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Physical–Mechanical Properties of Innovative Biobased Particleboards for Application in External Building Façades

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Abstract

Human activities undoubtedly increase greenhouse gases (GHG), negatively influencing global climate change. The building and construction sector uses at least 40% of the total energy consumption and produces the same percentage of GHG emissions. Therefore, the development of sustainable building materials is a crucial key factor for environmental protection. The study contributes to the development of bio-based façade materials using available raw biomass like wheat straw, grey alder, and softwood (a mix of spruce and pine), to promote reduced emissions of CO_2. Two technologies were used to produce high-density particleboards based on (1) steam explosion treatment and (2) the addition of bio-based suberinic acids as a binder. In addition to the biomass species and board type, the influence of conventional and mold hot-pressing was investigated on produced board properties: density, thickness swelling, modules of rupture and elasticity in bending, and internal bonding. The obtained particleboards demonstrate significant differences in terms of the tested properties depending on all variable factors. The best performance, in terms of physical–mechanical properties, was achieved by the conventionally hot-pressed board of steam-exploded grey alder particles, being influenced by the highest density (1380 kg/m^3). Mold hot-pressing in most cases resulted in decreased performance of obtained boards.

Keywords: wheat straw; grey alder; softwood; steam explosion; suberinic acids; high-density particleboard; bio-based façade materials

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1. Introduction

One of the global challenges observed over the past 200 years is climate change, that has been highly influenced by humans' activities, causing a rise in greenhouse gases (GHG), mostly carbon dioxide (CO_2), which results in global warming. The awareness of the threats resulted in a chain of global activities proposed in the Kyoto Protocol, Paris Agreement, and Europe 2020 Strategy [1,2], which, in general, aim to significantly reduce CO_2 and increase energy efficiency in all possible industries. The building sector is the largest user of energy, and CO_2 emitters, in the EU, making up about 40% of the total final energy consumption and GHG emissions. Furthermore, the problems were confirmed and accepted by all UN member states that signed the Millennium Development Goals, which especially highlight environmental sustainability and particularly address construction materials. In fact, the global construction industry is still unsustainable because it consumes more raw materials (about 3000 Mt/year, almost 50% by weight) than any other economic activity and keeps the clear tendency to grow [3]. Therefore, the building sector is a significant key factor to work on by developing building materials with decreased energy consumption and GHG emissions.

More than 40% of the existing building stock in Europe was built before the 1960s [4]; therefore, it undergoes active renovation in which the façade system receives some of the most attention, including in legal, technical, social, and financial sectors. Ventilated façade systems currently hold a substantial market share, with estimates ranging from 30% to 45% of the overall façade market. This dominance is expected to continue, with some reports predicting a leading position for ventilated façades throughout the forecast period [5].

The current commercial bio-based façade materials in Europe include straw and hemp systems, wood products, *Miscanthus* and cork materials, and biocomposites made from bamboo, recycled materials, and natural fibers. Bio-based external façade materials in Europe fall into several distinct groups and include the following:

1. Straw-based products and hemp-based systems (hempcrete and hemp batt), often used in timber frame and modular constructions [6,7];
2. Wood-based materials in various forms—untreated natural wood, modified wood, wood fiberboards, and recycled wood—applied as cladding or insulation [8–10];
3. *Miscanthus* boards and cork (raw or expanded), employed for thermal buffering, moisture regulation, and esthetic cladding [11];
4. Composites and biocomposites that incorporate bamboo, recycled PET, sanitary paper, grass, reeds, and recycled textiles with bio-based resin, as well as biomass-based insulation [12,13].

Studies indicate that these materials achieve thermal conductivities and moisture management properties comparable to conventional synthetic insulations while offering low embodied energy or even negative carbon footprints. Reported implementations range from laboratory and pilot-scale evaluations to fully commercial applications, with notable market presence in France, Germany, the Netherlands, and Italy.

The development of bio-based façade materials is driven by the need for environmental sustainability through carbon reduction, improved technical performance, and material innovation supporting modern design requirements. Bio-based external façade materials are pursued to reduce construction's environmental impact and to improve building performance. Studies report that renewable and recycled materials lower carbon footprints and embodied energy while enhancing ecological outcomes such as urban greening and air quality. Research on biocomposites [12,14,15], biopolymers [16], and bio-based concretes including hemp [7,17,18] and microalgae [19] indicates measurable gains in thermal insulation, energy efficiency, and acoustic performance along with compliance with safety codes. Reported drivers include the following:

1. Environmental sustainability through carbon reduction and the use of renewable or recycled resources;
2. Enhanced technical performance via improved thermal, acoustic, and structural properties;
3. Material innovation that supports lighter, modular, and code-compliant façade designs.

