Effect of Particle Size and Species Type on the Withdrawal Resistance to Screws and Nails in Wood Sawdust – High Density Polyethylene Composites

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The effects of particle size and species type were evaluated relative to the resistance to screwing and nailing of wood-plastic composites (WPC) made from the sawdust of pine, beech, poplar, and mixtures of these species (40%, 20%, and 40%, respectively), as well as alder species with a high-density polyethylene matrix. Wood-plastic composites were made from dried sawdust of the above species, after sizing to a weight ratio of 70% as filler with high-density polyethylene (HDP) by discontinuous pressing at a temperature of 185 °C, in two particle sizes of 40- and 80-mesh. Maleic anhydride polypropylene (MAPP) was used as a coupling agent. Then, their resistance to screw and nail penetration was measured and compared according to the BS EN 1382 (2016) standard. With increasing particle size in all species, the resistance to screwing and nailing decreased significantly by about 2 to 13%. There were obvious differences between the resistance to screwing and nailing of the species, but these differences were not significant, and the resistances of the mixtures were near to the averages for these species.

DOI: 10.15376/biores.20.4.10795-10805

Keywords: Plastic wood; Resistance to screw and nail penetration; Species type; Particle size; Heavy polyethylene

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INTRODUCTION

A significant increase in the production and use of wood-plastic composites (WPC) has been observed in recent years. Their properties and environmental benefits make them a good choice for many applications (Bansal *et al.* 2024). Wood-plastic composites are made by combining wood with a thermoplastic polymer, resulting in a composite that often combines the best properties of both materials (Takino *et al.* 2018; Yang *et al.* 2018).

Wood often has strength, hardness, and biodegradability (Marzi 2015; Kazmi *et al.* 2019), while plastic has the properties of being easily malleable and waterproof (Rivero-Be *et al.* 2018; Youssef *et al.* 2019).

Different species have different anatomical structures, and these structural differences affect the use of these materials in wood-plastic composites. For example, differences in fiber thickness and dimensions, strength, diversity, and structure between species are significant (Yorur *et al.* 2020). Maldas *et al.* (1989) are among the few researchers who have investigated the effect of wood species on the mechanical properties of wood/thermoplastic composites. They reported that differences in morphology, density, and aspect ratios across wood species account for varying reinforcement properties in thermoplastic composites. Higher fiber size produces higher strength and elasticity but lower energy to break and elongation. The effect of fiber size on water uptake is minimal. Increasing fiber load improves the strength and stiffness of the composite but decreases elongation and energy to break (Bouafif *et al.* 2009).

According to the European Committee for Standardization, wood-plastic composites (WPCs) are materials or products consisting of one or more lignocellulosic fibres, flours, and one or a mixture of thermoplastic resins, such as polypropylene (PP), polyethylene (PE), or polyvinyl chloride (PVC). WPCs are widely used in floorboards, house roofs, doors, and window frames. The usage of lignocellulosic fibers or flours in WPCs have some advantages, such as coming from bio-based resources, being inexpensive, widely availability, recyclability, biodegradability, low density, flexibility, water resistance, providing high filling levels of lignocellulosic material, and various specific properties, such as strength, stiffness, and resistance to wear (Cavus and Mengeloglu 2020).

In contrast, the use of different wood species and their sawdust is considered as a good opportunity to produce wood compounds with demanded properties and to provide compressed wood, and it is also necessary to determine the properties of the new product (Roig 2018; Youssef *et al.* 2019; Friedrich 2021).

Natural fibers offer a combination of attractive properties such as low density, high specific strength and modulus, renewability, biodegradability, wide availability and low cost. The main disadvantage of using natural fibers in wood plastic composites is the low compatibility between the hydrophilic character of the polar filler and hydrophobic character of the polyolefin matrix. Lignocellulosic fillers do not disperse easily in thermoplastic polymers and tend to agglomerate during the compounding process. Thus, the low compatibility and low interfacial adhesion lead to composites with low mechanical properties and low thermal stability. To improve interfacial adhesion coupling agents are widely used. Maleic anhydride-grafted thermoplastic polymers are the most common coupling agent used in WPC (Poletto 2017).

