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ORIGINAL ARTICLE

Characterization of randomly oriented strand boards manufactured from juvenile wood of underutilized wood species

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Abstract

The wood-based panel industry in Europe, which is dominated by the use of Norway spruce, will face new challenges due to environmental changes and the bark-beetle calamity, which started a new era of forestry. To explore the possibility of replacing spruce with other wood species, juvenile wood of nine underutilized wood species (Scots pine, European larch, poplar, willow, alder, birch, European beech, English oak and hornbeam) were used to make randomly oriented strand boards (OSBs). Single-layer OSBs were produced with 3% pMDI resin and 0.5% wax. Standard physical and mechanical properties were measured. The bending strength (MOR) values showed that there was no statistically significant difference between the values for, on the one hand, spruce (34.6 MPa) and, on the other, larch (25.9 MPa), poplar (25.2 MPa), willow (27.8 MPa), alder (34.3 MPa) or birch (27.1 MPa). A similar trend was found for the boards modulus of elasticity (MOE). The highest MOE values of 5,185 MPa and 4,472 MPa were found for spruce and alder, respectively. There was no significant difference between spruce and other wood species in internal bond strength. Boards made from high-density wood species showed better physical performance, whereas those made from low-density wood species (except pine) gave better mechanical properties. Strand-generalized characteristics, such as the slenderness ratio and specific surface, were analyzed for all investigated physical and mechanical properties. European larch, poplar, willow, and alder are potential wood species for manufacturing OSBs in future without mixing species, as they can replace spruce in the wood-based panel industry.

1 Introduction

Over recent decades, environmental changes and the bark-beetle calamity have begun a new era of forestry and wood-based composites. The wood-based panel industry in Europe, oriented mainly on spruce (*Picea abies*), will face new challenges too. Some studies show that the utilization of deciduous trees (larch, birch, aspen etc.) and fast-growing trees (poplar etc.) in the forest will be the way for the future forest (Pérez-Cruzado et al. 2012). The expected changes in forests from monocultures of spruce to mixed stands with expected thinning of forests will provide material with small diameters and low-quality logs. In oriented strand board (OSB) production, usually low-quality trees, small and thin logs, and mill residues can be used to make value-added products, and thereby the requirement for old-growth

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forests and high-quality logs could be diminished (Moses and Prion 2004; Ross 2010).

OSB production has recently increased worldwide from 34.8 million m^3 in 2020 to 36.3 million m^3 in 2022 (Food and Agriculture Organization of the United Nations 2023). Europe´s growing stock of main tree species in 2020 showed that there is 29.6% pine, 23.0% spruce, 11.9% beech, 10.0% oak, 6.6% birch, 3.2% fir and 15.7% of other species (Köhl et al. 2020), showing the huge potential for incorporating underutilized species into wood-based composites (Beck et al. 2009).

Lunguleasa et al. (2021) compared the properties of OSB made of spruce (*Picea abies*) and pine (*Pinus sylvestris*) with fast-growing poplar (*Populus tremula*) and willow (*Salix alba*). OSBs with a board density of 700 kg/m^3 were prepared using a 6% methylene diphenyl diisocyanate (MDI) adhesive. Willow and poplar panels gave improved bending strength (MOR) (44.5 MPa vs. 27.1 MPa) and greater internal bond (IB) strength (1.3 MPa). Okino et al. (2004) analyzed the influence of 80 mm-long pine strands (*Pinus taeda* L.) on the properties of OSBs with a density of 750 kg/m^3. The results confirmed the feasibility of using *Pinus taeda* L. for OSB manufacture. The role of three different lengths of *Pinus taeda* L. strand (120, 150 and 300 mm) was examined in a study by Chiromito et al. (2016). The increase in the length of the strand positively influenced both the bending strength (MOR) and the modulus of elasticity (MOE). Birch and aspen OSBs were investigated by Beck et al. (2009; 2010) bonded with a mixture of liquid and powder phenol–formaldehyde (PF) adhesive (7% by oven-dry wood weight). The mechanical parameters made the OSB prototypes capable of competing with similar engineered wood products. The authors point out the importance of optimizing the strand length, as long strands provided high bending properties, while short strands provided high compressive properties. An increase in the adhesive content resulted in greater IB strength, but the bending properties remained unaffected in the tested range of adhesive content.

A study by Dumitrascu et al. (2020) used thin logs for OSB production from fast-growing species of birch (*Betula pendula* Roth.), willow (*Salix alba* L.) and poplar (*Populus tremula* L.). Strands were blended with a pMDI adhesive (10%) to make a panel with a density of 610 kg/m^3. The results showed that these three wood species could be used as individual raw materials in OSB production. The use of kiri (*Paulownia tomentosa*), pine (*Pinus sylvestris*) and beech (*Fagus sylvatica*) for the manufacture of lightweight strand boards with a density of 300 and 400 kg/m^3 showed promising results for kiri and pine wood (Pham Van et al. 2021). Balsam fir, black spruce and jack pine were used with phenol-formaldehyde adhesive to make OSB panels with a density of 600 kg/m^3 (Zhuang et al. 2022). Here, the panels made from softwood species showed physical and mechanical properties that exceeded the standard requirements, except for higher-thickness swelling (TS). The combination of softwood and aspen strands significantly improved the TS of the prepared softwood OSB. A study by Ciobanu et al. (2014) focused on OSBs made from a mixture of 50% softwoods – spruce (*Picea abies)*, fir (*Abies alba)*, pine (*Pinus sylvestris)* and larch (*Larix decidua*) – 25% beech (*Fagus sylvatica*) and 25% different low-density hardwood species – poplar (*Populus tremula)*, birch (*Betula pendula)*, willow (*Salix alba)* and alder (*Alnus glutinosa*). The mixture of strands was combined with MUF adhesive for the face layer and pMDI for the core layer. The results showed that the panel made from the mixture of wood species met the requirements of EN 310 (1995) for mechanical properties but failed in the wood-water relations. The mixture of birch and aspen strands was investigated by Jin et al. (2009) in randomly oriented OSBs for the effect of vertical density profiles (VDP). About 10% of the improvement in MOE could be obtained by manipulating the VDP. The boards were prepared with 3.5% PF adhesive and 0.5% wax emulsion was used. In another study, Akyildiz et al. (2018) used a mixture of 80% black pine (*Pinus nigra* A.), 15% Scots pine (*Pinus sylvestris* L.) and 5% fir wood (*Abies nordmanniana* L.). Akrami et al. (2014a), 2015) analyzed the properties of an OSB board obtained from a mixture of beech and poplar. Increasing the proportion of beech strands improved the mechanical properties, but at the same time decreased TS. The effect of fine strands in the core layer mixed in different ratios and mixtures of beech and poplar was investigated in panels with a density of 650 kg/m^3 bonded with 5% pMDI resin (Akrami et al. 2014b).

In the production of wood-based panels, various adhesives can be used, such as amino plastic resins (UF, MF and MF/UF), phenolic resins and isocyanate (pMDI) (Dunky and Pizzi 2002; Irle and Barbu 2010; Mendes et al. 2013). pMDI resins with additives in different percentages, especially for the core layer, are used in OSB production in Europe (Mantanis et al. 2018). A mixed system PF for the surface layers and pMDI for the core layers has been used to produce OSBs from various wood species, such as aspen, pine, rubberwood, red maple and bamboo (Brochmann et al. 2004; Malanit and Laemsak 2007; Paredes et al. 2008; Ciobanu et al. 2014; Salem et al. 2018).

Based on previous research, wood species, specific mass, strand geometry, type of adhesive, amount of adhesive, pressing parameters and the structure of the board influence the physical and mechanical properties of OSBs (Candan et al. 2017; Mendes et al. 2013). A complex comparison of different European wood species underutilized in OSB manufacturing is missing, especially concerning the actual performance of low-quality trees, and small and thin logs typically employed.

In this study, we explored the uses of underutilized European wood species for engineered wood products, especially OSB panels. The main objective of the study was to find the most suitable wood species among the underutilized wood species for the replacement of Norway spruce for OSB manufacturing. The objectives were also (1) the cutting process of nine underutilized European wood species into strands to manufacture OSBs; (2) to determine the characteristics of the strands obtained from each wood species separately; (3) to perform a correlation analysis between the characteristics of the strands and those of the corresponding OSB boards; (4) and to make a comprehensive comparison of the physical and mechanical properties of OSBs manufactured from these species.

2 Materials and methods

2.1 Materials

Juvenile logs (25–35 years old) with a diameter in the range of 100–150 mm and moisture content 70–80% from Norway spruce (*Picea abies*) – NS (as a reference) and nine different underutilized wood species (Scots pine (*Pinus sylvestris*) – SP, European larch (*Larix decidua*) – EL, poplar (*Populus tremula* L.) – PO, willow (*Salix alba* L.) – WL, alder (*Alnus glutinosa* (L.) Gaertn.) – AR, birch (*Betula pendula*) – BI, European beech (*Fagus sylvatica*) – BE, English oak (*Quercus robur*) – OK and hornbeam (*Carpinus betulus*) – HBM) were split in half (for better parallel orientation to the knife during the cutting process) and cut to a length of 120 mm (the length of the final strands). All materials were then immediately disintegrated into strands (Fig. 1) using a knife ring flaker (Maier MSF 1400, Dieffenbacher-CZ s.r.o., Czech Republic). The strands were dried in a kiln dryer at 80 °C until they reached a moisture content (MC) of 4 ± 1%.