Laboratory prototypes, simulations, and limited field studies support these conclusions while also noting challenges in durability, weathering resistance, and scalability. Weathering resistance of bio-based façade materials, including acetylated medium-density fiberboard and ceramic-bamboo-coated particleboards, was reported [8].

Taking into account the observed literature and indicated challenges, the study aims development of novel fully bio-based particleboards for external façade applications. Based on the previous works of the authors [20–22], two types of high-density particleboards were investigated using steam explosion (SE) technology and suberinic acids (SA) as a binder. The novelty of the study is characterized by the fact that there was not found in the literature, including our previous works, the development of biobased particleboards for application in external façade using these two approaches. This article investigates the influence of technological aspects of board production, focusing on locally available lignocellulosic biomass (LCB), like wheat straw, hardwood (grey alder), and softwood (a mix of spruce and pine), board type (SE-treated and SA-bonded), and conventional vs. mold hot-pressing on the obtained board properties. In general, the study has shown the advantage of wood species vs. wheat straw and confirmed both used technologies are suitable for high-density board production using conventional hot-pressing.

2. Materials and Methods

2.1. Raw Materials

For the board production, three locally available LCB raw materials of wood and non-wood species were used in the study: wheat straw (WS, *Triticum aestivum*), grey alder (GA, *Alnus incana*), and softwood (SW) that was a mix of spruce (*Picea abies*) and pine (*Pinus sylvestris*) wood (50/50 wt.%). Each species was chopped according to the treatment described below.

For the production of SE boards, the raw materials were initially crushed using a knife mill (CM4000, LAARMANN, Roermond, The Netherlands) equipped with a 10 mm sieve. To produce SA-bonded boards, raw materials were subsequently processed using a cutting mill (SM 100, Retsch GmbH, Haan, Germany) fitted with a 2 mm sieve. A particle fraction ranging from 0.5 to 2 mm was then separated using a sieve shaker (Haver & Boecker, Oelde, Germany) and used for SE and SA board manufacturing.

Isolated and extracted birch (*Betula pendula*) outer bark with a moisture content (MC) of 4–5 wt.% and fraction of $1 < d \leq 2$ mm was kindly supplied by BetulinLab from AS Latvijas Finieris (Riga, Latvia). The feedstock was prepared by milling in an SM 100 cutting mill (Retsch GmbH, Germany), fractionating by sieving using an AS 200 Basic vibratory sieve shaker (Retsch GmbH, Germany), and extracted [23] in ethanol (96%, Kalsnava, Latvia). Potassium hydroxide (KOH) (Reag. Ph Eur, 85.0%) was provided by VWR International (Leuven, Belgium). Nitric acid (HNO_3) (65%) was obtained from Honeywell (Seelze, Germany).

2.2. Steam Explosion Pretreatment

Before SE treatment, crushed raw materials were moistened by water to achieve MC of 50% for WS and 60% for GA and SW. The materials were then pretreated separately using a custom-built SE device equipped with a 0.5 L batch reactor. SE pretreatment conditions, temperature 220 °C and residence time of 2 min (severity factor logR0 = 3.83), for WS and GA chips were selected based on previous studies [24,25]. The SE reactor's volume was filled by the prepared raw material, and the saturated steam was injected within 3–5 s to reach the pressure of 23 bar and maintained for 110 s. The steam pressure was then elevated to 30 bar for the last 10 s, after which the reactor was opened immediately, and a rapid decompression resulted in a steam explosion, providing the pretreated material to a receiver. The selection of SE conditions for SW species was based on the previous work [26] and approved during this study as 230 °C–90 s. The SE-pretreated LCB was centrifuged to separate the liquid fraction based on the literature recommendations [26,27]. The residual solid fraction was mechanically processed through a system of two rotating cylinders coupled with stainless steel wires as described in [28], and then oven-dried at a temperature of 60 °C to MC of 2% ± 0.2%.

2.3. Binder Preparation

The SA binder was obtained from extracted birch outer bark (1–2 mm) by hydrolytic depolymerization, which was carried out in a 100 L stainless steel reactor equipped with an oil heating jacket, reflux condenser, and a mechanical stirrer. A water solution of 4 wt.% KOH was used for depolymerization, and the bark was suspended at a bark-to-liquid mass ratio of 1:10. The depolymerization was carried out at 90 °C for 30 min; after that, the suspension was cooled to 30 °C and acidified with HNO_3 to pH = 2. Then, the mixture was filtered in a polypropylene filter bag with a fabric mesh size of 100 microns, rinsed with water, and filtered again to separate water-soluble KNO_3 and to obtain SA-containing binder with a solid content of 20%.

2.4. Production of Particleboards

Biobased particleboards were produced from LCB species using two manufacturing approaches (Figure 1): (1) binderless particleboards after SE treatment (SE-PB) and (2) milled particles bonded with SA binder (SA-PB). The SE boards were produced only from SE-pretreated LCB based on a previous study [22]. The SA boards were produced based on a previous study [21] using 16%–18% (o.d.) of SA binder added to prepared LCB particles and mixed to achieve homogenous furnish, then dried to MC of 2% ± 0.2% before the hot-pressing.