Bonding connections provide load path continuity and ensure structural integrity. When the importance of proper connection details is overlooked, structural failure can occur. Properly designed and detailed connections are what hold a structure together, and the designer needs to understand some fundamental principles associated with connections for wood structures (Eshaghi *et al.* 2013). Nail and screw connections have the advantage of being cheaper, easier to make, and requiring less preparation in comparison with various alternatives, and they can be easily made anywhere. Nails are the most common mechanical connection used in wood construction. The resistance to nail withdrawal from wood in the longitudinal direction is much lower than in the radial and tangential directions. The resistance to pulling a nail out of wood depends on the depth of penetration of the nail into the wood, the diameter of the nail, and the density of the wood (Prevatt *et al.* 2014; Zhang *et al.* 2024).

The resistance to screw pull-out varies directly with the square of the specific gravity of the wood, and the resistance is directly related to the depth of penetration of the threaded portion of the screw and the diameter of the screw. The performance of fasteners in wood flour thermoplastic composite panels have shown that the resistance to screws and nails is not affected by the amount of wood flour. The resistance to screw pull-out depends on the diameter of the screw, the corresponding pilot hole, and the depth of penetration of the screw into the main member, as well as the specific gravity of the wood and the shear strength parallel to the fibers in the wood. In addition, the amount of internal connections in medium-density fiberboard (MDF) and particleboard is a determining factor (Xu *et al.* 2021; Chen *et al.* 2022).

As the amount of wood in a wood-plastic composite increases, its resistance to nails and wood decreases, and composites with larger particle sizes have greater resistance to screws and nails (Lei *et al.* 2024), This is probably because small particles would tend to weaken the structure more due to the higher surface area and the poor bonding with the matrix. Large particles would be expected to act like "big defects" in the structure, thereby leading to a high chance of local failure of the structure when subjected to stress. In this study, the effect of particle size and species on the resistance properties of polyethylene composites reinforced with pine and beech sawdust to screws and nails was investigated.

EXPERIMENTAL

Preparation of Test Samples

The material used in this study was polyethylene polymer with a specific gravity of 960 kg/m³ and a melt flow index (MFI) of 18 g/10min. It was purchased from Arak Petrochemical Plant in the form of granules and used after being converted into powder. Sawdust from the species of pine, beech, poplar, mixtures of these species (in proportions of 40%, 20%, and 40%, respectively), and alder were selected as the reinforcing agent, and maleic anhydride coupled with polypropylene (MAPP) was also selected as the compatibilizing agent between the two phases.

Sawdust of these wood species was obtained in pure form from various lumberyards in the cities of Gorgan, Kordkoy, and Shirvan and was sized by sieve into two particle sizes of 40- and 80-mesh.

The measured sawdust was placed in an oven at 103 ± 2 °C for 24 h to reach a moisture content close to zero (less than 2%).

Table 1. Press Conditions

Conditions/Stages	Stage 1	Stage 2	Stage 3	Stage 4
Pressure (bar)	30-35	---	30-35	30-35
Temperature (°C)	185	185	185	---
Time (min)	1	4	10	5

Sawdust and polyethylene were mixed dry at 68.7% by weight of sawdust of the above species with 29.3% by weight of polyethylene, and with 2% of MAPP coupling agent. Plastic wood with dimensions of 15 × 20 cm^2 and a thickness of 0.65 cm was made from the resulting mixture in a discontinuous manner, with a density of 1 g/cm³, and using an OTT model laboratory press, under the conditions of Table 1. The amount of material required to make each board was calculated from Eq. 1,

$$P = \frac{m}{V} \Rightarrow 1 = \frac{m}{195} \Rightarrow m = 195\ g$$
$$195 + 10 = 205\ g \quad (1)$$
$$\frac{68.7}{100} = \frac{x}{205} \Rightarrow x = 140.84\ g\ \frac{29.3}{100} = \frac{w}{205} \Rightarrow w = 60.7\ g$$

$$\frac{2}{100} = \frac{y}{205} \Rightarrow y = 4.1\ g$$

where m is the mass of mixture required for 195 cm³ boards, W is the amount of polyethylene used at a ratio of 29.3%, x is the amount of sawdust in the ratio of 68.7%, and Y is the amount of MAPP used at a ratio of 2%.

To make the boards, first the necessary mixture was poured into the mold and pre-pressed. Then, the pressing stage began. In this stage, the prepared cake was first placed under a pressure of 30 to 35 bar and a temperature of 185 °C for 1 min (stage 1), then the pressure was removed for 4 min and the temperature remained constant (stage 2). After this time, the cake was again placed under a pressure of 30 to 35 bar and a temperature of 185 °C for 10 min (stage 3), and then the board was removed from the press and placed in the press machine for 5 min at a pressure of 30 to 35 bar and without heat (stage 4).