Polymeric 4,4-diphenyl methane diisocyanate (pMDI) resin (Ongronat® WO 2750; BorsodChem Zrt., Hungary) with a solid content of 100% and viscosity of 170–230 mPa.s, was used to resinate the strands. A water-based paraffin wax emulsion (SVH – 60; Dřevozpracující družstvo, Czech Republic) with a solid content of 60 ± 2% and a viscosity of approximately 24 mPa.s was used.

2.2 Manufacturing the strand boards

Single species randomly oriented strand boards were made using strands from only one wood species; a total of ten groups of panels from the ten wood species were produced. To make single-layer OSB panels, 3% pMDI resin by weight and 0.5% wax were used to resinate the strands. The resin was sprayed with an EL-4 model spinning disk atomizer (Coil Manufacturing, Surrey, BC, Canada) at a speed of 10,000 rpm. Three 12-mm thick panels with a target density of 600 kg/m^3 and dimensions of 600 mm × 600 mm were made for each group. The OSB panels were laboratory formed by hand without any attempt to orient the strands. The panels were pressed at a pressure of 3.5 MPa and a temperature of 180 °C with 30 s of closing, 240 s in position and 80 s to vent with a continuous decrease in pressure.

The compaction ratio (CR) of the strand boards was calculated as shown below:

$$CR = (Db - Dw)/Dw \times 100\,(\%)$$

where Db is the density of the board (kg/m^3), and Dw is the density of the wood (kg/m^3).

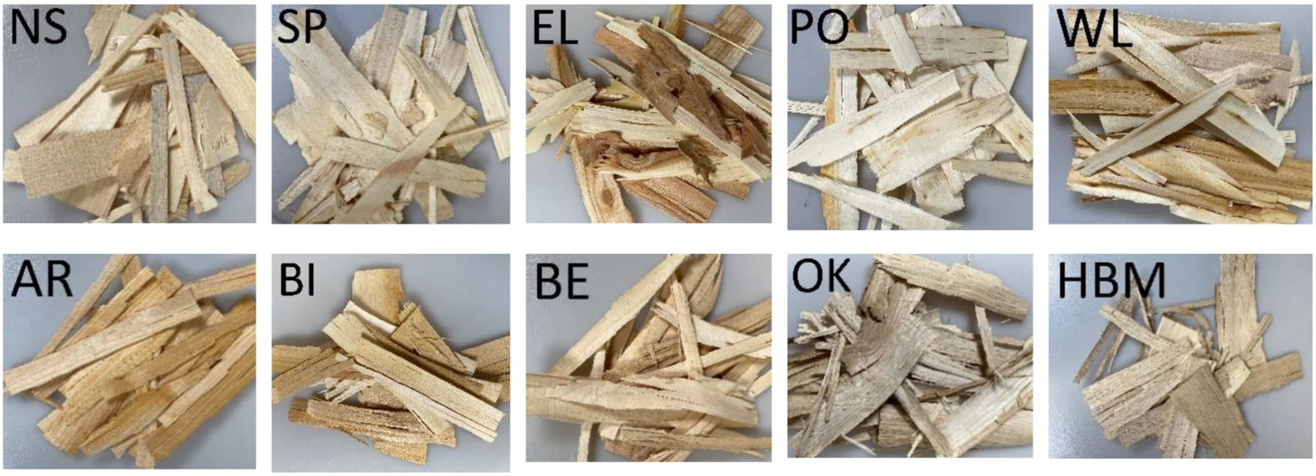

Fig. 1 Strands used for the manufacture of OSBs

2.3 Testing procedures

2.3.1 Dimensions of strands

Wooden blocks (made from logs) were measured and the density of the input material was calculated. After strands were made, all dimensions (thickness, width and length) were measured for 50 strands.

The specific surface values of the strands were calculated as (Moslemi 1974):

$$S_s = \frac{2}{t \cdot \rho}$$

where S_s is the specific surface (m^2/kg), t is the thickness of the strand (m), and ρ is the oven-dry wood density in the oven (kg/m^3).

The slenderness ratio is defined as the dimensionless ratio of the length and thickness of the strands and expresses the quality of the strands. The slenderness ratio is calculated as (Moslemi 1974):

$$S_r = \frac{l}{t}$$

where S_r is the slenderness ratio, l is the strand length (mm), and t is the strand thickness (mm).

Specimens were conditioned at 20 °C and 65% relative humidity (RH), before mechanical and physical property tests. All of these properties were tested according to European standards unless otherwise noted.

2.3.2 Density and density profile

The density EN 323 (1994) was determined for four specimens cut from each panel (three panels for each wood species). Density profiles were measured on three 50 mm × 50 mm × 12 mm specimens cut from each panel. Density profiles were obtained at an interval of 0.01 mm through the sample thickness using an X-ray density profile analyzer (DPX300-LTE, Imal, Italy) and the average density profile was calculated.

2.3.3 SEM analysis

A Tescan Mira II scanning electron microscope and scattered electron detector were used for surface topography characterization. Microtome-cut samples were placed on Cu tape and wrapped with Cu tape on the bottom and sides to ensure the necessary conductivity. Afterwards, 40 nm of Au/Pd was sputtered on the top of the samples to prevent charging during the scanning. The applied voltage was 10 kV, beam intensity 10.0.

2.3.4 Wood-water relations

The moisture content (MC) EN 322 (1994) was determined for ten specimens with dimensions of 50 mm × 50 mm. The thickness swelling (TS) EN 317 (1996) and water absorption (WA) were measured in specimens with dimensions 50 mm × 50 mm, after 24 and 48 h of immersion in water, respectively, using 12 specimens with the same dimensions.

2.3.5 Mechanical properties

Three-point bending tests EN 310 (1995) were performed to determine the MOE and MOR of four specimens cut from each panel (three panels for each wood species), having dimensions of 290 mm × 50 mm, with a span of 240 mm. The IB strength was determined according to the EN 319 (1994) standard for 12 specimens with dimensions 50 mm × 50 mm. Mechanical testing was carried out using a Zwick ® Z050 universal testing machine with testXpert v11.02 software and a 50 kN load cell (Zwick GmbH & Co. KG, Ulm, Germany).

2.4 Statistical analysis

Data were processed in Statistica 10 software (StatSoft Inc., USA) and evaluated using a one-factor analysis of variance (ANOVA), completed with Tukey's honest significance test (HSD test).

3 Results and discussion

3.1 Dimensions of strands

The size of the wood particles is one of the factors that significantly affect the properties of boards. In particular, the bending strength depends significantly on the size (length and thickness) of the wood strands. Since different types of wood were investigated with different densities and anatomical structures, it was important to find out whether the cutting process affected the formation of the sizes of wood strands. The dimensions of the wood strands, the resulting specific surface values and the corresponding slenderness ratios are set out in Table 1.

The lowest average thickness (0.70 mm) was recorded in beech strands and the largest (0.92 mm) was recorded in pine strands. However, the analysis of strand thickness showed that strands from all investigated wood species did not differ among themselves in this parameter. The longest length (107 mm) was recorded in alder strands and the shortest (78 mm) in pine strands. Only the alder strands differed significantly ($p < 0.05$) from the spruce strands in terms of length. Furthermore, the alder strands differed significantly ($p < 0.05$) in length from the spruce, pine, poplar and oak strands. In turn, the pine strands were significantly ($p < 0.05$) different in length from the willow, alder, birch and beech strands. The analysis of the width of the strands showed that, according to this parameter, the strands of all investigated wood species differed insignificantly ($p \geq 0.05$) from each other, except for the birch, beech and oak strands. The width of the birch strands was the largest and differed significantly ($p < 0.05$) from the width of the beech and oak strands. At the same time, the widths of the birch, beech and oak strands differed insignificantly ($p \geq 0.05$) from the width of the strands of other wood species. Furthermore, the strands obtained from the various investigated wood species differed insignificantly ($p \geq 0.05$) in width from the spruce strands. It was also observed that as the density of the wood species decreased, the specific surface of the strands increased.

Therefore, only the alder strands were significantly ($p < 0.05$) different in length from the spruce strands. The strands of other wood species differed insignificantly ($p \geq 0.05$) from the spruce strands in terms of thickness, length and width. Furthermore, there were no significant differences between coniferous and deciduous wood species in terms of strand sizes obtained from them. Minor differences in the strand sizes of different wood species indicate that the cutting process did not affect the strand sizes. Although it is obvious that in the process of cutting different wood species, the consumption of electricity for cutting will be different; however, this was not the purpose at this stage of the study.