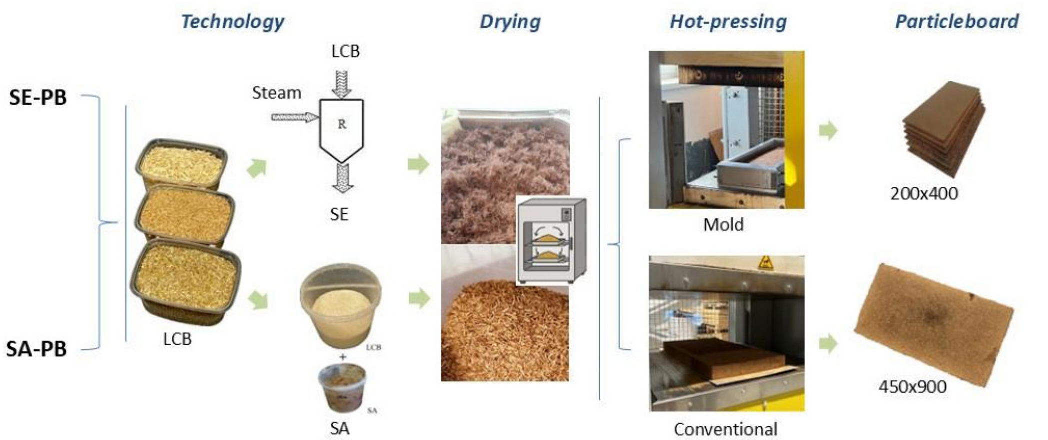

Figure 1. Production flow scheme of fully biobased particleboards from steam-exploded LCB (SE-PB) and suberinic acids-bonded LCB (SA-PB) following two types of hot-pressing.

In addition to the conventional board type, the influence of mold (M) hot-pressing was determined (Figure 1). In the case of conventional pressing, the boards were produced with the measurements of 450 mm × 900 mm, from which another four board samples were cut with the measurements of 200 mm × 400 mm. The M-boards were hot-pressed in the specific mold made from aluminum alloy with the inner measurements of 200 mm × 400 mm. The boards were hot-pressed, slightly varying the temperature and time to achieve the set thickness of 9.5 mm and density of 1200 kg/m^3. The pressing cycle for all board types consisted of two general steps: (1) pressing under the set temperature for 9 min; and (2) cooling under a decreased pressure to achieve the temperature of 90 °C. The pressing pressure in the first step varied within 10 ± 2 MPa to achieve the set thickness of the board and was diminished by approximately 20% in the second step. The type and conditions of produced particleboards are summarized in Table 1.

Table 1. Types and conditions of produced particleboards.

LCB	Board Type	Hot-Pressing	Temperature/Time * °C/min	Designation
WS	Crushing + SE	Conventional	160/20	WSSE
		Mold		WSSE-M
	Milling + SA	Conventional	180/20	WSSA
		Mold		WSSA-M
GA	Crushing + SE	Conventional	160/20	GASE
		Mold		GASE-M
	Milling + SA	Conventional	180/20	GASA
		Mold		GASA-M
SW	Crushing + SE	Conventional	165/20	SWSE
		Mold		SWSE-M
	Milling + SA	Conventional	180/20	SWSA
		Mold		SWSA-M

* The pressing time indicated here means holding in the press under a certain pressure and includes 9 min at the set temperature and cooling down to 90 °C.

2.5. Evaluation of Particleboards

The obtained PBs were characterized according to the relevant standards by density [29], modulus of elasticity (MOE), and modulus of rupture (MOR) in the 3-point bending test [30], with tensile strength perpendicular to the plane of the board (IB) [31], and thickness swelling/water absorption (TS/WA) after the immersion in water for 24 h [32]. Mechanical tests (MOE, MOR, and IB) were performed on a ZWICK/Roell Z010 (Ulm, Germany) universal machine for testing resistance of materials.

The size of specimens was 200 mm × 50 mm for the bending properties testing, and 50 mm × 50 mm for all other properties testing. Six specimens were determined in each test to calculate an average value of each property. The obtained board's properties were compared with the European requirements EN 312 for particleboards for use in humid conditions (Type P3) [33]. The factors of the influence on the mean values of the tested properties are analyzed at the confidence level $\alpha = 0.05$ by using the Excel software (version 2507) tool one-way ANOVA.

3. Results and Discussion

3.1. Physical–Mechanical Properties of the Boards

3.1.1. Density

The density of obtained particleboards is summarized in Figure 2 depending on raw material and used technology. In general, the density of the boards hot-pressed in the mold is slightly lower than for the boards hot-pressed by the conventional type.

