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ANALYSIS OF THE STRUCTURAL PARAMETERS OF ENGINEERED WOOD

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Abstract. This study hypothesises that the tensile strength of wood-duroplastic composites (WDPC) is influenced by wood waste particle size and shape. The research investigated whether variations in the structural composition of wood waste particles have a significant impact on the properties of composite materials. The analysis of the three types of wood waste – door production, packaging, and demolition waste – was conducted following mechanical and chemical treatment. The characterisation of particles was conducted through granulometric analysis and morphological evaluation using ImageJ software. Composite samples were then developed using biopolyurethane binders. Tensile strength tests were conducted after 30 days of curing. The findings of the present study indicated that the morphology of the particles, especially their aspect ratio and circularity, had a significant impact on the strength of the composite materials. Despite their comparatively greater density, attributable to their aluminium content, samples of door waste did not demonstrate superior tensile strength. The present study makes a contribution to the field of sustainable waste reuse strategies and presents practical insights into the development of engineered wood products.

Keywords: wood waste, wood-duroplastic composites, tensile strength, particle morphology, chemical treatment, biopolyurethane, sustainability, granulometry, recycling, circularity.

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1. Introduction

Demand for wood products as a natural, renewable raw material is continuing to increase. This growth is further fueled by the development of the bio-economy, which highlights the importance of wood resources. The European Union's biodiversity strategy is prompting the wood industry to seek alternative raw materials. We should note that the loss of forest biodiversity and the growing public expectations for the development of protected areas, both in Lithuania and across Europe, are contributing to the decline in the area of managed forests. This situation poses challenges for the forestry industry and timber sector in fulfilling the growing demand for raw materials.

Increased supply of quality timber is possible through the development of plantation forestry. However, this may not be a viable solution in the near future, as rising average annual temperatures, declining rainfall, and favorable conditions for the spread of fungal diseases, bacteria, and pests are creating an environment with an increased amount of dead wood. Studies have already shown that, in unmanaged forests in Central Europe, dead wood can account for up to 25% of the total forest wood stock (Gutowski et al., 2023; Merganiov et al., 2012). In 2015, the average volume of dead wood exceeded 11 m^3/ha, accounting for over 7% of the average volume of growing forest in Europe (Michalak & Ministerial Conference on the Protection of Forests in Europe, 2011).

It is well known that the production of wood products involves several stages, from log extraction to the finished product. Around 50% of live wood is converted into valuable products, while the rest is discarded as waste (Raši & Ministerial Conference on the Protection of Forests in Europe, 2020). The physical, mechanical, and chemical properties of dead wood change when it is exposed to biologically active organisms, reducing its suitability as a building material. However, it is altered chemical composition and morphological structure can be used as a filler for composite wood materials (Pandey, 2022). Therefore, today's focus must undoubtedly be on alternative organic resources to replace the shortage of industrially valuable wood in recycling plants, such as dead wood or wood waste of various origins. Analysis of literature and statistical data indicates that advanced technologies are not currently being applied sufficiently, and there is a lack of institutional support to exploit the full potential of waste. Studies show that wood waste can be a significant source of materials, but effective waste management rules must be developed to optimise this resource (Frihart et al., 2019; Statnik et al., 2020).

It is estimated that 70% more particleboard has been produced globally over the last two decades (Xiong et al., 2013), and given that these products have a lifespan of 5 to 30 years, it is crucial that today's preparations enable large quantities of this waste to be converted into alternative raw materials that can serve as a basis for the development of new materials.

This study investigates whether the size and shape of wood waste particles affect the strength of wood-duroplastic composites (WDPC). However, it does not address the influence of thermal and chemical treatment on the strength characteristics of the product, as demonstrated in a study (Mwanzia et al., 2024). This treatment has been shown to affect interfacial adhesion and therefore the strength characteristics of the product.

