose content, it is worth mentioning that SAR contains much less (9.0%) of this compound than the bark studied (26.8 and 25.4%

for spruce and aspen, respectively). Cellulose, as the elastic compound, plays namely a crucial role in giving a board elasticity. The lignin content was similar, around 20%. In another study, the MOE values of particleboards produced with a 25% share of black spruce bark ranged from 2000 to 2300 N/mm², with the MOE value increasing as the degree of gluing increased. The authors noted an increase in the MOE after increasing the share of bark to 50% (Blanchet et al. 2000). This means that SAR, even though it is a derivative of bark, does not translate into obtaining the expected properties at such a large mass fraction as bark added to particleboards. Its composition contains less valuable compounds than original bark. The explanation for the decrease in MOE and MOR with the increase in the SAR share can also be found in the adhesive properties of SAR, which could result in increased stiffness of the particleboards and, as a result, brittleness. The adhesive properties of SAR were demonstrated by Jeżo and Wronka (2022) and Jeżo et al. (2023). The UF resin is most likely influenced by the acidic components of the SAR. This could lead to a premature curing of the binder when pressing, resulting in lower mechanical properties. Also, the fact that in boards with increased SAR content more binder is absorbed by the dust particles, can negatively affect the proper binding process, thus negatively affecting MOR and MOE. As shown by Engehausen et al. (2024), MOR and MOE of a particleboard increase as the particle size changed from fine to coarse. As confirmed by Farrokhpayam et al. (2016), particle size can significantly affect the MOE and MOR of panels. Panels made of particles in medium and fine size showed maximum and minimum MOE and MOR, respectively. The opposite is the case with IB. Therefore, it appears that coarse particles are favorable for high MOR and MOE, while fine particles are favorable for high IB (Engehausen et al. 2024).

3.3 Internal bond strength (IB)

Figure 5 shows the IB test results for the tested panels. The highest values were obtained for SAR 5% samples (0.576 N/mm²), followed by SAR 10% samples (0.460 N/mm²), these samples have stronger IB than the reference samples (0.355 N/mm²). The SAR 15% samples (0.275 N/mm²) had the lowest results, at the same time not meeting the requirements set by EN 319 for P2 type particleboards. There were no statistically significant differences between the examined panels (all of them are signed on the graph with the letter a according to the Tukey test for homogeneous groups).

3.4 Screw withdrawal resistance (SWR)

Figure 6 shows the results of the SWR test. The results obtained for the SAR 0%, SAR 5%, SAR 10% and SAR 15% variants were: 104.13 N/mm, 126.76 N/mm, 112.97
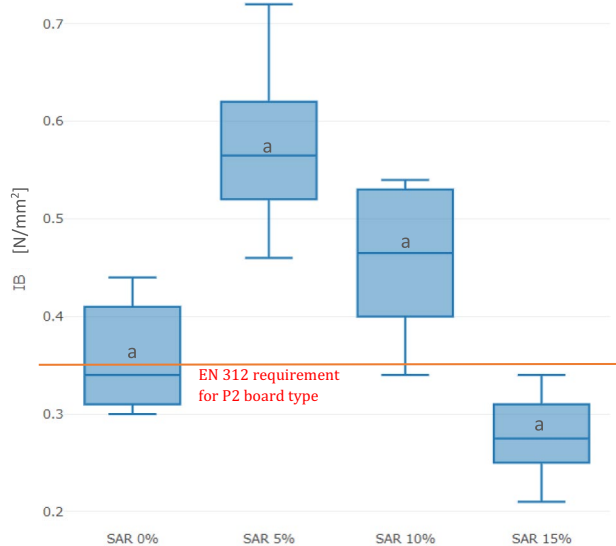
Fig. 5 Internal bond results for the examined panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 10) with significance groups marked on the boxplots, according to the Tukey's test (letter a)
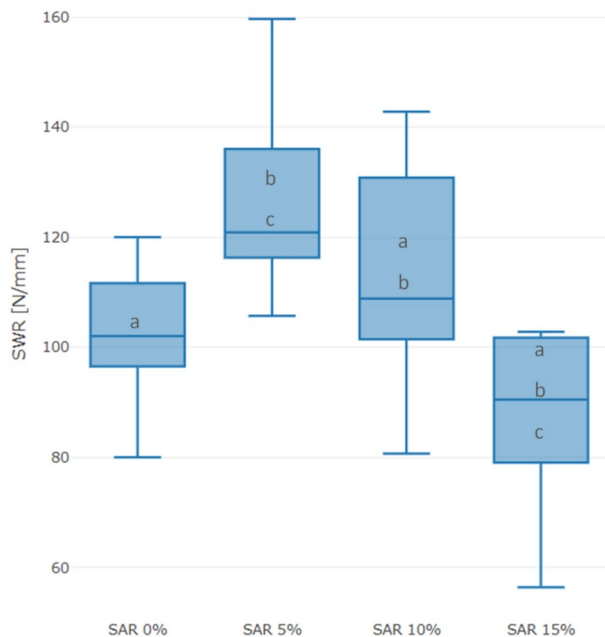