The significantly lower density values were achieved by the sample group of GASE-M obtained from steam-exploded grey alder using mold pressing. This could be explained by the fact that the samples were produced using new mold equipment for the first time with too low pressure (5 MPa), resulting in a higher thickness (10.9–11.4 mm) of the board group. To achieve the set density of the boards, the pressing pressure was further increased up to 10 MPa.

Significantly higher density values than the set one were achieved by some board samples made of GASE and SWSE by both pressing types (Figure 2). This result was influenced by the SE treatment, during which the plasticity of LCB is highly increased due to modification of lignin and hemicelluloses, as reported by various studies [26,27,34].

Figure 2. Density of particleboards depends on raw material and board type.

3.1.2. Water Resistance

Water resistance of investigated particleboards is summarized in Figures 3 and 4 in terms of WA and TS. The average values of WA vary significantly from 5% to 80% depending on raw materials, board type, and even pressing type (Figure 3).

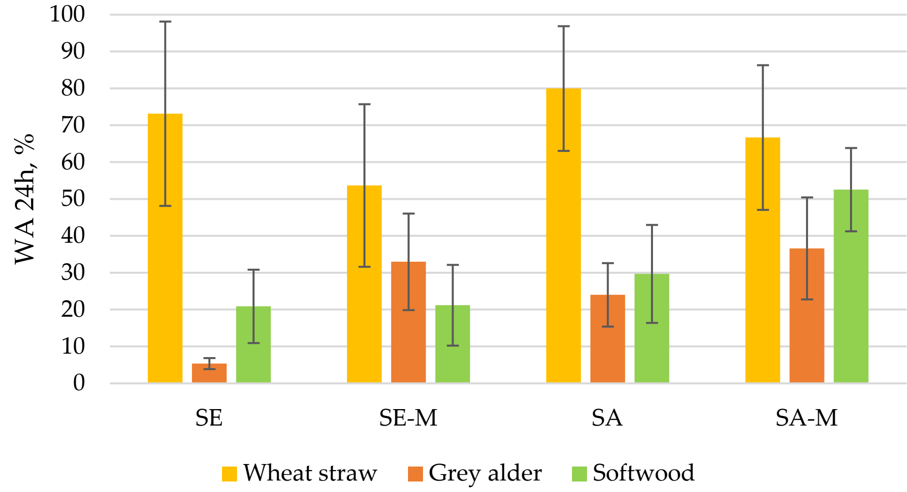

Figure 3. Water absorption of particleboards depending on raw material and board type.

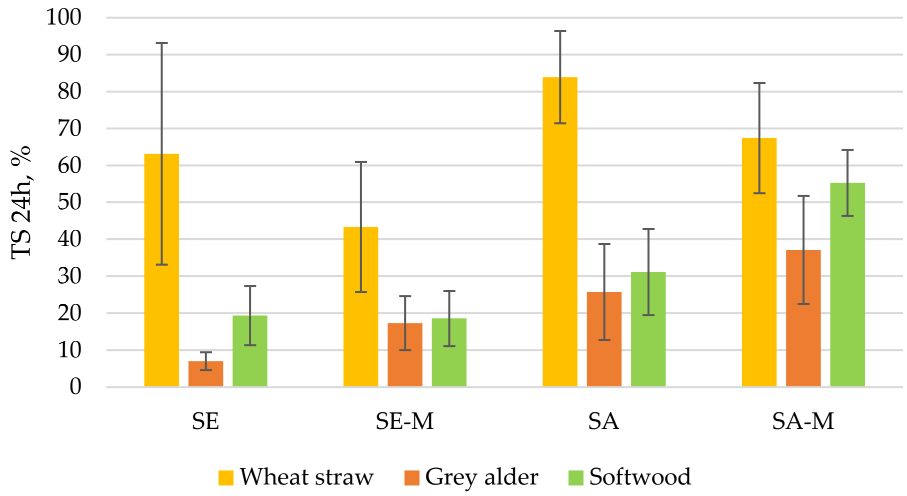

Figure 4. Thickness swelling of particleboards depending on raw material and board type.

The highest WA values achieved board samples made of WS, varying in range of 54%–80%. Different from wood species, both types of WS boards obtained by mold pressing achieved improved WA values. High standard deviation of WA values of WS boards could be related to insufficient cohesiveness and inhomogeneity of the samples. WA values of WSSE boards with similar density (1100–1160 kg/m^3) have been reported varying from 14% to 26% [22]. The reason for the significant difference between the WA values lies in manufacturing conditions of WSSE boards. Different from this study, the SE-pretreated WS biomass in the mentioned study was not centrifuged, meaning a retention of a higher amount of soluble degradation products on the furnish surface, which has been recognized as a cohesive improvement of SE boards [35].