2. Materials and methods

Wood waste from the door production industry (DW), the wooden packaging industry (W) and the furniture and demolition industry (PLY) was used for the study (Figure 1). Furthermore, the risks associated with wood waste contamination, due to its origin and surface treatment methods, were thoroughly assessed. The utilisation of lower-quality raw materials in the production of wooden packaging has been identified as a potential source of risk, as these materials may have been impregnated with biocidal substances or pentachlorophenol. This has the potential to result in the presence of residual toxic compounds, including formaldehyde, in the final product (European Chemicals Agency, 2024). Furniture waste, particularly chipboard and plywood, is frequently adhered with formaldehyde-based resins and coated with surface finishing materials such as nitrocellulose, polyurethane, or acrylic varnishes, paints, and plastic. These materials have been identified as a potential source of volatile organic compounds (VOCs), including toluene, acetone, and xylene (SGS Group, 2024). As suggested by Figure 1, the visual analysis reveals surface damage (i.e. cracks, discolouration, and roughness) and variances in finishing properties. These observations indicate the presence of multifaceted chemical contamination, which is hypothesised to be dependent on the type of wood waste and its previous use.

The sample of the softwood chips and aluminium fiber (10% of the total weight) was obtained from VILJANDI Windows and Doors, a door manufacturer in Estonia, and no additional mechanical treatment was applied. The second group of samples (W) consisted of wooden pallets, while the third group (PLY) consisted of waste from the furniture industry and construction demolition. The second and third waste types were both obtained from UAB "Ekobazė" (Vilnius, Lithuania). Due to the larger dimensions of these wastes, a GMM-S hammer shredder (manufactured by UAB Radviliškio mašinų gamykla in Radviliškis, Lithuania) was used for their mechanical treatment. The rotor speed of the shredder was 3000 rpm, and a 20 mm mesh was used. To increase adhesion of the wood particles to the binder, they were treated with 10% solutions of hydrogen peroxide (H_2O_2), sodium carbonate (Na_2CO_3) or calcium hypochlorite ($Ca(ClO)_2$), based on the weight of the sample. All chemicals were purchased from UAB Lerochem (Klaipėda, Lithuania).

The general scheme for processing wood waste is shown in Figure 2.

The wood waste particles were thoroughly washed by boiling them in a designated washing solution for a period of one hour. Following the boiling stage, the particles in washing solution was maintained at temperatures ranging from 18 to 22 °C for a duration of 23 hours. The particles were then subjected to six washing cycles with the purpose of removing any residual washing solution. Each washing cycle consisted of a five-minute period of particle mixing with cold water, in order to initiate the rinsing process. Subsequent to the mixing stage, the excess liquid was removed by draining the suspension through a metal mesh with 1 mm openings. The particles were then immediately rewashed using a fresh portion of clean water, thus initiating the subsequent cycle. Following the final washing cycle, the particles were transferred onto a metal sieve (1 mm) and filtered for a period of 24 hours. Finally, the particles were subjected to drying in a hot air chamber

Figure 1. Raw wood waste: a) door production (DW) industry; b) wooden packaging (W); c) furniture and construction demolition (PLY) industry

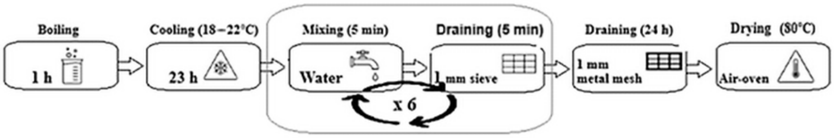

Figure 2. Thermochemical treatment of wood waste particles

at a temperature of 80 °C until they reached a constant weight. After thermochemical treatment the waste particles were subjected to granulometric analysis by sieving using woven wire mesh sieve with mesh sizes of 20, 10, 5, 2.5, 1.25, 0.63, and 0.315 mm (Glenammer Sieve Ltd., Ayr, Scotland), in order to determine their granulometric composition. Test sieving was carried out in accordance with ISO 2591-1. Additionally, the shape of each wood waste particle species and fraction was assessed using ImageJ. The following data set contains the number of used wood waste samples, as well as the granulometric composition of said samples and the chemical treatment solutions used are given in Table 1.

Biopolyurethane was used to bind the waste wood particles. The biopolyurethane binder consisted of isocyanate, polyol, and natural rapeseed oil. The ratios of biopolyurethane to wood waste used to prepare the blends are given in Table 2.