Table 1 Average values of strand dimensions

Wood species	Thickness [mm]	Width [mm]	Length [mm]	Slenderness ratio	Specific surface [m^2/kg]
Norway spruce (NS)*	**0.75 (0.30) A, B, C**	**15.9 (9.8) A, B**	**83 (32) A, B, C**	**111**	**6.80**
Scots pine (SP)	0.92 (0.23) C, D	15.0 (8.8) A, B	78 (31) A	85	5.03
European larch (EL)	0.84 (0.26) A, B, C, D	14.5 (6.2) A, B	94 (33) A, B, C, D	112	5.07
Poplar (PO)	0.83 (0.21) A, B, C, D	15.4 (7.3) A, B	83 (27) A, B, C	100	5.40
Willow (WL)	0.75 (0.22) A, B	14.0 (7.3) A, B	97 (28) B, C, D	129	4.59
Alder (AR)	0.73 (0.22) A, B	15.7 (7.6) A, B	107 (22) D	147	6.73
Birch (BI)	0.76 (0.23) A, B, C	18.6 (10.1) B	102 (24) C, D	134	5.17
European beech (BE)	0.70 (0.21) A	12.6 (5.1) A	101 (26) C, D	144	3.91
English oak (OK)	0.79 (0.26) A, B, C	13.0 (5.7) A	84 (26) A, B, C	106	3.33
Hornbeam (HBM)	0.88 (0.27) B, C, D	16.9 (11.6) A, B	97 (27) A, B, C, D	110	3.17

*Reference. Means with the same letter in the column do not differ statistically by Tukey′s test (α = 0.05). Numbers in parentheses represent the standard deviation

3.2 Density of board samples

The density of the input material ranged from 392 kg/m^3 (spruce) to 761 kg/m^3 (oak) and influenced the final board density, which ranged from 656 kg/m^3 (spruce) to 799 kg/m^3 (hornbeam) (Table 2). The densities of boards made from spruce, pine, poplar, larch and alder strands differed insignificantly ($p \geq 0.05$), considering that the densities of these wood species differed slightly from each other. Similarly, the densities of boards made from birch, beech, oak and hornbeam strands differed insignificantly ($p \geq 0.05$) from each other, considering that the densities of these wood species differed slightly from each other. The density of boards made of larch and willow strands differed insignificantly ($p \geq 0.05$) from the density of boards made of beech and oak strands. In addition to the input density of wood, the compaction ratio (CR) also affected the density of the boards. Boards using such strands reached almost the same density since larch and willow strands were more compacted (56% and 28%, respectively) than beech and oak ones (4% and 11%, respectively). OSBs from low-density wood species such as alder, poplar and pine had almost the same density as OSBs from spruce strands; moreover, they also demonstrated a similar CR. It is quite natural that low-density wood species demonstrated higher CR than high-density wood species (Table 2).

Changes in the wood structure are related to the CR of the panel, higher CR caused higher changes in the deformation of the wood structure for OSB. A comparison of the non-densified wood and the final panel showed significant changes in the wood structure in the spruce OSB, shape deformation of the cell walls in the birch OSB and no changes in the beech panel compared to beech wood (Fig. 2).

The density of a board is determined by the input density of the wood species used and the pressing modes. Since in this study the pressing parameters and the planned CR of strands to form a board carpet were constant, the density of the boards was determined by the input density of the wood and the CR. In this study, the softwoods and hardwoods demonstrated different compressibility at high pressure and temperature due to the difference in the wood species

Table 2 Average values of the input density of wood species, density and MC of strand boards

Wood species	Input wood density [kg/m^3]	Density of board [kg/m^3]	Compaction ratio [%]	Moisture content [%]
Norway spruce (NS)*	**392 (12)**	**656 (42) A**	**67**	**6.5 (0.3) A**
Scots pine (SP)	432 (28)	669 (30) A	55	9.7 (0.1) D, E
European larch (EL)	470 (37)	731 (32) B, C	56	9.7 (0.2) D, E
Poplar (PO)	446 (22)	680 (32) A, B	52	8.6 (0.1) C
Willow (WL)	581 (31)	746 (54) C, D	28	9.3 (0.1) D
Alder (AR)	407 (33)	685 (31) A, B	68	6.9 (0.4) A
Birch (BI)	509 (23)	761 (51) C, D	50	6.8 (0.4) A
European beech (BE)	730 (6)	758 (58) C, D	04	7.7 (0.6) B
English oak (OK)	761 (20)	798 (56) D	05	9.5 (0.4) D, E
Hornbeam (HBM)	717 (41)	799 (43) D	11	9.9 (0.4) E

*Reference. Means with the same letter in the column do not differ statistically by Tukey's test ($\alpha = 0.05$). Numbers in parentheses represent the standard deviation

(Table 2) and this difference was reflected in the vertical density profiles (VDPs) of the boards. Figure 3 illustrates the correlation between the density of boards and the density of wood based on the complete set of results obtained for all investigated wood species. The high value of the determination coefficient $R^2 = 0.8$ demonstrates a good linear correlation between the density of the wood and the density of the board. As the density of used wood increases, the density of the board increases too.

The MC of the panels after conditioning showed lower values for spruce, alder, birch and beech, and higher values for the rest of the panels.

3.3 Density profile of board samples

The vertical density profile (VDP) showed a typical U-shape (Kelly 1977) for some of the low-density wood species, especially spruce, pine, poplar and alder (Fig. 4). These results are consistent with previous findings (Wang and Winistorfer 2000; Beck et al. 2009). A comparable VDP was also observed by Beck et al. (2009) for birch with a slightly higher density near the surface and almost even density through the thickness. The other high-density wood species (birch, beech, hornbeam, oak and willow) showed a nearly uniform density profile (small difference between face and core) through the thickness of the boards without higher densities at the surface. This can be explained by the easier compaction of low-density wood species strands (CR = 52–68%) under high pressure and temperature in the surface layers than in the core layer of the boards. Although high-density wood species strands are very hard to compact (CR = 4–28%), the density of such boards in the core and surface layers is almost the same (Fig. 4). Zhuang et al. (2022) also found that the difference in density between the surface and core layers of OSBs was less with an increase in species wood density. Furthermore, for the same reason, it was not possible to achieve the target thickness of the boards using high-density wood species strands. Panels made from these wood species showed a high spring break immediately after the hot press was opened – for most of them up to 15.5 mm from the target thickness of 12 mm. This will need to be taken into account in practice by selecting the appropriate pressing parameters for high-density wood species.

In general, VDP is one of the factors that most affects the physical and mechanical properties of wood-based panels. Some researchers (Chen et al. 2010) argue that a U-shaped VDP is beneficial for MOR and MOE and that a flatter VDP would result in greater dimensional stability and IB. The homogeneous density profile of an OSB provided by high-density wood species can be seen as a benefit that favors a uniform stress distribution in structural members and facilitates the use of fasteners in building construction.

3.4 Physical properties of board samples

The TS and WA results were unexpected. As can be seen in Table 3 and Fig. 5, lower values of TS and WA were found in boards of higher density made with high-density wood species (beech, hornbeam, oak and willow, but not birch). The TS results of this study are contrary to common experience. In this study, with an increase in the density of the boards, the TS decreased. Usually, as the density of boards increases, the TS increases and WA decreases. The reason for this can be found when we look at the density profile of the boards (Fig. 4). As mentioned above, high-density wood species showed an almost uniform density profile with practically the same density through the thickness of the boards. Usually, board samples absorb water through the edges. In the board samples made from low-density wood species, the density of the core layer is low, and water can easily penetrate through the edges of the board. However, in boards made from high-density wood species, the density of the core layer is high, practically the same as the surface layers, and it is difficult for water to penetrate inside the board. However, the same cannot be said about the effect of the density of boards on the TS. In this study, with an increase in density, TS decreases as well, which does not agree with the generally known trend. However, various research results on the influence of density on TS conducted by other authors are also contradictory. Wu and Piao (1999) demonstrated that TS and WA increased with increasing