Fig. 6 Screw withdrawal resistance of the manufactured panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 10) with significance groups marked on the boxplots, according to the Tukey's test (letters a–c)

N/mm and 90.03 N/mm, respectively. The SAR 5% and SAR 10% samples showed higher SWR than the reference

sample, where the 5% SAR was statistically significantly different from the control board and from the SAR 10% variant (Tukey statistical significance group). The 15% SAR variant showed a statistically insignificant decrease in strength.

It was shown by Fehrmann et al. (2023) that SWR decreased with particle size reduction. Various studies have shown a strong influence of many interrelated factors on SWR, where particle size (Arabi et al. 2012) and board's IB (Rajak and Eckelman 1993; Semple and Smith 2006) can be mentioned as factors resulting from the board's properties, where core density significantly influences IB strength in the particleboard. Since in this study the core densities are alike each other, the hint could be found in the particle size. However, there has not been a significant decrease in SWR by implementation of small SAR dust-particles observed. A possible explanation for this phenomenon can be the adhesion properties of SAR working as a hardener for the binder due to its acidic nature (Ježo and Wronka 2022). According to the test results conducted by other scientists (Akyüz et al. 2010), it was determined that the amount of hardener should not exceed a certain proportion, and acidity of the particles should be controlled after the blending process by pH test for good quality particleboard manufacturing. This may explain the results obtained in this study. Also, the fact that in boards with increased SAR content, more binder is absorbed by the dust particles, can negatively affect the proper binding process, despite the hardening provided by SAR. Another potential explanation can be that SA due to the long fatty acid molecules increase the elasticity of the composites which is important for SWR.

3.5 Water absorption (WA), thickness swelling (TS)

In Figs. 7 and 8, the WA and TS results for the examined panels are illustrated, respectively. As can be seen in Fig. 7, the WA after 24 h of soaking in water was as follows for the SAR 0%, SAR 5%, SAR 10% and SAR 15% variants, respectively: 112.90%, 96.34%, 108.27% and 120.16%.

Statistical analysis indicated that after 2 h of soaking, the SAR 0% and SAR 15% variants absorbed moisture in a similar way, however, in the SAR 5% and SAR 10% samples, the WA resulted in statistically different values (statistical significance groups a and b on blue bars). After 24 h of soaking, the behavior of the SAR 0%, SAR 5% and SAR 10% samples was similar and the WA values obtained by the samples did not differ statistically significantly. However, the 10% SAR variant obtained statistically insignificantly different values only when compared to the 5% SAR variant (statistical significance letters A and B on the orange bars in the chart). SAR 5% and SAR 10% variants showed lower WA after 24 h of soaking, however, SAR 15% samples showed a higher WA value. The explanation for this phenomenon could be the same as in the case of mechanical
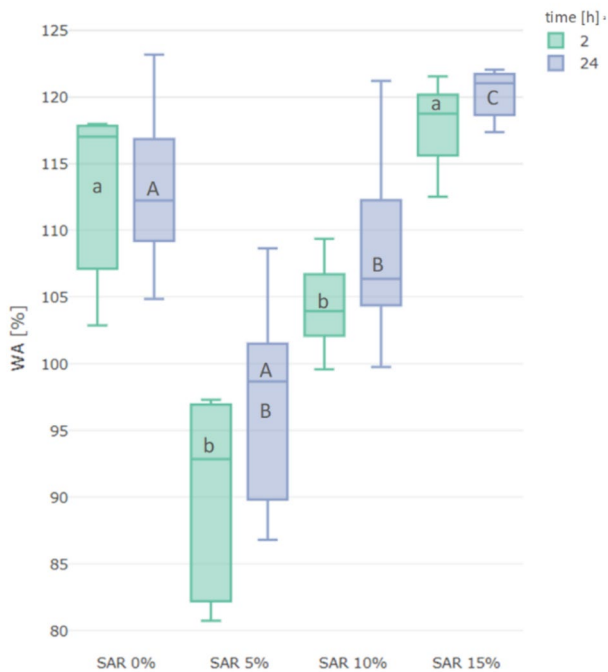
Fig. 7 Water absorption of the manufactured panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 5) with significance groups marked on the boxplots, according to the Tukey's test (letters a, b; A–C)
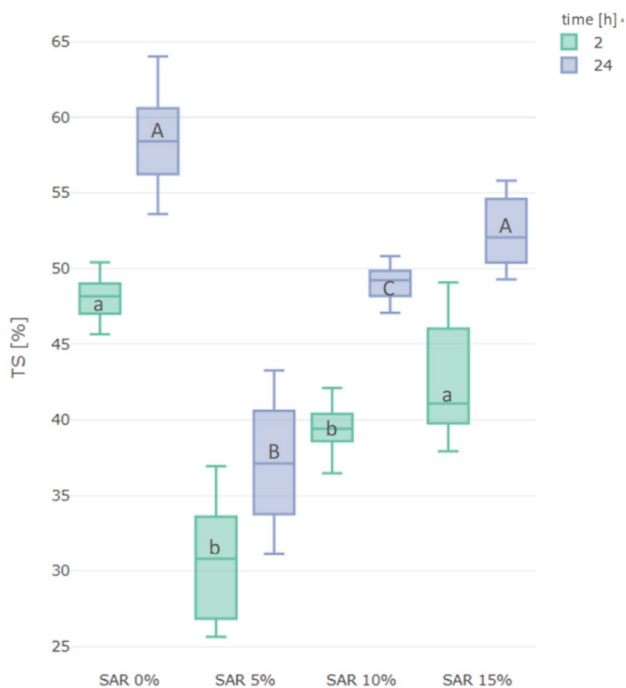