The hardener in this study was Lupranat M20S polymer 4,4-diphenylmethane diisocyanate with 31.5% NCO (BASF, Berlin, Germany). The other components of the binder were Biopolyol RD polyol (SIA PolyLabs, Riga, Latvia) with a hydroxyl value of 350 KOH/g and a water content of less than 0.2%, and natural rapeseed oil (UAB "Lomista", Kaišiadorys, Lithuania).

Engineered wood-plastic composites were formed using the known grain size and shape of the particles. The wood waste and bio-polyurethane were poured into a 50 l plastic container and mixed for one minute using a mixer (Apex ST2, Wagner S.p.A., Italy). The mixer speed was 200 rpm. After 30 seconds of mixing, the mixture was placed in a mould and pressurised to 0.9 MPa. A pneumatic-hydraulic Tongrun T40 press (Shanghai Tongrun Imp. & Exp. Co., Ltd., Shanghai, China) was used for the formation of samples. The samples were held in mold for 30 minutes and then demolded.

The strength of the formed samples was determined 30 days after formation. The strengths were determined using a Hounsfield H10KS universal test press (Hounsfield Test Equipment, Redhill, UK). Three samples were prepared for each composition for the evaluation of the strengths. Before performing the tensile strength test, the density of the test samples was determined in accordance with the standardised methodology specified in EN 323:1999 (European Committee for Standardization, 1993). Prior to the testing procedure, the samples were subjected to a conditioning process, during which they were maintained at a relative humidity of 65 (±1%) and a temperature of 20 (±2 °C). The moisture content of the wood waste particles ranged from 9.3% to 10.7%. Tensile strength was determined according to EN ISO 29766:2022 (International

Table 1. Wood waste samples

No.	Coded sample	Source of the wood waste	Wood waste particle size, mm	Chemical treatment solution, 10%
1	PLY 0/20_ H_2O_2	PLY	≤20	hydrogen peroxide
2	PLY 0/20_ Na_2CO_3			sodium carbonate
3	PLY 0/20_ $Ca(OCl)_2$			calcium hypochlorite
4	DW 0/20_ H_2O_2	DW	≤20	hydrogen peroxide
5	DW 0/20_ Na_2CO_3			sodium carbonate
6	DW 0/20_ $Ca(OCl)_2$			calcium hypochlorite
7	W 0/20_ H_2O_2	W	≤20	hydrogen peroxide
8	W 0/20_ Na_2CO_3			sodium carbonate
9	W 0/20_ $Ca(OCl)_2$			calcium hypochlorite

Table 2. The ratios of the raw materials in the mixture are as follows

Biopolyurethane, %			Wood waste, %
Isocyanate	Polyol	Rapeseed oil	
18	22	10	50

Organization for Standardization, 2022). The test samples were "bone" shape, with dimension in center of samples of 20×20 (±2) mm. The crosshead movement was maintained at a constant speed of 10 mm/min, in accordance with standard mechanical testing procedures.

3. Results

A representative sample was assessed from each fraction to determine the shape of the wood waste particles. Figure 3 shows the particle images of the different fractions.

Tensile strength tests were carried out next. These are shown in Figure 4.

Figure 5 shows the tensile strength results for all samples in relation to density and the chemical treatment solutions used.

Figures 6a, 6b, and 6c show the density and tensile strength dependencies for each waste type, treated with different solutions. As detailed in Tables 3, 4 and 5, the measurement results of density and tensile strength are presented together with the calculated standard deviation and coefficient of variation values. Three measurements were performed for each wood waste sample in which density and tensile strength were determined.

The diagrams clearly show that the nature of the waste wood determines both density and strength results. Comparing the average density values, we can see that the density of the samples prepared from construction and demolition recycling waste and packaging waste differs by almost 1.2 times, that of packaging waste and door production waste by almost 1.2 times, and that of construction and demolition recycling waste and door production waste by almost 1.4 times. The average values of the tensile strengths show that the tensile strengths of the samples prepared from construction and demolition recycling waste and packaging waste differ by 1.3 times, those of packaging waste and door production waste by 1.1 times, and those of construction and demolition recycling waste and door production waste by almost 1.4 times. No direct influence or tendencies related to the solutions used for chemical treatment are observed. Of the three different wastes used, the highest tensile strength is obtained from door waste (DW), followed by waste from the furniture and construction industry (PLY), and the lowest tensile strength is obtained from waste from the packaging industry (W).