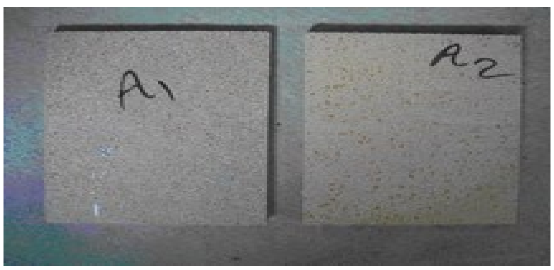

Fig. 1. Boards made from *Abies* sawdust and polyethylene (A1: 40-mesh and A2: 8-mesh0)

Fig. 2. Boards made from *Fagus* sawdust and polyethylene (B1: 40-mesh and B2: 80-mesh)

Fig. 3. Boards made from *Populus* sawdust and polyethylene (C1: 40-mesh and C2: 80-mesh)

Fig. 4. Boards made from a mixture of sawdust of the above species and polyethylene (D1: 40-mesh and D2 80-mesh)

The produced boards were kept at room temperature for 2 weeks. To measure the resistance of the boards to nails and screws, test samples measuring 0.5 × 4 × 4 cm^3 were prepared from the boards manufactured by the discontinuous method using a circular saw. After preparing the samples, nail and screw resistance tests were performed.

In this study, to investigate the resistance of wood-plastic composites to screw and nail penetration, sawdust from the species of fir and beech, poplar, mixtures of these species (with a ratio of 40%, 20% and 40%, respectively), and alder were used in two meshes of 40 and 80 and a mixing percentage of 70 in combination with polyethylene. To investigate these variables, 4 treatments were considered on the composite and 4 replications were considered for each treatment (Table 2).

Table 2. Amount and Percentage of Materials used in Treatments

Treatment Number	Treatment Name	Type of Species	Particle Size	Amount Sawdust (%)	Amount PE (%)	Amount MAPE (%)
1	A1B1	Abies	Mesh 40	68.7	29.3	2
2	A1B2	Abies	Mesh 80	68.7	29.3	2
3	A2B1	Fagus	Mesh 40	68.7	29.3	2
4	A2B2	Fagus	Mesh 80	68.7	29.3	2
5	A3B1	Aspen	Mesh 40	68.7	29.3	2
6	A3B2	Aspen	Mesh 80	68.7	29.3	2
7	A4B1	Mixed	Mesh 40	68.7	29.3	2
8	A4B2	Mixed	Mesh 80	68.7	29.3	2
9	A5B1	Alnus	Mesh 40	68.7	29.3	2
10	A5B2	Alnus	Mesh 80	68.7	29.3	2

Conducting a Test

To test the resistance to screw connection, screw number 5 of the belak type with a pitch of 8 teeth per inch and a shank diameter of 4.36 mm was used, and to test the resistance to nail connection, a regular galvanized nail with a length of 5 cm and a shank diameter of 2.88 mm was used.

The center of the screw connection test specimens was determined, and a hole was drilled using a 2.5 mm drill bit, and the screw was driven into each specimen perpendicular to the specimen surface such that the screw tip protruded 3 mm beyond the cross-section of the test specimens. For the nail connection test, a nail was placed completely vertically inside each of the specimens using a hammer so that the tip of the nail was 3 mm outside the test specimens. Finally, the screw and nail resistance test of the composite specimens was carried out using a Schenck Trebel machine and in accordance with the standard BS EN 1382 (2016) (Figs. 5 and 6).

Fig. 5. Screw connection resistance test

Fig. 6. Nail connection resistance test

Finally, the results of the experiments were analyzed using a factorial test in a completely randomized design using SPSS 13 software.

RESULTS AND DISCUSSION

The results showed that with increasing particle size, the resistance to screwing and nailing decreased significantly in all species. This was generally attributed to the fact that particle size affects the density and compactness of wood materials and affects the strength of the boards. Also, considering the specific gravity of different species, it affects the density of the final boards and ultimately the resistance to screwing and nailing, so the higher the density of the final board, the greater the resistance to nailing and screwing.

After performing the screw and nail connection resistance tests with 4 repetitions for each treatment, these values were analyzed, and Table 3 shows the average results of the 4 repetitions obtained for each treatment.