Fig. 8 Thickness swelling of the manufactured panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 5) with significance groups marked on the boxplots, according to the Tukey's test (letters a–b; A–C)

properties—with the addition of SAR at the level of 15%, fine SAR particles absorbed the glue, which made the bond of the boards not even and weaker. Therefore the "dry" particles were able to absorb more water, resulting in increased weight of the panels.

Figure 8 shows the results of the swelling-thickness test of the manufactured panels. After 24 h of soaking in water, the thickness swelling for the SAR 0%, SAR 5%, SAR 10% and SAR 15% variants was as follows: 58.53%, 37.22%, 49.03% and 52.42%. Statistical analysis indicated that after 2 h of soaking, the SAR 0% and SAR 15% variants absorbed moisture in a similar way, however, in the SAR 5% and SAR 10% samples, the water absorption resulted in statistically different values (statistical significance groups a and b on blue bars), same as for the water absorption analysis.

After 24 h of soaking, exclusively the values obtained for the SAR 0% and SAR 15% were statistically insignificantly different. As other scientists (Kariuki et al. 2019) showed, the presence of cellulose and hemicelluloses increases the TS in particleboards, which may explain the reduced swelling in boards with the addition of SAR dust. Additionally, increased swelling was noted for increased particle size, especially for the pine species (Kariuki et al. 2019). The improved WA behavior in the case of SAR 5% and SAR 10% particleboards and improved TS results for all variants reinforced with SAR could be the high content of lignin (over 21 wt%) and hydrophobic suberinic acids (29.4%) in SAR. These compounds determine the physical properties of the particleboard, including WA and TS. Lignin added into a composite material during particleboard formulation reduces WA and TS (Abu-Zarifa et al. 2018) since it contains a small number of hydroxyl groups that form hydrogen bonding with water (Nemli et al. 2009a, b). Particleboard manufactured by Kariuki et al. (2019) with a high lignin content of 21.5% showed reduction in WA. Regarding SA as particleboard adhesive, it also decreases TS to 4.5% being a hydrophobic substance and excellent adhesion to wood after hot pressing (Tupciauskas et al. 2019). Another aspect being the particle size, has been investigated by Farrokhpayam et al. (2016), whose research shows that the swelling of the boards within 2 and 24 h decreases as the particle size decreases. This tendency is also visible in our study. Fine particles are compressed better than coarse particles and exhibit more IB. However, fine particles with a large specific surface area can absorb more moisture than larger particles. The better IB in fine particle panels could not compensate for the tendency of small particles to absorb water (Farrokhpayam et al. 2016).