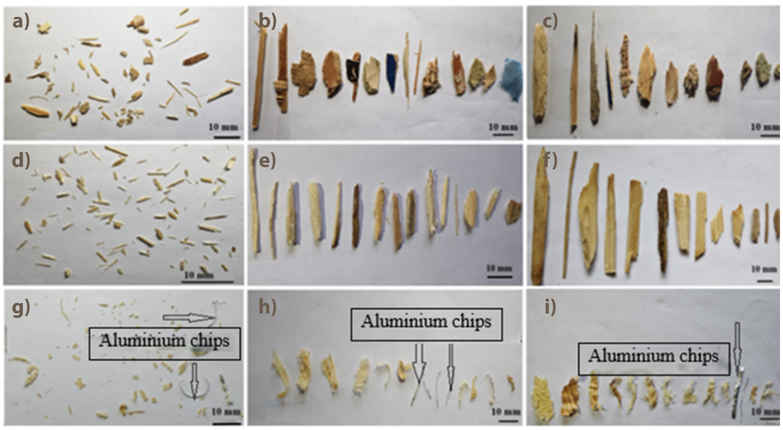

Figure 3. Image of wood waste particles of different fractions, mm: a) 0÷5, PLY; b) 0÷10, PLY; c) 0÷20, PLY; d) 0–<5, W; e) ≥5–<10, W; f) ≥10–<20, W; g) 0÷5, PLY; h) 0÷10, PLY; i) 0÷20, DW (source: Rimkienė et al., 2024)

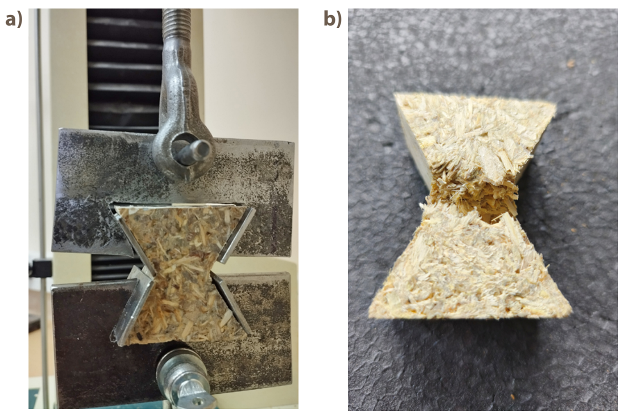

Figure 4. Tensile strength test: a) sample in metal grips before testing; b) sample after testing

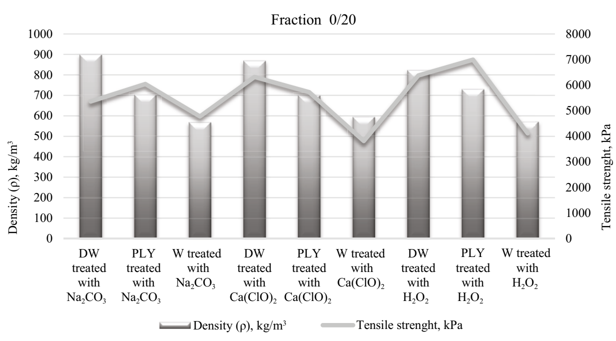

Figure 5. The dependence of the tensile strength on the density of the waste samples from the door production industry (DW), the construction and demolition industry (PLY), and the wooden packaging industry (W)