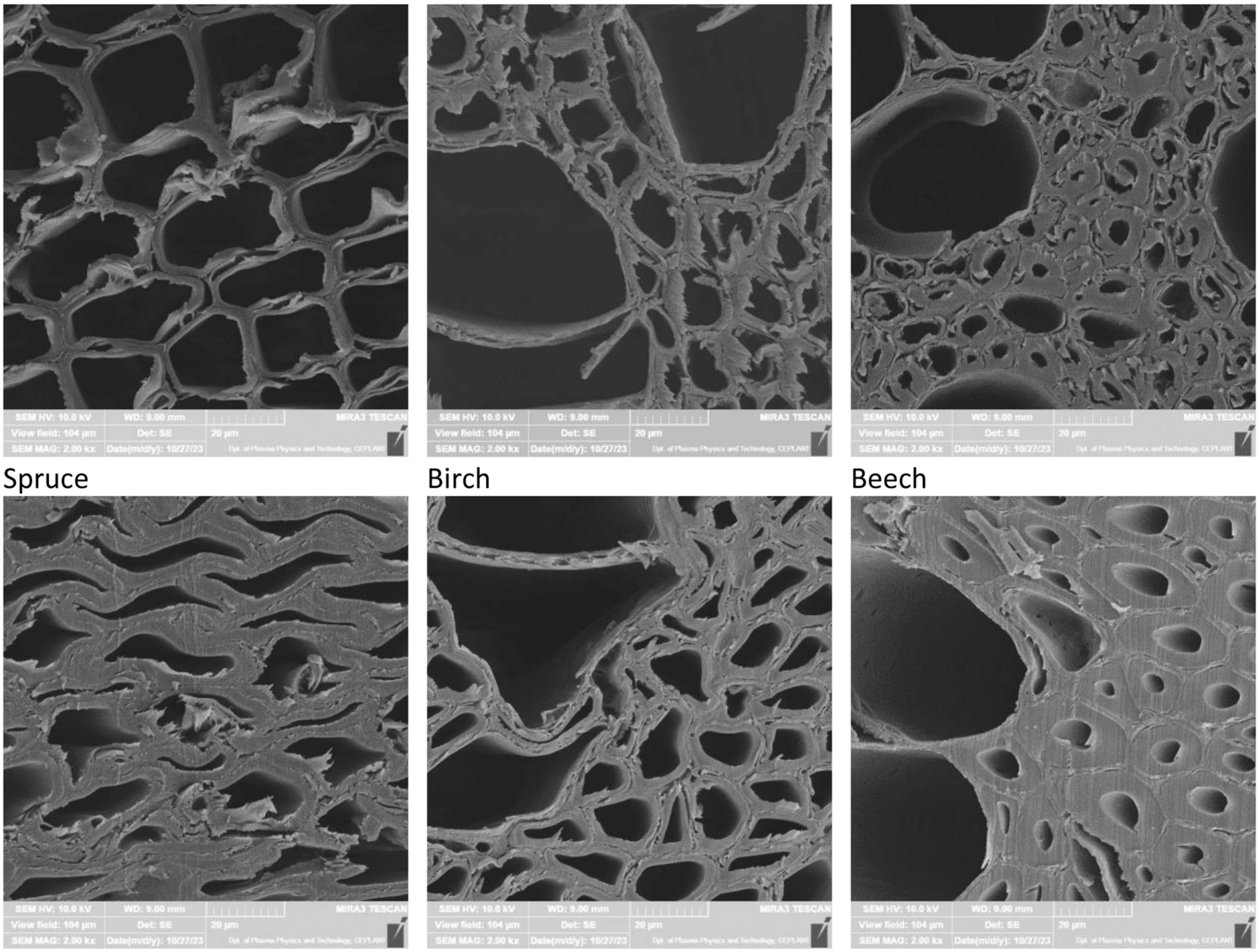

Fig. 2 Densification of the selected wood and OSB with SEM

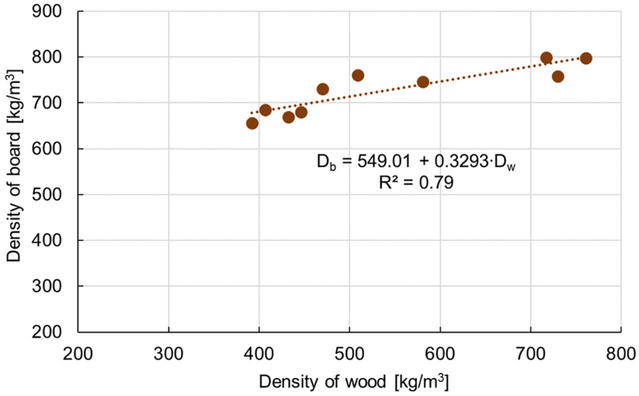

Fig. 3 Correlation between the density of board (D_b) and the density of wood (D_w)

specimen density. Chen et al. (2010), investigating the influence of board density on OSB properties, found that TS and WA linearly decreased with increasing board density, similarly to our findings. In the same way, Geimer (1982), studying flakeboard TS, pointed out that TS was lower in high-density boards. Jin et al. (2009) indicated that WA was well correlated with the density of random OSB, whereas the relationship between TS and density was not straightforward. TS initially increased with an increase in density, but after reaching a peak point of around 650 kg/m^3, the trend reversed. Wang et al. (2003) compared the properties of commercial aspen, pine and mixed hardwood OSBs and observed that, within a species, their data did not show consistent relationships among WA, TS and board density.

TS after 24 h showed low values for hornbeam, beech and oak of around 10% compared to spruce at 25.4% which was the highest value of TS after 24 h (Table 3). The same trend was observed in TS after 48 h. A study by Akrami et al. (2014a) of OSBs made of beech and poplar with a density of 720 kg/m^3 showed TS after 24 h 12% and 23%, respectively, which is on the same trend as this study, TS after 24 h for beech 10.3% and poplar 13.9%. WA showed the lowest value for beech of 22.5% after 24 h, oak and larch showed WA 24.8% and 32.9%, respectively. The highest values for WA after 24 h were 58.3% and 58.0% for birch

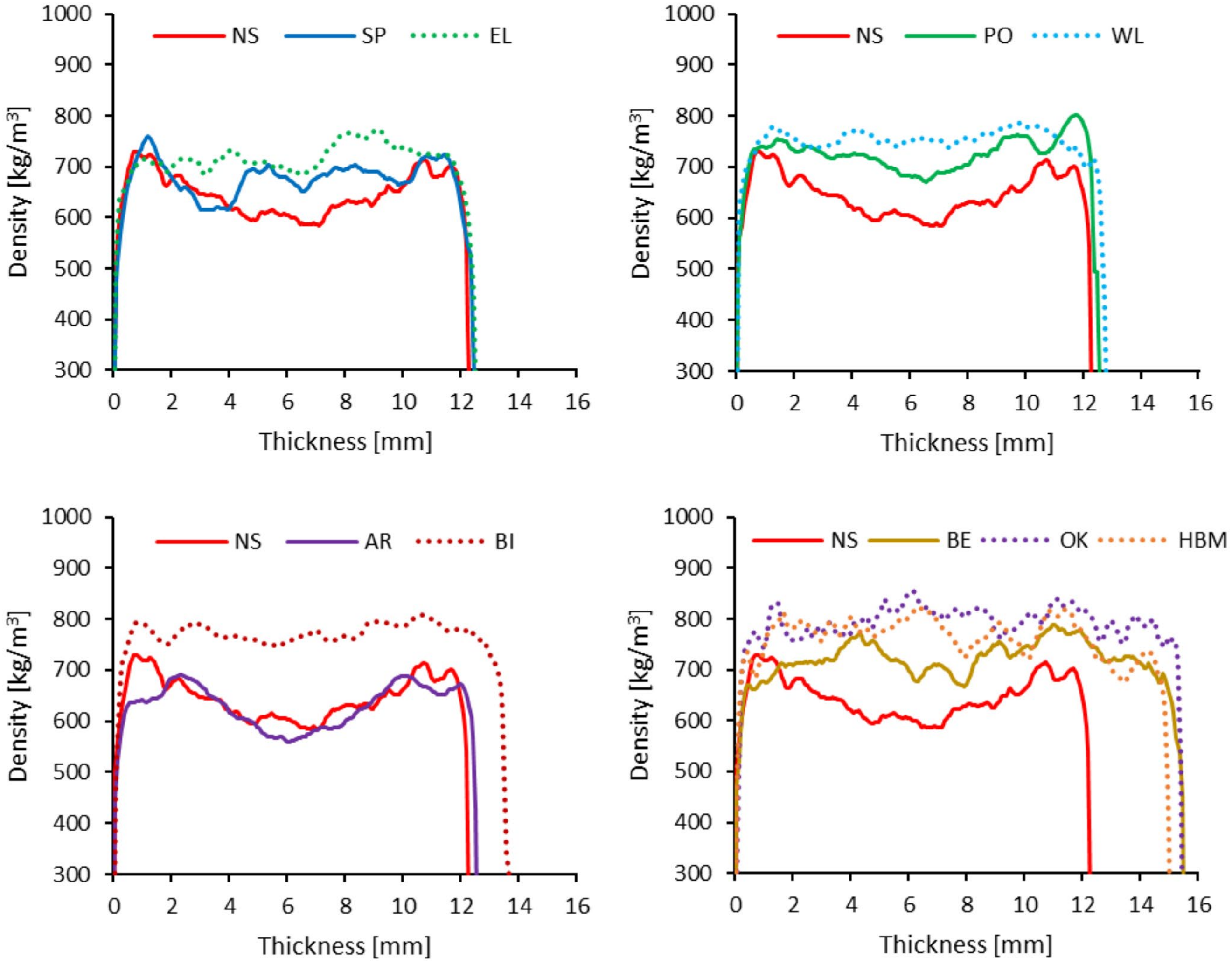

Fig. 4 The vertical density profile of OSB specimens: Norway spruce (NS), Scots pine (SP), European larch (EL), poplar (PO), willow (WL), alder (AR), birch (BI), European beech (BE), English oak (OK) and hornbeam (HBM)

and spruce, respectively. The same trend was observed for WA after 48 h.

We found that the density of wood had a strong effect on the TS and WA of the boards (Fig. 5). Both TS and WA decreased with an increase in the density of the wood. Since the dimensions of the strands were much larger than the dimensions of the structural elements of the wood tissue (cells), the strands can be considered as particles that have the properties of solid wood. Therefore, high-density wood species, which have less porosity, absorb less water and swell less than low-density wood species. Accordingly, boards with higher density absorb water more slowly, reducing the rate of TS. Jin et al. (2009) stated that the relatively poor strand-to-strand contacts in low-density boards result in weak bonds that are more likely to fail during water soaking, increasing TS. Moreover, low-density boards are highly porous because of the many voids in their structure, which facilitate the penetration and absorption of water, and thus swelling.