In spite of different density and SE conditions, WA of GASE boards achieved the lowest value (Figure 3), that is very similar to those reported before [20]. However, the pressing type by using the mold significantly increased WA values for both wood species and both board types, except for SWSE, indicating significant differences during the pressing types. Different from this study investigating binderless and natural adhesive-bonded particleboards, the particleboards bonded by synthetic adhesives in a sealed pressing showed a higher performance of water resistance vs. conventional pressing [36].

The same tendencies were observed for TS values of the obtained particleboards varying in the range of 7%–84% (Figure 4). According to specifications for the particleboards for use in a humid environment, the TS value should not exceed 17% [33]. As seen in Figure 4, the TS requirement was achieved only by the SE boards made of GA wood regardless of pressing type. However, the SWSE boards achieved TS values very close to the requirement value, showing the potential of the boards to be used in an external environment.

All the SA-bonded boards achieved significantly higher TS values compared to SE boards. In spite of the higher density, which usually tends to decrease TS values, these results are obviously impacted by the lower content of SA binder and lower pressing temperature. For example, SA-bonded birch particleboards, with a density of 860–1005 kg/m^3 and hot-pressed at 220–230 °C, have shown TS values within 4.5%–11.3% [21]. From another point of view, the higher pressing temperature and higher amount of SA binder, that have been tried within this study, resulted in negative results by means of the external flowing of the binder on the board surfaces (impact of higher amount of the binder) or even the explosion of the board sample after the press opening (impact of higher temperature). These negative experiments, in details not described here, resulted in the selection of optimal pressing parameters for SA boards described in details above.

3.1.3. Bending Properties

The bending properties of the investigated particleboards are summarized in Figures 5 and 6. MOE values of the boards vary in the range of 3720–9980 N/mm^2 (Figure 5), while MOR values vary within 18–66 N/mm^2 (Figure 6). The minimum and maximum of both MOE and MOR values achieved belong to the SE boards. Both MOE and MOR values of the SE boards from wood (GA and SW) are significantly higher than those obtained from wheat straw by both pressing types. Due to the high standard deviation, there is no significant difference in MOE values between the WSSE samples, depending on the pressing type. However, WSSE board samples hot-pressed by the conventional type achieved significantly higher results of MOR compared to the samples obtained by the mold pressing (Figure 6).

The studies performed before on WSSE and GASE with different conditions by conventional hot-pressing reported values for MOE of 3400–4640 N/mm^2 and 6260–7260 N/mm^2, and for MOR of 20–28 N/mm^2 and 27–32 N/mm^2, respectively [20,22]. This means that the bending properties of WSSE remain at the same degree regardless of the manufacturing condition differences; however, both MOE and MOR of GASE boards were significantly increased during this study. As a result, the bending properties of GASE boards were improved by separation of the soluble fraction after the SE processing even with reduced pressing time.

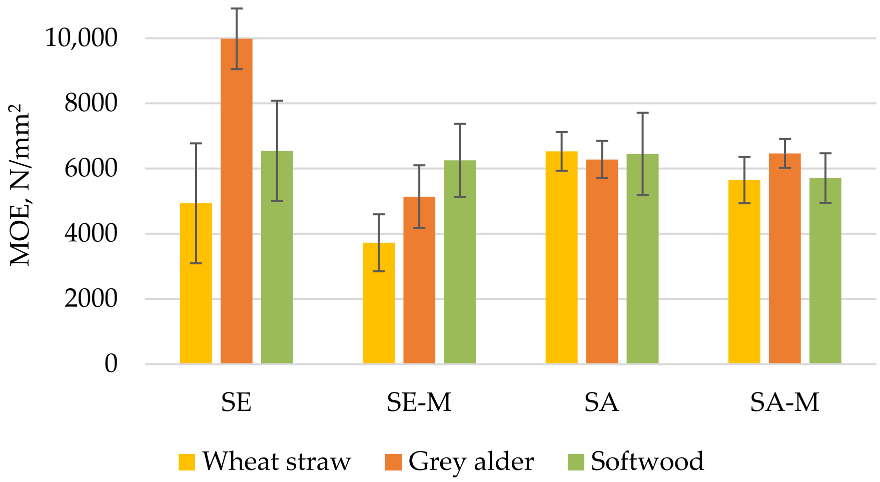

Figure 5. MOE of particleboards depending on raw material and board type.