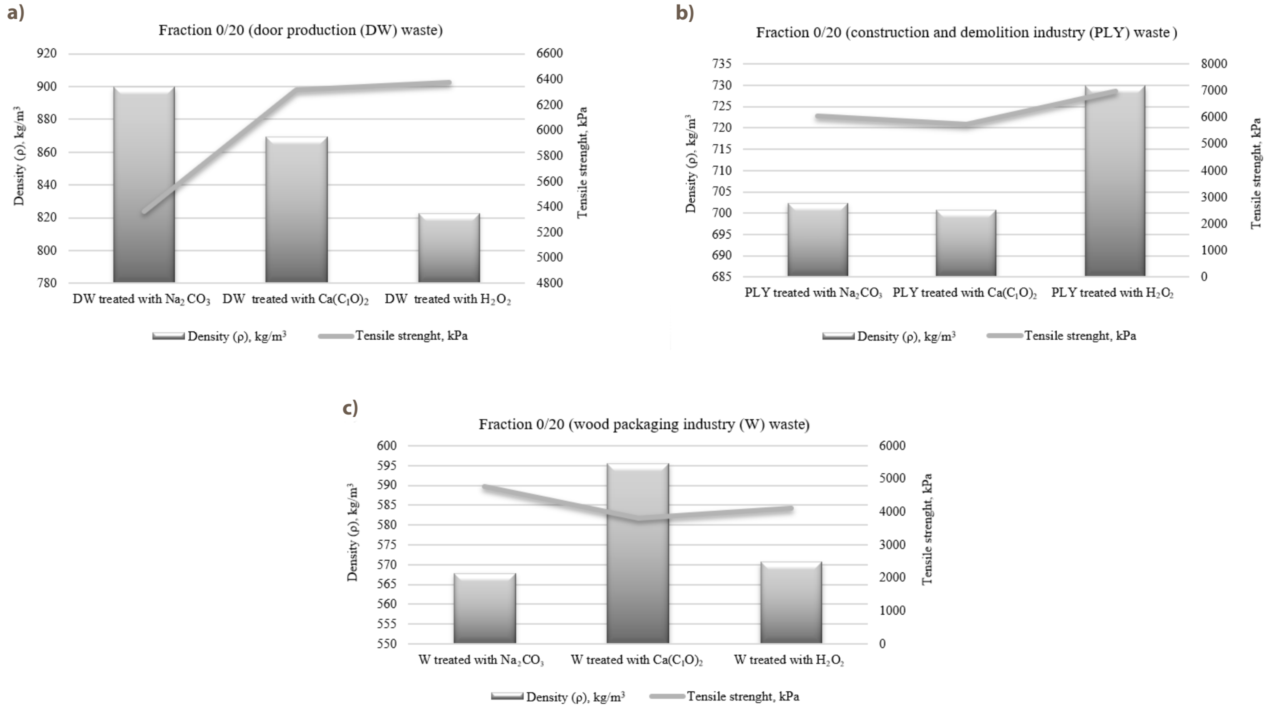

Figure 6. The dependence of waste type on tensile strength and density: a) door production (DW) industry; b) furniture and construction demolition (PLY) industry; c) wooden packaging (W)

Table 3. The measurement results for tensile strength of door production waste

No.	Coded sample	Average meaning of **density**, kg/m^3	Standard deviation	Coefficients of variation	Average meaning of **tensile strenght**, kPa	Standard deviation	Coefficients of variation
1	DW 0/20_ H_2O_2	822.75	13.70	1.66	6376	180.27	2.84
2	DW 0/20_ Na_2CO_3	899.71	35.53	3.95	5365	1158.24	21.59
3	DW 0/20_ $Ca(OCl)_2$	869.30	35.18	4.05	6315	1939.59	30.71

Table 4. The measurement results for tensile strength of door production waste

No.	Coded sample	Average meaning of **density**, kg/m^3	Standard deviation	Coefficients of variation	Average meaning of **tensile strenght**, kPa	Standard deviation	Coefficients of variation
1	PLY 0/20_ H_2O_2	729.89	11.81	1.62	6995	334.63	4.78
2	PLY 0/20_ Na_2CO_3	702.32	16.79	2.39	6042	1215.38	20.12
3	PLY 0/20_ $Ca(OCl)_2$	700.65	1.23	0.18	5727	76.37	1.33

Table 5. The measurement results for tensile strength of door production waste

No.	Coded sample	Average meaning of **density**, kg/m^3	Standard deviation	Coefficients of variation	Average meaning of **tensile strenght**, kPa	Standard deviation	Coefficients of variation
1	W 0/20_ H_2O_2	570.68	48.13	8.43	4115	577.57	14.04
2	W 0/20_ Na_2CO_3	567.78	13.93	2.45	4772	475.88	9.97
3	W 0/20_ $Ca(OCl)_2$	595.54	25.05	4.21	3814	90.51	2.37

