Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials

26: 3 (2026) 171–178

COMPOSITES THEORY AND PRACTICE

ISSN (online): 2299-128X

Katarzyna Bryll[1,*] (https://orcid.org/0000-0002-2437-9356), Karolina Baszak[2] (https://orcid.org/0000-0002-5621-6324), Jacek Gryta[1], Andrzej Jakubowski[1] (https://orcid.org/0000-0002-0331-3147), Jan Drzewieniecki[1] (https://orcid.org/0000-0001-8758-8131)

[1] *Maritime University of Szczecin, Faculty of Mechanical Engineering, Waly Chrobrego 1-2, 70-500 Szczecin, Poland*
[2] *Maritime University of Szczecin, Doctoral School, Waly Chrobrego 1-2, 70-500 Szczecin, Poland*
* *Correspondence*: k.bryll@pm.szczecin.pl

Received (Otrzymano) 6.06.2026
Published on-line (Opublikowano) 30.09.2026

SELECTED MECHANICAL PROPERTIES OF POLYMER COMPOSITES CONTAINING RECYCLED FRACTION

https://doi.org/10.62753/ctp.2026.02.3.3

For environmental protection reasons and, consequently, improving people's quality of life, proper waste management is crucial. According to the Waste Act, waste management primarily involves preventing or reducing waste generation, as well as recovering and disposing of waste that cannot be reused. While glass waste is not problematic (it can be reprocessed through melting), the situation is different for glass (glass fibers) obtained from wind turbine blades. The authors of this paper decided to produce polymer (epoxy) composites with an addition of post-consumer glass. The resulting composites were subjected to mechanical testing (flexural strength, impact strength, and hardness).

Keywords: polymer composites, wind turbine blade waste, mechanical properties, waste management

INTRODUCTION

The rapid expansion of wind energy has led to a significant increase in decommissioned wind turbine blades, primarily composed of glass fiber-reinforced polymer (GFRP) composites, creating an urgent need for sustainable waste management solutions. Mechanical recycling–shredding, grinding, and milling–has emerged as the most commercially viable method for processing these blades, enabling the recovery of glass fibers and their reuse in new composite materials for applications such as construction, automotive parts, and 3D printing [1–6]. While mechanical recycling is cost-effective and environmentally preferable to landfilling or incineration, it often results in reduced mechanical properties of the recovered fibers as a consequence of damage and loss of surface functionality [7–9]. Nevertheless, advances in processing techniques and surface treatments have shown that recycled fibers can significantly enhance the stiffness, strength, and durability of new composites when properly integrated [10–13]. The environmental benefits are substantial: mechanical recycling reduces landfill waste, lowers CO_2 emissions compared with virgin-material production, and supports circular-economy principles [14–16]. Nonetheless, challenges remain regarding the economic feasibility at scale, market acceptance of recycled materials, and optimization of composite performance [17, 18].

 All rights reserved

Mechanical recycling processes

Mechanical recycling involves shredding or grinding wind turbine blades into smaller fragments or powders that can be used as fillers or reinforcement in new polymer matrices. [1–4]. The process is solvent-free, more energy-efficient compared to chemical and thermal methods, as well as scalable for industrial applications. [9, 18, 19]. It should be emphasized, however, that the processes usually produce short fibers, for which a partial reduction in tensile strength is observed resulting from damage and breakage during processing. [8, 18, 20].

Properties of composites containing recycled glass fibers

Composites containing glass fibers from recycled wind turbine blades have shown significant improvements in mechanical and performance properties, including growth in stiffness by up to 74%, tensile strength by up to 71%, modulus of elasticity by up to 147%, impact resistance by up to 95%, as well as increased hydrophobicity, fire resistance, UV aging resistance and thermal stability compared to pure polymers or wood-plastic composites (WPC) [1, 10–12].

It has also been shown that surface treatments such as silanization or NaOH etching allow partial restoration of the adhesion at the fiber-matrix interface lost during recycling [8, 13]. Additionally, the use of coupling agents leads to further improvement in interfacial bonding and more effective stress transfer in the composite. [13].

Environmental impact and economic profitability

Life cycle analyses (LCA) have shown that mechanical recycling has a lower environmental impact than landfilling or incinerating waste, mainly owing to the reduction in CO_2 emissions by reusing materials instead of producing virgin raw materials [9, 14–16]. The possibility of achieving economic competitiveness on an industrial scale was also indicated, provided that a sufficiently high level of fiber recovery was achieved [9]. A comparison of the process economics is presented in Table 1.

This process is in line with the principles of a circular economy, but its further development is limited by market barriers resulting from the lower mechanical properties of recycled fibers compared to virgin fibers [9].