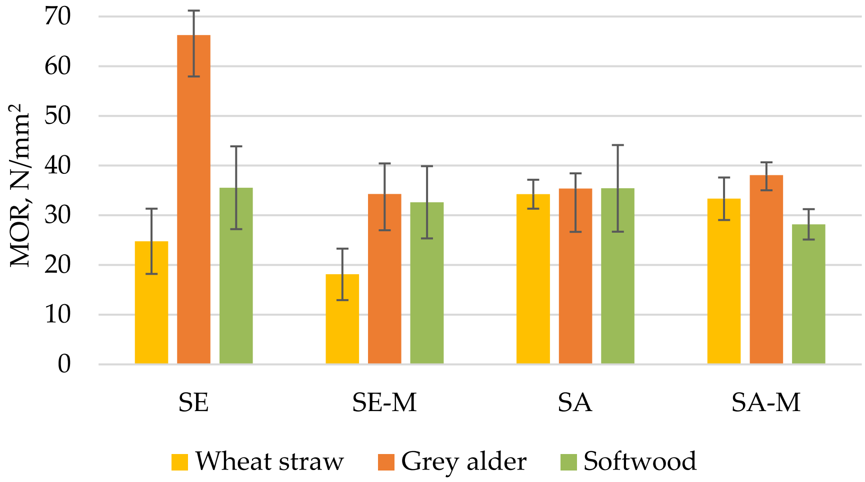

Figure 6. MOR of particleboards depending on raw material and board type.

Between the samples bonded by SA binder, there is no significant difference in both MOE and MOR values regardless of the LCB species and pressing type used. Only the SWSA-M sample achieved a significantly lower MOR value compared to other SA-bonded boards (Figure 6). Both MOE and MOR (the difference is significant) values of WSSA samples are higher than those of WSSE samples, indicating a positive influence of the SA binder and its compatibility with wheat straw particles. The previous study on particleboards composed of birch wood particles bonded by the SA binder reported MOE values in the range of 1645–2772 N/mm^2 and MOR of 8.7–18.7 N/mm^2 [21]. This means that during this study the bending properties of SA boards were significantly increased to a great extent due to the higher density (850–1000 kg/m^3 vs. 1170–1245 kg/m^3, respectively). It is worth noting that the content of the SA binder was decreased to 16% during this study (vs. 20%–30% in the previous study) because of the higher density of the boards, which was not able to penetrate the higher content of the SA binder.

According to EN 312 specifications for the particleboards for use in a humid environment [33], the MOE and MOR values should achieve at least 2050 N/mm^2 and 15 N/mm^2, respectively. Our results show that the requirements for both bending properties were achieved in all produced particleboards, exceeding the values from 1.8× to 4.9× in the case of MOE (Figure 5) and from 1.2× to 4.4× in the case of MOR (Figure 6).

3.1.4. Internal Bonding

The most essential property of wood-based panels characterizing adhesion between the particles is IB. The determined IB values of the obtained particleboards, depending on the board type and pressing type, are summarized in Figure 7. The IB values vary significantly from 0.44 N/mm^2 to 3.04 N/mm^2 depending on all the variables. The lowest IB values were achieved by the boards from WS (0.44–0.67 N/mm^2) with no significant differences regardless of the board type and pressing type. In spite of the high bending properties achieved by WS boards, especially those bonded by SA binder (Figures 5 and 6), the IB values indicate a poor adhesion compared to all other boards obtained from wood species (Figure 7). This indicates the significant differences between the wood and non-wood species, the latter containing a higher content of hemicelluloses and minerals, obviously resulting in poorer properties of the produced boards [35].

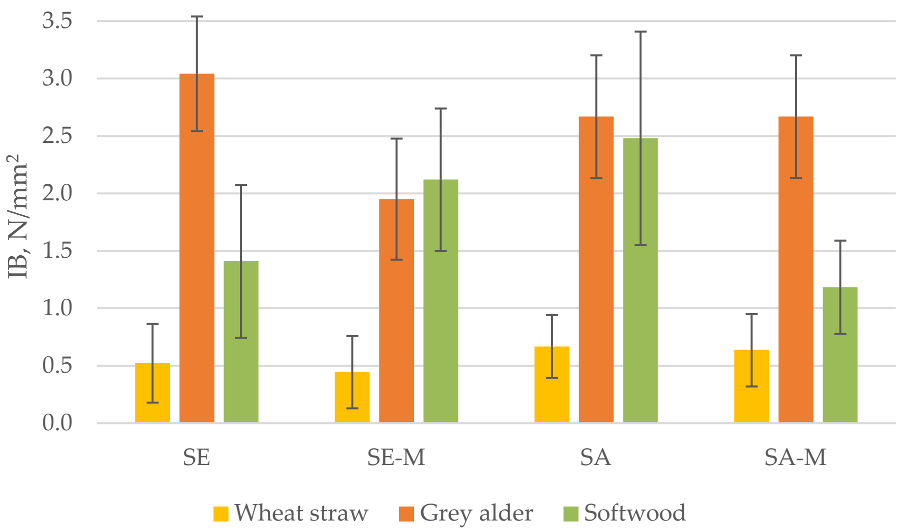

Figure 7. IB of particleboards depending on raw material and board type.