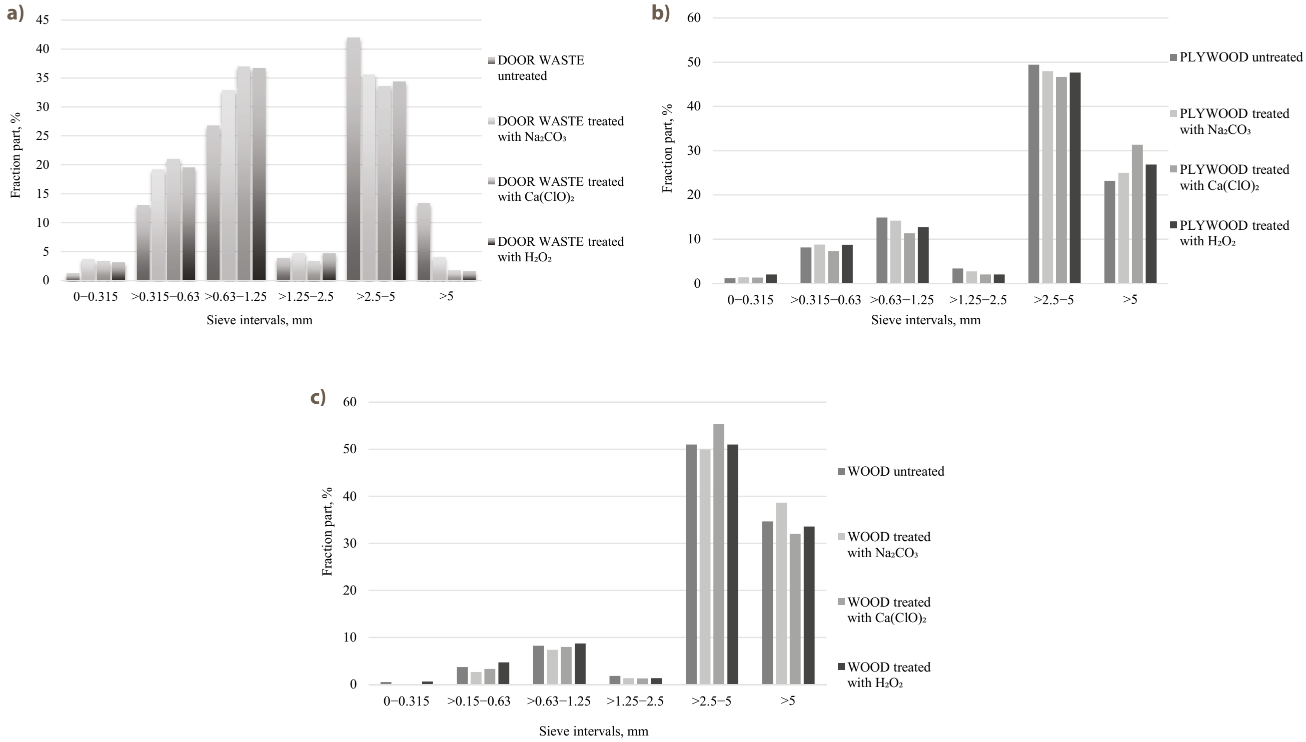

Figure 7. Granulometric composition of waste: a) door production (DW) industry; b) furniture and construction demolition (PLY) industry; c) wooden packaging (W)

The results were further grouped according to the nature of the wood waste particles and the granulometric composition (Figures 7a, 7b, and 7c), and the influence of the chemical treatment was assessed, with the size and shape of the particles being important for determining the results (Table 6).