The CR and the specific surface of the strands also have a strong effect on the TS and WA. Boards with a higher CR and a specific surface of strands showed higher TS and WA. As shown in Table 2, a lower wood density resulted in a higher CR; consequently, according to Hsu (1987), it will increase the WA and TS values. The stress within the board is partially released when it is immersed in water.

It is known that TS and WA are exposure-time dependent. Wu and Lee (2002) demonstrated that a higher density three-layer board tended to have greater TS, whereas in single-layer uniform-density boards, density had a mixed effect on TS. Jin et al. (2009) argued that despite the greater swelling potential, higher-density boards usually do not receive full water penetration during a 24-hour water-soaking test to release deformation. Therefore, the findings of this study indicate that the relationship among TS, WA and board density appears to be fairly complex and more studies are needed to identify reliable correlations.

Table 3 Thickness swelling and water absorption of the specimens

Wood species	TS 24 h [%]	WA 24 h [%]	TS 48 h [%]	WA 48 h [%]
Norway spruce (NS)*	**25.4 (3.4) B**	**58.0 (3.1) E, F**	**29.9 (4.1) C**	**66.5 (3.1) E, F**
Scots pine (SP)	20.8 (4.6) B	47.6 (7.4) D, E	25.2 (3.6) B, C	61.6 (6.4) D, E, F
European larch (EL)	12.0 (4.6) A	32.9 (10.2) A, B, C	21.2 (7.5) A, B	48.4 (12.5) B, C
Poplar (PO)	13.9 (3.9) A	50.9 (10.4) D, E, F	19.6 (4.4) A, B	64.2 (10.9) E, F
Willow (WL)	10.5 (4.2) A	43.0 (9.2) C, D	16.7 (4.2) A	56.5 (10.3) C, D, E
Alder (AR)	21.4 (5.8) B	48.2 (7.3) D, E, F	27.8 (5.4) C	59.3 (7.9) C, D, E, F
Birch (BI)	21.2 (3.4) B	58.3 (8.6) F	28.9 (3.0) C	68.9 (7.3) F
European beech (BE)	10.3 (2.6) A	22.5 (3.1) A	18.2 (3.7) A	30.6 (3.2) A
English oak (OK)	10.4 (3.6) A	24.8 (4.0) A, B	17.5 (4.2) A	40.2 (7.1) A, B
Hornbeam (HBM)	9.1 (3.9) A	34.7 (11.9) B, C	15.4 (4.5) A	49.9 (14.7) B, C, D

*Reference. Means with the same letter in the column do not differ statistically by Tukey's test ($\alpha = 0.05$). Numbers in parentheses represent the standard deviation

3.5 Mechanical properties of board samples

Spruce and alder boards had the highest MOR values (34.6 MPa and 34.3 MPa), and pine boards had the lowest MOR value (20.5 MPa). The MOR values showed that there was no statistically significant difference between the values of spruce (34.6 MPa), larch (25.9 MPa), poplar (25.2 MPa), willow (27.8 MPa), alder (34.3 MPa) and birch (27.1 MPa) (Fig. 6). Similarly, there was no significant difference in MOR values between pine, larch, poplar, willow, birch, beech, oak and hornbeam. Such a picture is unexpected since wood species of different densities were used in the experiments. Since we produced all boards under the same pressing parameters and the analysis of strand sizes showed that the strands had the same size regardless of the wood species, the MOR values practically do not differ significantly among themselves. Furthermore, no strong relationship was found between MOR and board density of the boards ($R^2 = 0.26$); a slightly better relationship was found between MOR and wood density ($R^2 = 0.39$). Moreover, a negative effect of the densities of wood and boards was found on the MOR. The relationships between MOR and the densities of board and wood are shown graphically in Fig. 7. However, as is well known, the MOR is affected not

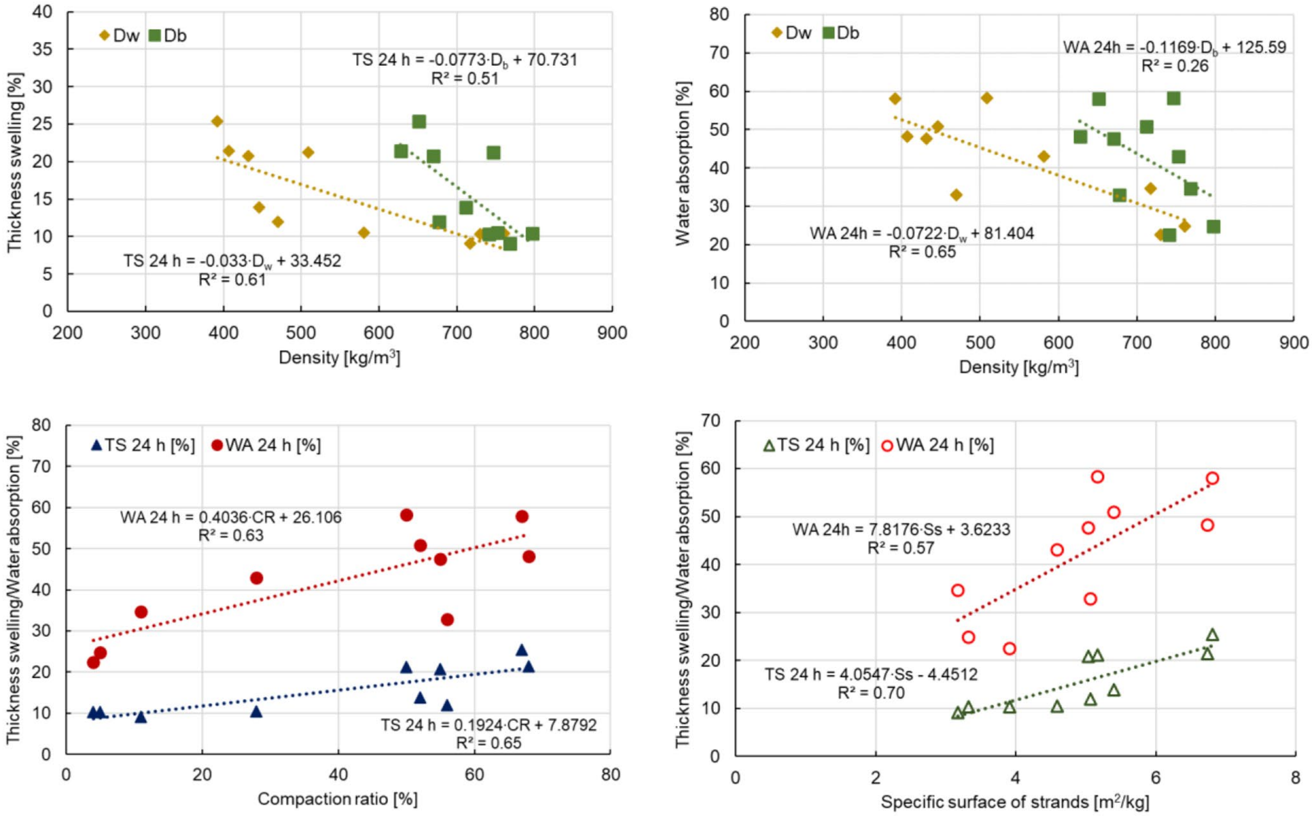

Fig. 5 Correlations between thickness swelling, water absorption and densities of boards (D_b) and wood (D_w), compaction ratio (CR) and specific surface (Ss) of strands

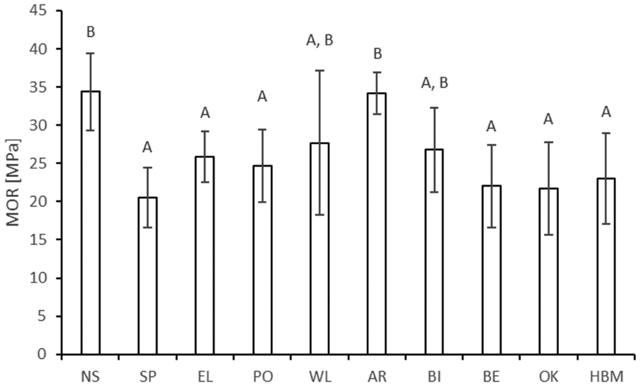

Fig. 6 Bending strength (MOR) of OSBs made from different wood species – Norway spruce (NS), Scots pine (SP), European larch (EL), poplar (PO), willow (WL), alder (AR), birch (BI), European beech (BE), English oak (OK) and hornbeam (HBM). Error bars represent the standard deviations

only by the density of the boards but also by many other factors, including CR, the thickness and length of the strands, slenderness ratios, specific surface, the amount of adhesive in the outer layers etc. The compaction and slenderness ratios, as well as the specific surface of the strands, had a positive effect on MOR (Fig. 7). In general, an increase in all these parameters increased MOR. The strongest relationship demonstrated the specific surface of the strands ($R^2 = 0.70$) based on the complete set of results obtained for all wood species. A higher specific surface of the strands resulted in increased MOR because strands with a higher specific surface area occupy a larger volume than those with a lower specific surface. Thus, strands with a higher specific surface at high pressure and temperature during hot pressing are more compacted and increase strand-to-strand contact because of the higher number of strands and reduced void volume. Longer and thinner strands (higher slenderness ratio) resulted in better MOR than shorter and thicker strands as a result of better alignment among longer strands and increased overlap length (Barnes 2001). Other authors (Beck et al. 2009; Chiromito et al. 2016) also showed that the length and thickness of the strand influenced MOR and MOE positively and significantly.