Table 3. Average Results Obtained in Nail and Screw Connection Resistance

Type of Species	Particle Size	Resistance to nail withdrawal (N/mm)	Resistance to Screwing withdrawal (N/mm)	Density of Boards
Abies	Mesh 40	73	610.25	0.815
Abies	Mesh 80	82.5	625	0.885
Fagus	Mesh 40	86.5	634.75	0.885
Fagus	Mesh 80	92.75	656.5	0.893
Aspen	Mesh 40	66.75	454.25	0.804
Aspen	Mesh 80	75.75	469.75	0.820
Mixed	Mesh 40	70.75	540	0.828
Mixed	Mesh 80	79.5	554.5	0.839
Alnus	Mesh 40	79.75	632.75	0.873
Alnus	Mesh 80	88	643.75	0.886

Effect of Particle Size on the Resistance to Screw and Nail Connections

As shown in Tables 4 and 6 and Figs. 7 and 8, the effect of particle size on the resistance to nail withdrawal and screw withdrawal connections in the tested wood-plastic composites was significant at the 1% and 5% levels, respectively. This is because as the particle size decreases, the density of the boards increases and the density of the wood material increases. These results are consistent with the findings of Shakeri and Omid (2006), who reported that smaller particles are a factor in increasing mechanical resistance.

Table 4. Analysis of Variance of Nail Connection Resistance Values

Source of changes (S.O.V)	Sum of Squares (S.S)	Degree of Freedom (df)	Mean Squares (M.S)	Test Statistic (F)	Signifi-cance Level (P)	Signifi-cance
Factor A (species type)	1695.350	4	423.838	26.122		**
Factor B (particle size)	697.225	1	697.225	42.972		**
Interaction (A*B)	12.650	4	3.162	0.195		ns
Error	486.750	30	16.225			
Total	255861.000	40				