3.6 Contact angle (CA)

Table 1 illustrates the results obtained in the study of the CA of the produced samples. For the reference sample with 0% SAR content, after a second of wetting the CA was 105°,

Table 1 Contact angle (CA) of the manufactured panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 3)

Variant label	CA [°]	
	1 s	60 s
SAR 0%	105	100
SAR 5%	101	52
SAR 10%	92	27
SAR 15%	75	0

Table 2 TVOC and HCHO emissions of the manufactured panels (sample dimensions: 50 mm×50 mm, repetitions per variant: 10)

Variant label	TVOC	HCHO
	mg/m²·h	
SAR 0%	0.120	0.186
SAR 5%	0.024	0.003
SAR 10%	0.019	0.000
SAR 15%	0.011	0.000

and after 60 s–100°. Already with the addition of 5% SAR, a reduction in the angle was observed and after a second it was 101°, and after 60 s–52°. For the 10% SAR variant these values were for 1 s and 60 s: 92° and 27°, and for SAR 15% 75° and 0°, respectively. Additionally, in the case of the SAR 15% sample, significant delamination was observed on the surface after contact with a water drop. After just a few seconds, the drop penetrated the sample surface. Statistical analysis revealed significant differences between all of the examined panels.

Although suberin derivates showed hydrophobic properties as a filler for finishing films (Heinämäki et al. 2015; Handiso et al. 2021; Kumar et al. 2022), these properties did not work for the extraction residues as a feedstock for particleboards. The reason may be the lower quality of gluing resulting from the absorption of a significant part of the adhesive by the fine SAR and the lower homogeneity of the wetted surface. SAR has been tested as a filler for biopolymers in terms of their hydrophobicity, however, in the case of PLA no significant improvement in these properties was demonstrated after the addition of SAR, and in the case of PCL a decrease in the CA values was observed (Jeżo and Kowaluk 2023a).

3.7 Formaldehyde (HCHO) and total volatile organic compounds (TVOC) emissions

Table 2 illustrates the TVOC and HCHO emissions for the manufactured panels. The SAR 0% variant showed the highest emission levels of both TVOC and HCHO, and as the SAR share increased, the emission values of both substances decreased. In the case of SAR 10% and SAR 15% samples, the measuring device did not detect the HCHO content in the measuring chamber. This does not necessarily mean there was a complete absence of these substances in the air, but

it is possible that these values were too low for the device given its sensitivity.

Kowaluk and Jeżo (2023) also showed that the addition of carbon-rich SAR to finishing films on wood and wood-based surfaces significantly improves the barrier properties of coatings based on biopolymers—PLA and PCL (Jeżo and Kowaluk 2023b). Bark flour obtained from various tree species with high polyphenol content (walnut, chestnut, fir and spruce) showed HCHO scavenging properties when added to adhesive mixtures for gluing plywood (Aydin et al. 2017; Ružiak et al. 2017). It was found that the use of powdered beech bark reduces HCHO emissions from plywood by up to 74%, while maintaining good mechanical properties of the boards (Réh et al. 2019). The decrease in HCHO emissions can be attributed to the greater number of polyphenols in bark than in wood.

4 Conclusion

The research presented in this article concerned the possibility of using post-extraction residues (SAR) from birch bark (*Betula pendula*) as a filler material for the production of three-layer particleboards. In the light of the conducted research, it was shown that the addition of SAR has an adverse effect on the mechanical properties of particleboards, causing a decrease in MOR and MOE. In the case of IB and SWR, the SAR 5% variant showed a significant increase in value and a smaller one for the SAR 10% variant, but with a visible decrease for the SAR 15% variant. The authors state that the reason for the observed phenomenon is the possible occurrence of adhesive properties, absorption of the binder by fine SAR dust or a lower cellulose content in the material. In the case of WA, a decrease in the values for the SAR 5% and SAR 10% variants was noticed, and this phenomenon can be explained by the reduced share of absorbent cellulose, as well as the potential adhesive properties of SAR. A similar observation was made for TS, which can be explained by the fact that SAR, in the form of dust, had lower WA capacity than larger wood particles. Moreover, a positive effect of the addition of SAR on the HCHO and TVOC emission levels of particleboards was demonstrated, showing the scavenger effect of SAR, which may be due to the significant share of lignin and polyphenols in this raw material. Contact angle tests, however, showed a negative effect of the addition of SAR to particleboards, resulting in a deterioration of the hydrophobic properties of the boards, until the water drops were completely absorbed by the SAR 15% variant after 60 s. Since the manufactured variants with the addition of SAR met the requirements set for P2 type boards by European Standards (except for IB in the case of SAR 15% variant), the authors see potential in developing

research on the potential use of SAR in wood composite technology.

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Availability of data and materials The data and materials can be shared on request.

Declarations

Conflict of interest The Authors declare that they have no conflicts of interest to report regarding the present study.

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