The results of this study show that to have comparable bending properties for spruce, pine, beech, oak and hornbeam boards, pine strands must have a higher slenderness

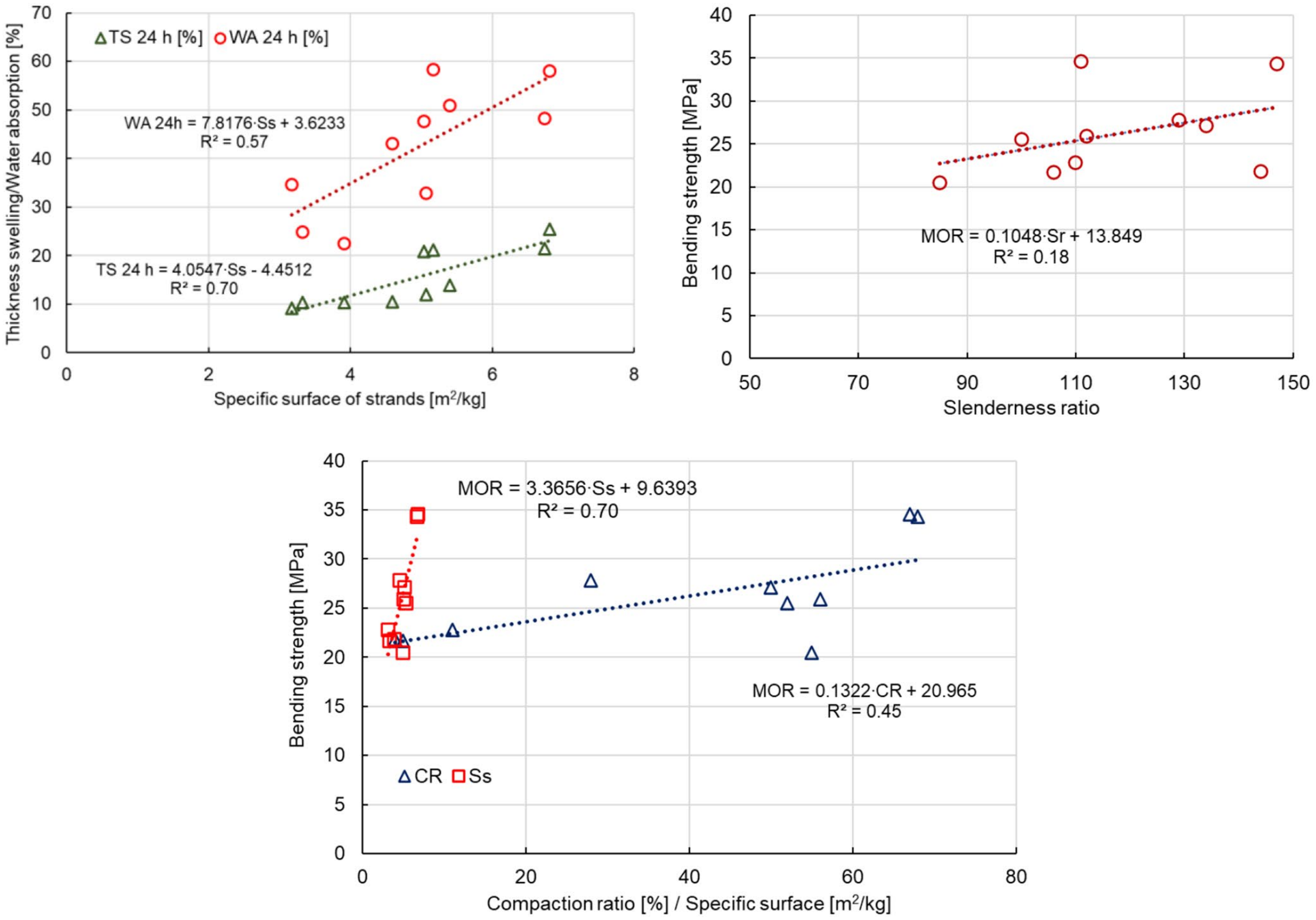

Fig. 7 Correlations between bending strength and average densities of boards (D_b) and wood (D_w), slenderness ratio (Sr), compaction ratio (CR) and specific surface (Ss) of strands

ratio whereas beech, oak and hornbeam strands must have a higher specific surface, which can be obtained using thinner strands at a given length.

A study by Lunguleasa et al. (2021) focused on OSBs made from willow, poplar, pine and spruce and showed MOR values in the parallel direction around 44.54 MPa for willow and 27.07 MPa for spruce; in this study a decrease in the values from willow, poplar to pine was also observed. A comparison of birch, willow and poplar in a research by Dumitrascu et al. (2020) gave values for MOR in the parallel direction of 36.0 MPa, 36.6 MPa and 43.3 MPa and for MOR in the perpendicular direction of 33.0 MPa, 35.3 MPa and 18.2 MPa, respectively.

A similar trend, with values on the MOR, was also observed on the MOE values (Figs. 8 and 9). The highest values of MOE were 5,185 MPa for spruce and 4,472 MPa for alder, without significant differences. The MOE values for larch (4,110 MPa), poplar (3,815 MPa) and willow (3,939 MPa) did not show a significant difference from alder. The results of this study are in good agreement with those obtained by other authors (Chen et al. 2010; Zhuang et al. 2022). Zhuang et al. (2022) showed a similar tendency for MOE values to decrease with increasing species wood density. Chen et al. (2010) found that the relationships between the bending properties and density were best described with quadratic regression curves. Both the MOR and MOE values increased with increasing board density, but the increase slowed when the density reached approximately 690 kg/m^3 (for MOR) and 660 kg/m^3 (for MOE). The density of boards in this study was in the range of 650–800 kg/m^3.

The study by Lunguleasa et al. (2021) showed MOE values for OSBs made from willow of around 4,700 MPa and for poplar around 4,600 MPa in the parallel direction; for pine, MOE values in the parallel direction were around 3,200 MPa and in the perpendicular direction around 3,000 MPa, which is comparable to the results from our study. Poplar OSBs in an earlier study by Dumitrascu et al. (2020) showed a lower value of MOE in the parallel direction of 3,147 MPa than the values of this study; willow (5,665 MPa) and birch (4,636 MPa) showed higher MOEs in the parallel direction than we did in this study focused on unoriented OSBs.

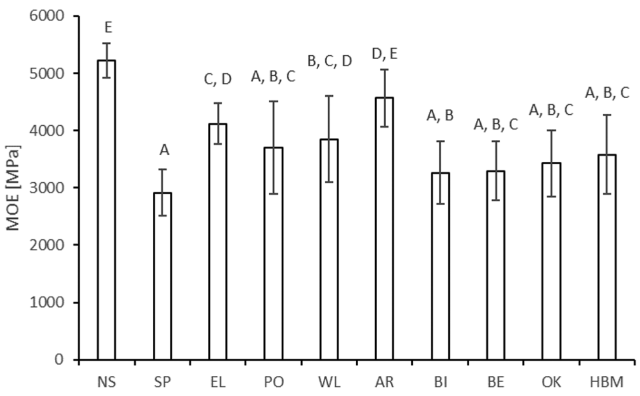

Fig. 8 Modulus of elasticity (MOE) of OSBs made of different wood species – Norway spruce (NS), Scots pine (SP), European larch (EL), poplar (PO), willow (WL), alder (AR), birch (BI), European beech (BE), English oak (OK) and hornbeam (HBM). Error bars represent the standard deviations

The IB strength reached the highest average value for birch, 0.9 MPa, but there was no significant difference between spruce and other wood species (Fig. 10), which confirms that, for IB as one of the crucial parameters, it is possible to make OSBs with comparable properties from all our investigated underutilized wood species. The reasons for the lack of difference in IB strength values may be the same as those for MOR. The degree of correlation between IB and board density in this study was very low, and this may be the result of differences in VDP and strand geometry. The effects of investigated variables on IB are very complicated. In general, increasing the density of wood resulted in a decrease of IB, whereas increasing the CR and the specific surface of the strands increased IB. The relationships between IB and these factors are shown graphically in Fig. 11. Beck et al. (2009) also found that strand geometry and wood species had no significant effect on IB. Xu and Winistorfer (1995) found a positive correlation between IB and OSB, although the coefficient of determination (R^2) was only 0.20–0.25.

OSB reached higher IB values in the study by Dumitrascu et al. (2020) of 1.05 MPa, 1.33 MPa and 1.28 MPa for birch, willow and poplar, respectively. The IB values from the study by Beck et al. (2009), with a comparison of the different strand dimensions, showed the average values for aspen of 0.69 MPa, and for birch of 0.77 MPa, which are comparable with the results of this study. A study by Akrami et al. (2014a) for OSBs made from beech and poplar with a density of 720 kg/m^3 showed IB of 0.7 MPa, and 0.6 MPa, which are contrary to this study. IB for beech was 0.55 MPa and for poplar 0.67 MPa.