** Indicates significance at the 1% level, * indicates significance at the 5% level, and ns indicates non-significant

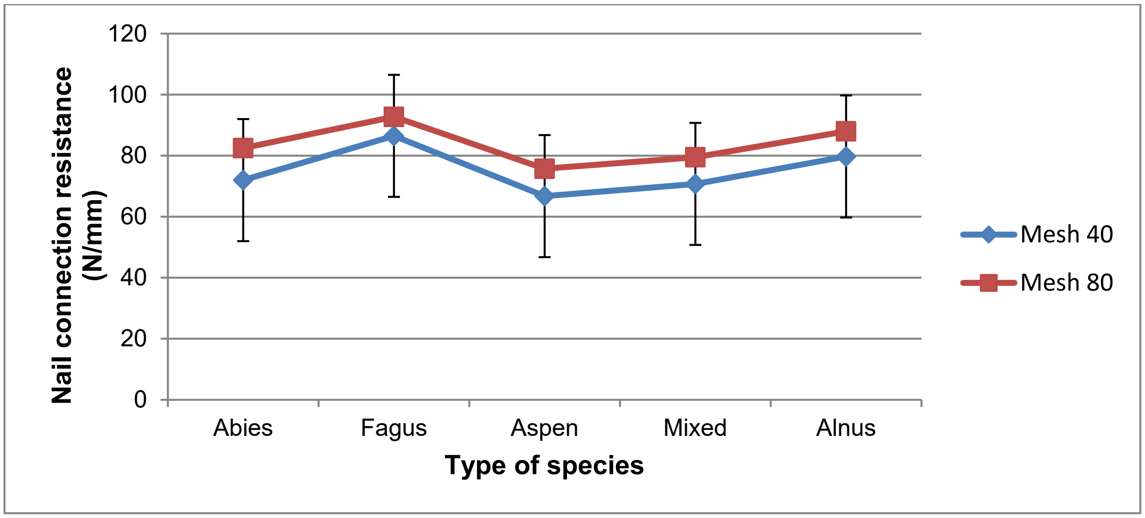

Fig. 7. Diagram of the effect of particle size on nail connection resistance

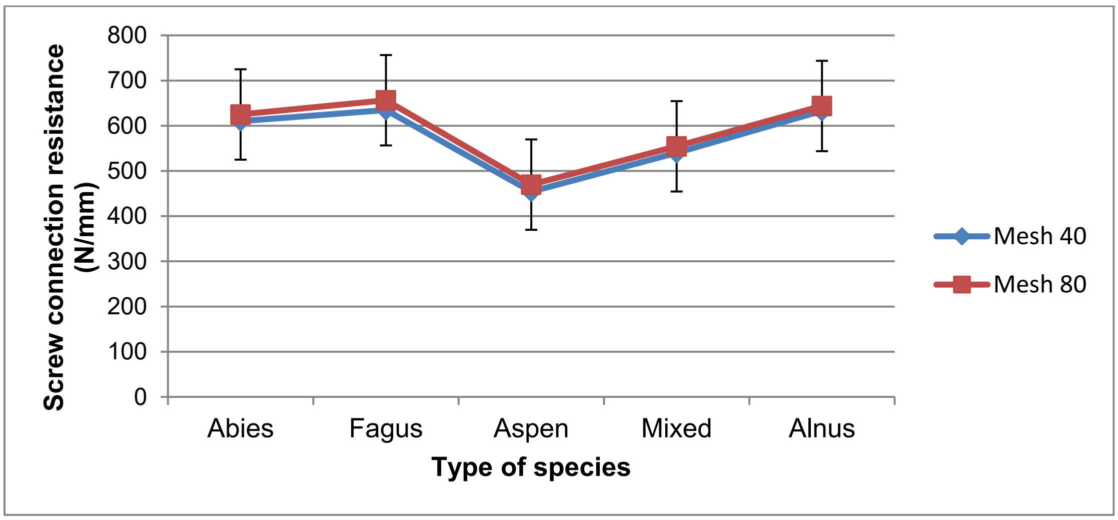

Fig. 8. Diagram of the effect of particle size on screw connection resistance

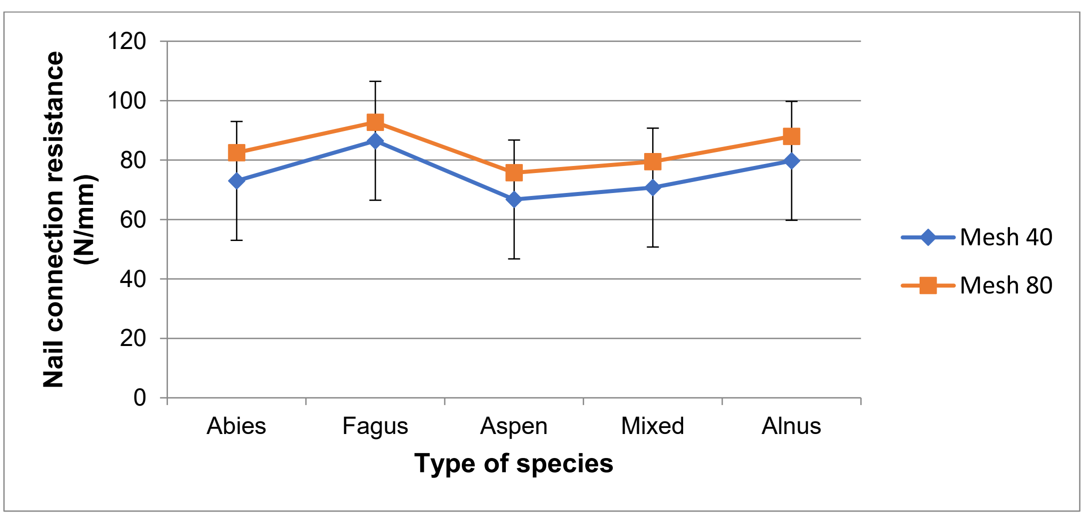

Fig. 9. Diagram of the effect of species type on nail connection resistance

Table 5. Duncan Test Results in Dividing Species into Similar Subsets in Resistance to Nail Connection

Type of Species	Number of Data	Subsets			
		1	2	3	4
Aspen	8	71.2500			
Mixed species	8	75.1250	75.1250		
Abies	8		77.7500		
Alnus	8			83.8750	
Fagus	8				89.6250
Meaningfulness		0.064	0.202	1.000	1.000