Analysis of the results shows that the granulometric percentage composition of wood waste from the door industry is dominated by particles of ~20% >0.315÷0.63 mm, ~33% >0.63÷1.25 mm and ~37% >2.5÷5 mm. The granulometric percentage composition of wood packaging and construction and furniture industry waste is dominated by particles with a size of >2.5÷5 and >5 mm, with fractional shares of ~50% and ~30%, respectively. This indicates a very similar fractional distribution for the two waste samples, both of which are dominated by particles sized 2.5–5 mm. In contrast, the composition of the waste from door production is substantially different, with more than 50% of the total mass being made up of the ultrafine fraction, which has a particle size of 0÷0.315 mm. When analysing the 0–2.5 mm particle size fraction of the door production waste, an increase in the number of fine particles is observed after chemical treatment compared to the untreated waste. It is likely that the fine wood particles are more easily leached out, while the heavier fine aluminium particles have a greater influence on the particle mass distribution. This significant difference is due to the technological characteristics of door production, which determine the morphological structure of the waste.

The shape of the waste particles influences the properties of the engineered wood. The particles representing the studied fraction were analysed using ImageJ, a public domain image processing and analysis software. The analysis was carried out to determine the aspect ratio (AR), the roundness (R) and the circularity (C) of the particle, and the results are presented in Table 6.

The aspect ratio (AR) is calculated by using the height-to-width ratio of a particle as a measure of its proportional dimensions. Roundness (R) describes how rounded a shape is. Values approaching 1 indicate a particle that is more circular, while lower values indicate a more irregular shape. Similarly, circularity (C) measures how circular the particle is. As with circularity, a value of 1 corresponds to a perfect circle, while values less than 1 indicate deviations from circularity (Rimkienė et al., 2025). Analysing the roundness and circularity results indicates that the particles in all samples are characterised by irregular, asymmetrical and angular shapes with values far from 1. Notably, the particles from the construction and demolition industry

Table 6. The results of particle shape analysis

Sample fractions	Aspect ratio, (AR)	Roundness, (R)	Circularity, (C)
W (0/20)	3.228±2.352	0.460±0.242	0.616±0.235
PLY (0/20)	6.952±5.874	0.210±0.112	0.389±0.151
DW (0/20)	3.348±2.350	0.391±0.165	0.378±0.198

(PLY) demonstrate particularly irregular shapes. Regarding the aspect ratio of the particles, the highest value is again found for particles from the construction and demolition waste industry (PLY). Figures 3b and 3c shows the aspect ratio visually, while Figures 3e, 3f, 3h and 3i shows the particles of waste from the door production industry (DW) and waste from the wood packaging industry (W). The aspect ratios of these particles are twice as low as those of the particles of waste from construction and demolition industry (PLY).

4. Discussions

The tensile strength test was selected as the reference method because it provides the most reliable and direct indication of the bonding quality between the engineered wood particles as a filler and the binder. This method is characterised by its sensitivity to the internal cohesion of the composite material, thus resulting in its optimal suitability for the assessment of the effectiveness of the adhesive interaction within the structure. The application of tensile forces in the test provides a simulation of the type of stress that most critically challenges the integrity of the bond. This aspect of the test allows for a more accurate evaluation of material performance.

Analysis of the results shows that fillers of different natures but with the same granulometric composition can be used to produce engineered wood with different strength parameters. However, it cannot be claimed that tensile strength is directly dependent on the density since the average tensile strengths of the construction and demolition industry waste (PLY) and door production waste (DW) samples were similar (6255 kPa and 6018 kPa respectively), but the average density values were significantly different (710 kg/m^3 and 863 kg/m^3 respectively). The higher densities of the door production waste samples were due to the presence of the aluminium chips accounting for 10% of the total waste mass. Should be noted that at this stage of the study, preliminary studies are being conducted to determine the characteristics of the natural waste origin. During the study, minimal (but necessary) chemical and mechanical waste treatment methods were used, as each additional waste treatment cycle (e.g. sedimentation) requires additional energy or material resources, which is not efficient in terms of sustainability. No direct influence or tendencies related to the solutions used for chemical treatment were observed. Of the three types of waste used, samples from construction and demolition industry waste (PLY) had the highest tensile strength, followed by samples from door production waste (DW), with samples from wood packaging waste (W) having the lowest tensile strength.