It is well known that high-density woods are difficult to bond because of their thicker cell walls and smaller diameter lumens (Frihart and Hunt 2010). In this case, the adhesives do not easily penetrate into the wood, preventing good mechanical interlocking. Furthermore, high-density wood species are characterized by a higher concentration of extractives that can interfere with the cure of adhesives (Frihart and Hunt 2010). Therefore, much greater pressure is required to compress stronger, stiffer, high-density wood to bring the adhesive into contact with the wood surfaces.

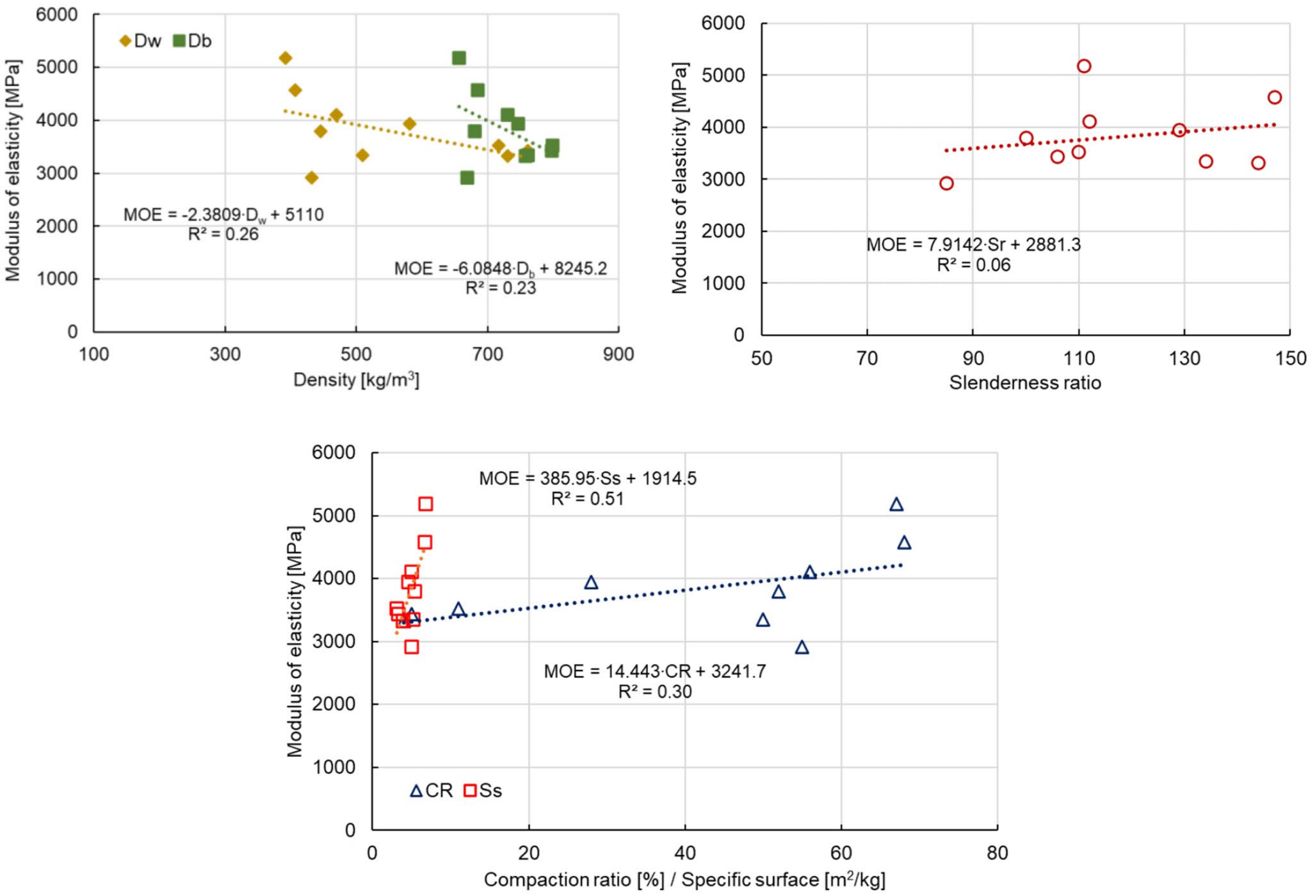

Fig. 9 Correlations between the modulus of elasticity and the average densities of boards (D_b) and wood (D_w), and the slenderness ratio (Sr) and specific surface (Ss) of strands

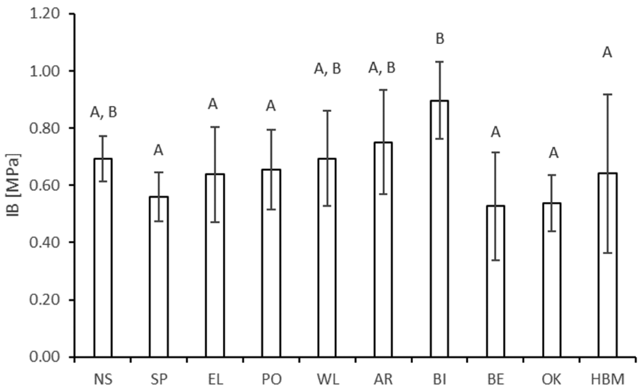

Fig. 10 Internal bond (IB) strength of OSBs made from different wood species – Norway spruce (NS), Scots pine (SP), European larch (EL), poplar (PO), willow (WL), alder (AR), birch (BI), European beech (BE), English oak (OK) and hornbeam (HBM). Error bars represent the standard deviations

The overall results obtained for OSB properties met the EN 300 (2006) standard of minimum requirements for OSB/2 (MOR > 20 MPa, MOE > 3,500 MPa (except boards made with pure pine, birch, beech or oak), IB > 0.32 MPa, TS 24 h < 20% (except boards made with pure spruce, pine, alder or birch) for board thickness range of 10 mm to 18 mm) and OSB/3 (MOR > 20 MPa, MOE > 3,500 MPa (except boards made with pure pine, birch, beech or oak), IB > 0.32 MPa, TS 24 h < 15% (except boards made with pure spruce, pine, alder or birch) for board thickness range of 10 mm to 18 mm) boards. Furthermore, IB was found to reach values 1.7–2.8 times higher than the levels specified in the EN 300 (2006) standard. TS after 24 h for boards of larch, poplar, willow, beech, oak and hornbeam strands was 9.1–13.9%, which is around 54.5–30.5% and 39.3–7.3% less than the EN 300 (2006) standard allows for OSB/2 and OSB/3, respectively.

The results of this study correspond to the results described by other authors (Chen et al. 2010) who found that the effects of board density on MOR, MOE and IB can be approximated with convex quadratic functions, implying that in the lower density region, these board properties improve more rapidly with increasing density than for higher density. When the density reached a certain elevated level (660–690 kg/m^3), little benefit was achieved with further increases in density.

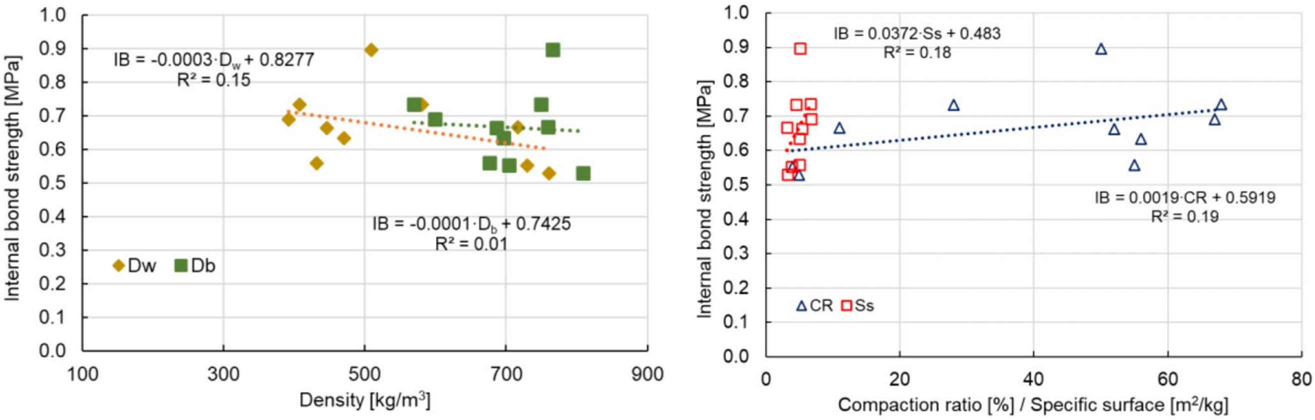

Fig. 11 Correlations between internal bond strength and average densities of boards (D_b) and wood (D_w), compaction ratio (CR) and specific surface (Ss) of strands

4 Conclusion

We have shown that the quality of strands produced from underutilized wood species, i.e., Scots pine, European larch, poplar, willow, alder, birch, European beech, English oak and hornbeam is comparable to the quality of the spruce strands used in the majority of OSB manufacturing. Since strand quality has a major impact on the final performance of OSBs, this leads to the conclusion that OSB boards with acceptable physical and mechanical properties can be produced from these wood species too. The results of the actual characterization of OSBs show that four species – larch, poplar, willow and alder – should be considered as a suitable replacement of spruce in the manufacture of OSBs.