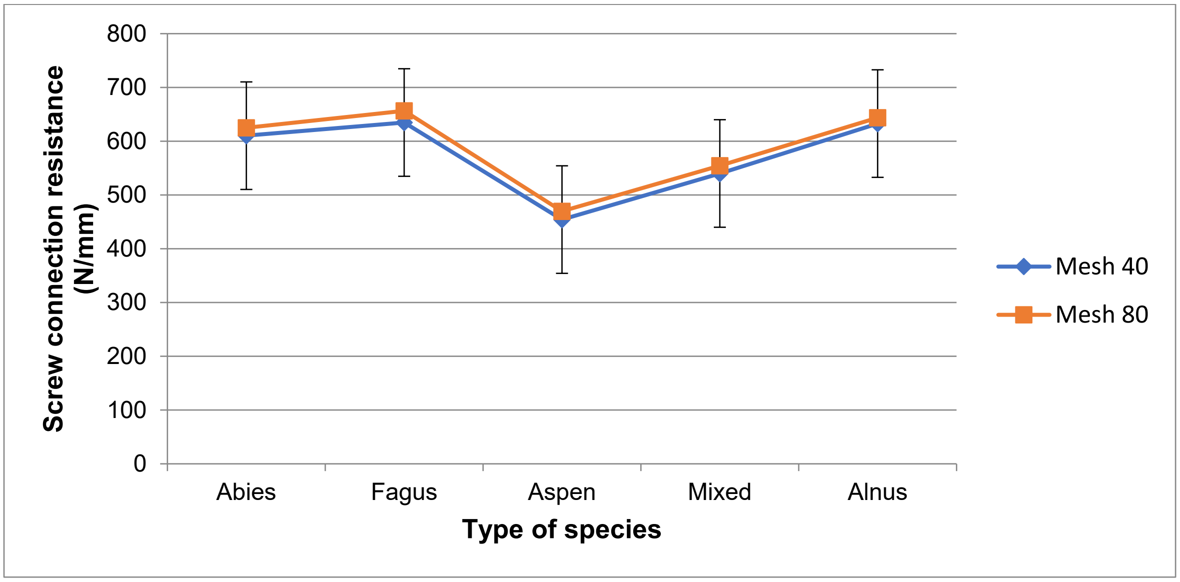

Fig. 10. Diagram of the effect of species type on screw connection resistance

Effect of Species Type on Resistance to Screw and Nail Connections

As shown in Tables 5 and 7 and Figs. 9 and 10, there were differences between the resistance to screw and nail connections in different species, and these differences were significant at the 1% level for both nail and screw connection resistance, and Duncan's test presented these differences in four subsets.

The resistance to withdrawal of screw and nail connections of composites is directly related to the density (Romer and Winistorfer 2001). Increased specific gravity generally resulted in an increased resistance to screw and nail connections. Because the type of species affects the degree of compaction and consequently the degree of dimensional recovery, as a result, highly porous species that are more compactible have a greater degree of dimensional recovery during the climatic period, which reduces the density of boards related to these species and probably causes the difference in these strengths. The effect of extractives present in the wood on the degree of bonding, both chemically and physically, is another possibility. However, finding definitive reasons requires more research and experiments.

Table 6. Variance Analysis of Bolted Connection Resistance Values

Source of Changes (S.O.V)	Sum of Squares (S.S)	Degree of Freedom (df)	Mean Squares (M.S)	Test Statistic (F)	Significance Level (P)	Significance
Factor A (species type)	192710.350	4	48177.588	102.662	0.000	**
Factor B (particle size)	2402.500	1	2402.500	5.120	0.031	*
Interaction (A*B)	121.750	4	30.437	0.065	0.992	ns
Error	14078.500	30	469.283			
Total	13765258.000	40				

** Indicates significance at the 1% level, * indicates significance at the 5% level, and ns indicates non-significant

Table 7. Duncan's Test Results in Dividing Species into Similar Subsets in Resistance to Bolting

Type of species	Number of data	Subsets			
		1	2	3	4
Populus	8	462.0000			
Mixed species	8		547.2500		
Abies	8			617.6250	
Alnus	8			638.2500	638.2500
Fagus	8				645.6250
Meaningfulness		1.000	1.000	0.067	0.501

CONCLUSIONS

1. In all tests, the resistance to plastic wood screws was greater than the resistance to nails.
2. Increasing particle size reduced bolting resistance in all species.
3. Among the species studied, the highest resistance to screws and nails was for beech and then alder, and the lowest resistance to screws and nails was for poplar. The mentioned resistances in the mixture used were equal to the average resistance of the species, and the difference between the species was obvious but not significant.
4. The results obtained from this study are valid for the particle size examined, the type of wood used, the percentages of mixing used, the type of wood-plastic production process, and the type of screw (thread, diameter, and material). Different types of wood species, different sizes of wood particles, types of screws used, and different methods of producing wood-plastic composites can have different performances, so to find the optimal strength, other species, different particle sizes, *etc.*, should be investigated.

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Article submitted: March 13, 2025; Peer review completed: May 28, 2025; Revised version received and accepted: August 16, 2025; Published: October 28, 2025.
DOI: 10.15376/biores.20.4.10795-10805