IB values of the boards from wood species vary in the range of 1.41–3.04 N/mm^2 for the SE board type and 1.18–2.67 N/mm^2 for the SA-bonded board type (Figure 7). The influence of pressing type differs depending on wood species and board type. Hot-pressing in the mold of GASE (representing hardwood) shows significantly reduced IB values, while, for SWSE (representing softwood), IB values are significantly lower if hot-pressed by conventional type (Figure 7). The tendency absolutely differs for SA-bonded boards from SW (the highest IB values achieved by conventional pressing), while the boards from GA achieved IB values with no significant difference depending on the pressing type (Figure 7).

Comparing the GASE processing technology on the achieved IB values, there is a significant positive influence of soluble fraction separation after the SE. The GASE boards obtained by conventional hot-pressing without separation of liquid fraction achieved IB values in the range of 0.92–1.06 N/mm^2 [20], while the separation of liquid fraction after the SE during this study increased the IB value up to 3.04 N/mm^2 (Figure 7). The study investigating the boards from steam-exploded softwood under similar conditions (SE temperature 221 °C, residence time 2.1 min, logR0 = 3.9, obtained by hot-pressing in mold) reported an IB value around 2 N/mm^2 [26], and that is the same result achieved during this study (Figure 7).

Our results of GASA and SWSA fit the IB values reported in the range of 1.2–3.7 N/mm^2 for the SA-bonded boards of birch wood particles that were influenced by the binder content (20%–30%), density (840–1000 kg/m^3), pressing temperature (220–230 °C), and even time (2–6 min/7 mm) [21]. Finally, according to EN 312 specifications for the particleboards of Type P3 [11,33], the requirement of IB value is 0.45 N/mm^2, and that was achieved even by WS boards (except for WSSE-M), exceeding the values from 2.6× to 6.7× achieved by the boards from GA and SW (Figure 7). In conclusion, the obtained IB values of the investigated particleboards show high adhesion between the particles, particularly from wood species, indicating the potential for their use in external environments.

3.2. Relation of the Boards' Properties to Density and IB

Relation of the detected properties of the investigated boards to the density was expressed by the coefficient of correlation and is summarized in Figure 8.

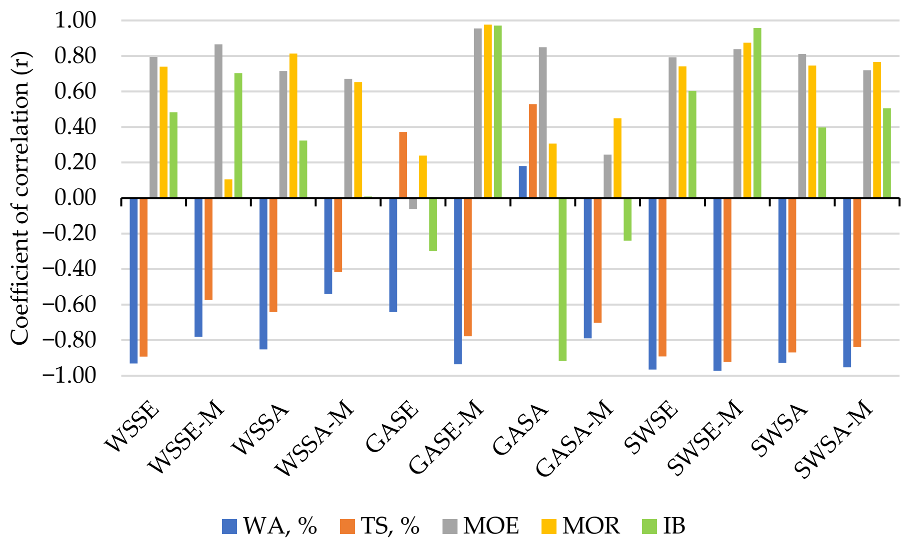

Figure 8. Correlation between density and the tested properties of particleboards.

As is seen from the Figure, the correlation of WA/TS to density, in general, is negative (the property decreases with increasing density) with some exception in the case of GASE (WA negative, TS positive) and GASA (WA/TS positive). High correlation ($0.60 \leq r \leq 0.79$) is observed for WSSE-M, WSSA (TS), GASE (WA), GASE-M (TS), and GASA-M, indicating high relation between WA/TS and the density of these boards. In the cases of WSSE, WSSA (WA), GASE-M (WA), SWSE, SWSE-M, SWSA, and SWSA-M the correlation is very high ($r \geq 0.8$).

As is seen from Figure 8, correlation between the bending properties (MOE/MOR) and the density of the boards is positive (the property increases with increasing density) with only one insignificant exception in the case of GASE (MOE negative, MOR positive, both showing low to very low correlation). Half of the boards (WSSE, WSSA, WSSA-M, SWSE, SWSA, and SWSA-M) showed high correlation between both bending properties and density. Four boards (WSSE-M, only MOE, GASE-M, GASA—only MOE, and SWSE-M) showed very high correlation indicating strong linear dependence of the bending properties of the boards on the density.