Our results also show that OSBs made from high-density wood species swelled less than boards from low-density wood species, which corresponds well with the lesser relative compaction of these high-density wood species. There is, however, one notable exception: juvenile European larch, in which boards swelled only 12% in thickness despite a relatively high compaction ratio of 56%. Analysis of board density profiles showed a thin, denser face layer in boards made from low-density species (spruce, pine, poplar and alder) than their less dense core layer, while the use of high-density wood species (birch, beech, hornbeam, oak and willow) resulted in uniform face and core density layers. Here juvenile European larch represents an exception again, as a uniform VDP was present at low-density species.

In general, our results indicate that the influence of wood species on the characteristics of strand board is very complex and cannot be accurately explained by a simple linear regression model. Higher-level models and optimizations of these variables should be considered to explain the complexity of the interactions between factors. In further research, OSBs should be made from different proportional mixtures of underutilized wood species from European forests.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Akrami A, Barbu MC, Fruehwald A (2014a) Characterization of properties of oriented strand boards from beech and poplar. Eur J Wood Prod 72:393–398. https://doi.org/10.1007/s00107-014-0793-9

Akrami A, Fruehwald A, Barbu MC (2014b) The effect of fine strands in core layer on physical and mechanical properties of oriented strand boards (OSB) made of beech (Fagus sylvatica) and poplar (Populus tremula). Eur J Wood Prod 72:521–525

Akrami A, Frühwald A, Barbu MC (2015) Supplementing pine with European beech and poplar in oriented strand boards. Wood Mater Sci Eng 10(4):313–318

Akyildiz MH, Dogan K, Kaymakci A (2018) The impact of density and mixture ratio of melamine on some properties of oriented strand board. Maderas Ciencia Y tecnología 20(3):417–430

Barnes D (2001) A model of the effect of strand length and strand thickness on the strength properties of oriented wood composites. For Prod J 51(2):36–46

Beck K, Cloutier A, Salenikovich A, Beauregard R (2009) Effect of strand geometry and wood species on strandboard mechanical properties. Wood and Fiber Science: 267–278

Beck K, Cloutier A, Alexander S, Beauregard R (2010) Comparison of mechanical properties of oriented strand board made from trembling aspen and paper birch. Eur J Wood Prod 68(1):27–33

Brochmann J, Edwardson C, Shmulsky R (2004) Influence of resin type and flake thickness on properties of OSB. For Prod J 54(3):51–55

Candan Z, Shaler MS, Heller JJP, Edgar R (2017) Enhancing dimensional stability of oriented strand composites within biorefinery. Maderas Ciencia Y tecnología 19(3):387–398

Chen S, Du C, Wellwood R (2010) Effect of panel density on major properties of oriented strandboard. Wood Fiber Sci 42(2):177–184

Chiromito EMS, Campos CI, Ferreira BS, Christoforo AL, Lahr FAR (2016) Mechanical properties of wood panels produced with wood strands with three different lengths. Scientia Forestalis 44:175–180

Ciobanu VD, Zeleniuc O, Dumitrascu AE, Lepadatescu B, Iancu B (2014) The influence of speed and press factor on oriented strand board performance in continuous press. BioResources 9(4):6805–6816

Dumitrascu AE, Lunguleasa A, Salca EA, Ciobanu VD (2020) Evaluation of selected properties of oriented strand boards made from fast growing wood species. BioResources 15(1):199–210

Dunky M, Pizzi A (2002) Wood adhesives. in: Adhesion Science and Engineering, Elsevier: 1039–1103. https://doi.org/10.1016/B978-0444

EN 319 (1994) Particleboards and Fibreboards—Determination of Tensile Strength Perpendicular to the Plane of the Board. European Committee for Standardization: Brussels, Belgium

EN 323; Wood-Based Panels—Determination of Density (1994) European Committee for Standardization: Brussels, Belgium

EN 300 (2006) Oriented Strand Boards (OSB) — Definitions, classification and specifications. European Committee for Standardization: Brussels, Belgium

EN 310 (1995) Wood-based panels—determination of Modulus of elasticity in bending and of bending strength. Brussels, Belgium, European Committee for Standardization

EN 317; Particleboards and Fibreboards (1996) Determination of swelling in thickness after immersion in Water. Brussels, Belgium,, European Committee for Standardization

EN 322 (1994) Wood-based panels—determination of moisture content. Brussels, Belgium, European Committee for Standardization

Food and Agriculture Organization of the United Nations (2023) Forestry production and trade, (https://www.fao.org/faostat/en/#data/FO), Accessed 26 September 2023

Frihart CR, Hunt CG (2010) Adhesives with Wood Materials. Bond Formation and Performance In Wood Handbook—Wood as an Engineering Material; General Technical Report FPL-GTR-190; U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA, 2010; Chap. 10, pp. 10-1-10–24

Geimer RL (1982) Dimensional stability of flakeboards as affected by board specific gravity and flake alignment. For Prod J 32(8):44–52

Hsu WE (1987) A process for stabilizing waferboard/OSB. In: Proceedings of Particleboard Symposium. Washington State University, Washington, DC, USA, 1987, pp. 219–236

Irle M, Barbu MC (2010) Chap. 1 Wood-based panels technology. In: Thoemen H, Irle M, Sernek M (eds) Wood-Based panels. An introduction for specialists. Brunel University, London, UK, pp 1–94

Jin J, Dai C, Hsu WE, Yu C (2009) Properties of strand boards with uniform and conventional vertical density profiles. Wood Sci Technol 43(7–8):559–574. https://doi.org/10.1007/s00226-009-0248-3

Kelly MW (1977) Critical literature review of relationships between processing parameters and physical properties of particleboard. Gen. Tech. Rep. FPL-10. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, p 10

Köhl M, Linser S, Prins K (2020) State of Europe's Forests 2020. Ministerial Conference on the Protection of Forests in Europe. FOREST EUROPE Liaison Unit Bratislava, Slovakia

Lunguleasa A, Dumitrascu AE, Spirchez C, Ciobanu VD (2021) Influence of the strand characteristics on the properties of oriented strand boards obtained from resinous and broad-leaved fast-growing species Applied sciences 11, no. 41784. https://doi.org/10.3390/app11041784

Malanit P, Laemsak N (2007) Effect of strand orientation on physical and mechanical properties of rubberwood oriented strandboard. Walailak J Sci Technol (WJST) 4(2):215–223

Mantanis GI, Athanassiadou ET, Barbu MC, Wijnendaele K (2018) Adhesive systems used in the European particleboard, MDF and OSB industries. Wood Mater Sci Eng 13(2):104–116

Mendes RF, Junior GB, de Almeida NF, Surdi PG, Barbeiro IN (2013) Effects of thermal pre-treatment and variables of production on properties of OSB panels of Pinus taeda. Maderas- Ciencia y tecnología 15(2):141–152

Moses DM, Prion HGL (2004) Stress and failure analysis of wood composites: a new model. Compos Part B: Eng 35(3):251–261. https://doi.org/10.1016/j.compositesb.2003.10.002

Moslemi AA (1974) Particleboard. Volume 1: materials. Southern Illinois University

Okino EYA, Teixeira DE, De Souza MR, Santana MAE, De Sousa ME (2004) Properties of oriented strandboard made of wood species from Brazilian planted forests: part 1: 80 mm-long strands of Pinus taeda L. Eur J Wood Prod 62(3):221–224

Paredes JJ, Jara R, Shaler SM, Van Heiningen A (2008) Influence of hot water extraction on the physical and mechanical behavior of OSB. For Prod J 58(12):56–62

Pérez-Cruzado C, Mohren GMJ, Merino A, Rodríguez-Soalleiro R (2012) Carbon balance for different management practices for fast growing tree species planted on former pastureland in southern Europe: a case study using the CO2Fix model. Eur J for Res 131(6):1695–1716. https://doi.org/10.1007/s10342-012-0609-6

Pham Van T, Schöpper C, Klüppel A, Mai C (2021) Effect of wood and panel density on the properties of lightweight strand boards. Wood Mater Sci Eng 16(4):237–245

Ross RJ (2010) Wood handbook: wood as an engineering material, USDA Forest Service., Forest Products Laboratory. https://doi.org/10.2737/FPL-GTR-190

Salem MZM, Böhm M, Šedivka P, Nasser RA, Ali HM, Elgat WA (2018) Some physico-mechanical characteristics of uncoated OSB ECO-products made from scots pine (Pinus sylvestris L.) and bonded with pMDI resin. BioResources 13(1):1814–1828

Wang S, Winistorfer PM (2000) The effect of species and species distribution on the layer characteristics of OSB. Prod J 50(4):37–44

Wang S, Gu H, Neimsuwan T, Wang S (2003) Layer thickness swell and related properties of commercial OSB products: A comparative study. Pages 65–76 in Proceedings of 37th International Wood Composite Materials Symp, 7–10 April 2003. Washington State Univ., Pullman, WA

Wu Q, Piao C (1999) Thickness swelling and its relationship to internal bond strength loss of commercial oriented strandboard. Prod J 49(7/8):50–55

Xu W, Winistorfer PM (1995) Layer thickness swell and layer internal bond of medium density fiberboard and oriented strandboard. For Prod J 45(10):67–71

Zhuang B, Cloutier A, Koubaa A (2022) Physical and Mechanical Properties of Oriented Strand Board made from Eastern Canadian Softwood Species. Forests 13(4):523