Several factors contribute to this. Firstly, analysing Figures 6a, 6b, and 6c shows that tensile strength decreases at higher densities. This could be explained by the fact that, with an increased number of particles or particles with a high surface area, the same amount of binder will not cover all the particles. This results in a smaller adhesion area and, consequently, a lower tensile strength (Chen et al., 2006; Mwanzia et al., 2024). Thirdly, researchers (Vasiliev et al., 2021) state that the strength properties of composite materials are influenced by the geometric shape, size and mass fraction of the particles in the various fractions. Researchers who have studied the mechanical properties (Kociszewski et al., 2012) hypothesise that the higher the aspect ratio (AR) of the particles, the better the mechanical properties of a fibre-reinforced composite and the greater the stress transfer from the polymer to the fibre. The researchers also state that we should not exclude the possibility of large particles breaking during the formation of the samples and that theoretical data and practical results may not be consistent.

5. Conclusions

The study shows that the best tensile strengths were obtained from the construction and demolition industry waste (PLY) samples when composite materials were produced from three different types of waste. Considering that this type of waste cannot be recovered as biofuel due to the presence of formaldehyde resins, these promising results suggest a potential advantage over other types of waste that can be recovered in different ways. This could contribute to the environmental sustainability policy by the European Commission, known as the Green Deal, by ensuring the future recycling of all types of waste.

Author contributions

Conceptualisation, A. R.; methodology, S. V. (Sigitas Vėjelis) and A. R.; software; A. R.; validation, A. R. and S. V. (Sigitas Vėjelis); formal analysis, A. R. and S. V. (Sigitas Vėjelis); investigation, A. R., S. V. (Sigitas Vėjelis); resources, A. R. and S. V. (Sigitas Vėjelis); data curation, A. R. and S. V. (Sigitas Vėjelis); writing, A. R. and S. V. (Sigitas Vėjelis); writing—review and editing, A. R. and S. V. (Sigitas Vėjelis); visualisation A. R.; supervision, A. R. and S. V. (Sigitas Vėjelis). All authors have read and agreed to the published version of the manuscript.

Disclosure statement

Authors declare they have not any competing financial, professional, or personal interests from other parties.

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DIRBTINĖS MEDIENOS STRUKTŪRINIŲ PARAMETRŲ ANALIZĖ

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Santrauka

Šio tyrimo hipotezė teigia, kad medienos duroplastiko (WDPC) kompozitų tempiamasis stipris priklauso nuo medienos atliekų dalelių dydžio ir formos. Tyrime buvo nagrinėjama, ar skirtinga medienos atliekų dalelių struktūrinė sudėtis veikia kompozitinių medžiagų savybes. Buvo tiriamos trijų tipų medienos atliekos – durų gamybos, pakavimo pramonės bei baldų ir statybos pramonės atliekos – analizę atliekant po mechaninio ir termocheminio atliekų apdorojimo. Dalelėms charakterizuoti buvo nustatinėjama granuliometrinė sudėtis bei kiekvienos rūšies ir frakcijos medienos atliekų dalelių forma, vertinimui naudojant *ImageJ* programinę įrangą. Atlikus medienos atliekų dalelių analizę, naudojant biopoliuretaninį rišiklį, suformuoti kompozitinės medžiagos bandiniai. Bandiniai 30 dienų buvo kietinami ir vėliau atlikti bandymai nustatant tempiamąjį stiprį. Nustatytas reikšmingas ryšys tarp kompozitą sudarančių dalelių morfologinių parametrų, ypač AR (*aspect ratio*), apskritumo ir stipruminių savybių. Nepaisant to, kad bandiniai iš durų gamybos atliekų turėjo didesnį tankį dėl sudėtyje buvusių aliuminio dalelių, tempiamojo stiprio rezultatai reikšmingai nesiskyrė. Šis tyrimas prisideda prie tvaraus atliekų naudojimo strategijų kūrimo, taip pat jame pateikiamos praktinės įžvalgos, susijusios su dirbtinės medienos gaminių kūrimu.

Reikšminiai žodžiai: medienos atliekos, medienos duroplastiko kompozitas, tempiamasis stipris, dalelių morfologija, cheminis apdorojimas, biopoliuretanas, tvarumas, granuliometrija, atliekų perdirbimas, žiedinė ekonomika.