Table 1. **Assessment of economic profitability of various recycling methods. Own study based on [5,9,10,12,15,20,21]**

Economic and technological criteria	Mechanical recycling – coarse fraction (50–100 mm)	Mechanical recycling – fine fraction (<10 mm, powder/fibers)	Pyrolysis	Solvolysis	Co-processing in cement plants
Process type	Cutting, shredding	Grinding, micronization	Thermal decomposition 450–700°C	Chemical depolymerization	Fragmentation + combustion/mineralization
CAPEX (Capital expenditures)	Low	Medium	High	Very high	Medium
OPEX (Operating expenses)	The lowest	Low-medium	High	Very high	Low
Typical process cost [€/t]	Approx. €50–150/t	Approx. €90–250/t	Approx. €700–1000 /t	>€1000/t	Approx. €300–600/t
Energy consumption	Low	Medium	Very high	High	Medium
Value of recovered product	Low	Medium	Medium-high for CFRP	High	Low
Degradation of fiber properties	High	High	Medium for CFRP, high for GFRP	Low	Total
Overall economic assessment	The most cost-effective material method	The best cost/quality compromise	Profitable mainly for CFRP	Prospective, but expensive	The cheapest industrial method

 All rights reserved

Applications and limitations

GFRP composites from recycled wind turbine blades have been utilized, among others, in building materials (e.g. concrete reinforcement), automotive components, particleboards, wood-plastic composites (WPC), thermoplastic granulates for injection molding and 3D printing, wind turbine nacelle covers, superhydrophobic anti-icing coatings, geopolymers, cement additives, as well as structural elements of bridges and buildings [9, 10, 22, 23].

The main limitations include reduced plasticity and lower ultimate strength at high fiber contents, which is related to the concentration of stress around fiber agglomerates or resin residues [1]. An additional problem is the difficulty in achieving uniform material quality between subsequent production batches.

The aim of this work is to produce polymer-glass composites where the glass fraction comes from wind turbine blade waste. The authors focused on the evaluation of selected properties of polymer composites depending on the different sizes of the recycled glass fraction.

RESEARCH MATERIAL

Base material and reinforcements

To produce the composite material, a polymer matrix was employed in the form of Epidian 5 epoxy resin hardened with PAC hardener (polyaminoamide curing agent) i.e. a polyaminoamide curing agent dedicated to epoxy resin systems. The crosslinking system was prepared using the proportion of 100 g of resin: 60 g of hardener, in accordance with the recommended stoichiometric ratio for the analyzed epoxy system given on the manufacturer's packaging. The epoxy resin was selected because of its favorable adhesion properties, low processing shrinkage in addition to high mechanical and chemical stability of the hardened matrix [24].

Waste composite material from wind turbine blades was utilized as the reinforcement phase. The waste material was subjected to a mechanical crushing process and then to grain classification. The particle-size ranges of the separated fractions were determined on the basis of the mesh size of the sieves used during the sieving process. The fine fraction was defined as the material passing through a sieve with a mesh size of 0.25 mm, whereas the coarse fraction was defined as the material retained within the sieve range corresponding to particle sizes of 2–8 mm. Therefore, the declared particle-size ranges resulted directly from the sieve mesh sizes employed for granulometric separation. Two fractions of reinforcing material were obtained:

- fine fraction with a particle size up to 0.25 mm
- coarse fraction with a particle size in the range of 2–8 mm.

The waste material from wind turbine blades contained mainly glass fibers embedded in a hardened polymer matrix, which allowed its use as a secondary filler and composite reinforcement.

Composite manufacturing

The composites were manufactured by means of the compression casting method [25–27]. The technological process included preparation of the strengthening phase, preparation of the polymer matrix, homogenization of the components and the formation of composite panels.

In the first stage, the strengthening phase was prepared by mechanically crushing waste composites from wind turbine blades. The crushed material was sieved to obtain two given granulometric ranges: fine fraction and coarse fraction. After grain classification, the material was dried in a laboratory dryer at a temperature of 60–80°C. The drying process was carried out to reduce the moisture content in the reinforcement material, which was aimed at improving adhesion at the phase boundary and limiting the formation of porosity in the finished composite.

In the next stage, the resin system was prepared. Epidian 5 epoxy resin was mixed with PAC hardener in a ratio of 100:60 by mass. Mixing was carried out until a homogeneous mixture was obtained with the hardener distributed as evenly as possible in the resin volume (Fig. 1a).

 All rights reserved

a)

b)

Fig. 1. Composite manufacturing a) prepared matrix material; b) preparation of reinforcement material

An appropriate amount of reinforcing material was introduced into the prepared epoxy matrix (Fig. 1b), and then the whole mixture was mechanically homogenized to obtain the most uniform distribution of the waste composite particles in the resin volume. The mixture thus prepared was placed in a mold (Fig. 2).