Relation of IB to density of the boards is uncertain (Figure 8). In most cases, there are positive correlations observed; however, in the case of GASE, GASA ($r = -0.92$), and GASA-M the correlation is negative. High correlation of IB to density is observed only for WSSE-M and SWSE ($r = 0.60$); and very high correlation is observed for GASE-M, GASA, and SWSE-M (Figure 8).

Relation of detected properties of investigated boards to IB is summarized in Figure 9. As is seen from the Figure, the correlation between WA/TS and IB, in general, is negative

(IB decreases with increasing property), with some insignificant exceptions for WSSA-M, GASE, SWSE, and SWSA-M. High correlation is observed for WSSE, WSSE-M, GASE-M, SWSE-M (TS), and SWSA indicating high relation between WA/TS and IB of these boards. In the case of GASA and SWSE-M (WA) the correlation is very high.

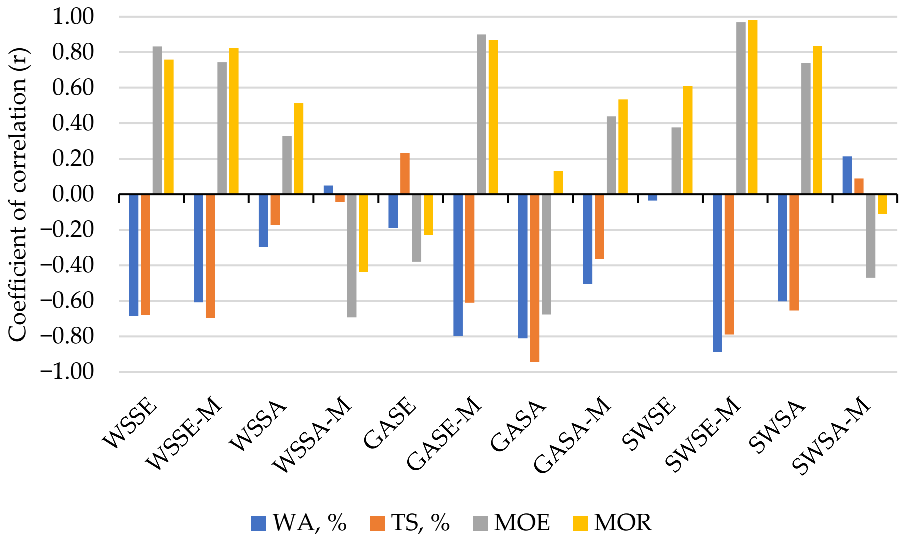

Figure 9. Correlation between IB and tested properties of particleboards.

The correlation between the bending properties and IB of the boards is uncertain, having mostly positive tendency (Figure 9). In four cases, the correlation is negative, with two of them (WSSA-M and GASA (only MOE)) indicating strong relation. High to very high correlation is observed for WSSE, WSSE-M, GASE-M, SWSE-M, and SWSA, indicating high relation between the bending properties and IB of these boards.

4. Conclusions

Based on the study results, two technologies for manufacturing high-density particleboards were investigated for potential application in external building façades. Wood-based particleboards outperformed wheat straw in both approaches—steam explosion pretreatment and suberinic acid bonding. Each technology was adapted to the specific raw material and proven suitable for producing high-density boards. Furthermore, conventional hot-pressing demonstrated superior performance compared to mold hot-pressing in terms of the mechanical and physical properties achieved.

According to the EN 312 standard requirements for the boards for use in humid conditions, water resistance was met only by the boards from steam-exploded grey alder wood (TS 7%–17%), regardless of the pressing type. This indicates the suitability of GASE for external façade applications, but also indicates the weakness of other investigated board types. The bending properties of all obtained boards were excellent (MOE 3720–9980 N/mm^2, MOR 18–66 N/mm^2) and met the standard requirements. Almost all investigated boards achieved higher IB values according to the standard requirement (0.45 N/mm^2), in the best case exceeding the value up to 6.7×.

Further research on the investigated particleboards is ongoing, aiming at the surface treatment and variation in steam explosion conditions, and testing water resistance in specific conditions by boiling and determining water drop angle, followed by weathering in the open air.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse gases
CO_2	Carbon dioxide
LCB	Lignocellulosic biomass
SE	Steam explosion treatment
SA	Suberinic acids
WS	Wheat straw
GA	Grey alder wood
SW	Softwood
EN	European norm
MOE	Modulus of elasticity according to EN 310
MOR	Modulus of rupture according to EN 310
WA	Water absorption
TS	Thickness swelling according to EN 317
IB	Internal bonding according to EN 319

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