Fig. 2. Composites in molds

The forming process was conducted by means of casting. After casting, the material was compressed in the mold. The parameters of the compression casting process were selected experimentally. The pressing pressure was 2 MPa and the curing time was 30 min. The parameters were selected to ensure effective consolidation of the epoxy composites containing fine and coarse fractions of wind turbine blade waste. The applied pressure enables a reduction in porosity, improvement in wetting of the waste particles by the resin and better contact at the matrix-filler interface, without excessive resin flow from the mold or additional degradation of the fragmented glass reinforcement [25, 28–30]. The time of 30 minutes ensures sufficient progress of the epoxy resin crosslinking reaction and stabilization of the sample shape while maintaining efficiency of the technological process. The selection of these parameters is a compromise between the required quality of the composite structure, the limitation of technological defects and the production cycle time. After the curing process was completed, composite plates were obtained, from which specimens were cut for mechanical testing.

As part of the research, material mixtures were prepared as shown in Table 2.

Table 1. **Designations of research materials**

Material designation	**Contribution of strengthening phase [wt%]**		**Share of matrix phase [wt%]**
	Fine fraction	Coarse fraction	
E0	0	0	100
E+G	0	10	90
E+D	10	0	90
E+G+D	5	5	90

RESEARCH METHODS

Bending strength test

Three-point bending tests were performed utilizing a Quasar 600 universal testing machine equipped with a force and displacement recording system. The test was carried out in accordance with ISO 178 for polymer materials and polymer composites. The tests were conducted using a universal testing machine equipped with a force and displacement recording system for the loading beam.

Specimens with dimensions of 80 x 10 x 4 mm were prepared for testing.

Impact test

Impact tests were performed by means of the Charpy method employing a LabTest CHK 50J pendulum impact tester. The tests were conducted in accordance with the PN-EN ISO 179 standard using a pendulum hammer. The aim of the research was to determine the material's ability to absorb energy during dynamic impact loading.

Specimens with dimensions of 80x10x4 mm were prepared for testing. The tests were carried out on unnotched specimens.

Hardness test

Hardness measurements of the polymer composites were performed using the Shore D method. Shore D hardness measurements were conducted utilizing a Sauter Shore durometer. The measurements were carried out in accordance with ISO 868. The indenter was applied perpendicularly to the tested surface, and the hardness value was read after a stabilization time of 15 s. The method was selected due to the nature of the studied materials and the possibility of assessing the surface resistance to local deformation.

Specimens with a minimum thickness of 4 mm and a flat measuring surface were employed for the tests. Before starting the measurements, the specimens were conditioned at room temperature for 24 hours.

The measurements were carried out by pressing the hardness tester indenter perpendicularly to the specimen surface. The hardness value was read after a stabilization time of 15 s. For each specimen, at least five measurements were made at different points on the surface, maintaining the minimum distance between the impressions and from the edge of the specimen.

RESEARCH RESULTS AND ANALYSIS

Based on the static bending strength results (Fig. 3), it was found that the E0 matrix material reached a value of 85 ± 4 MPa. The addition of 10 wt% of the coarse fraction (E+G) resulted in a reduction in the strength to 76 ± 5 MPa, i.e. by approximately 10.6% compared to the unmodified material. This may indicate that the coarse fraction particles acted as local stress concentrators [31, 32]. In the case of the E+D composite, a rise in strength of approximately 5.9% was observed compared to E0. The highest value was obtained for the E+G+D material, for which the strength was 93 ± 4 MPa, i.e. approximately 9.4% higher than the matrix. This can be attributed to a more favorable packing of particles with different granulation in addition to more effective load transfer by the matrix-filler system. The dependence of the properties of the particle composites on the particle size, filler content and adhesion at the interface is described in the literature as one of the key mechanisms shaping the strength of such materials [33, 34].

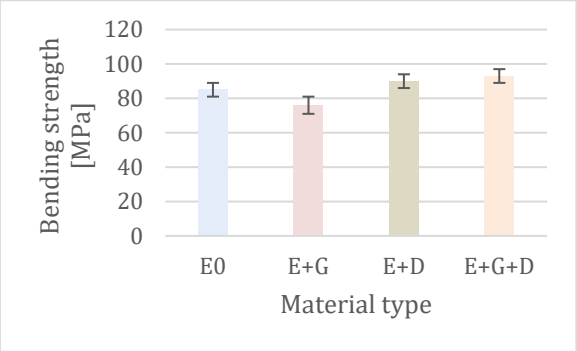

Fig. 3. Static bending strength test results

The flexural modulus (Fig. 4) grew after the introduction of each type of additive. For the E0 matrix it was 2.75 ± 0.12 GPa, while for E+G it increased by about 10.9%. For the E+D composite, 3.25 ± 0.14 GPa was obtained. The highest stiffness was demonstrated by the E+G+D material, for which the modulus was 3.35 ± 0.15 GPa, i.e. approximately 21.8% higher than the matrix. These results indicate that the addition of particles limited the deformability of the matrix during bending, causing the material to become stiffer [31–34].

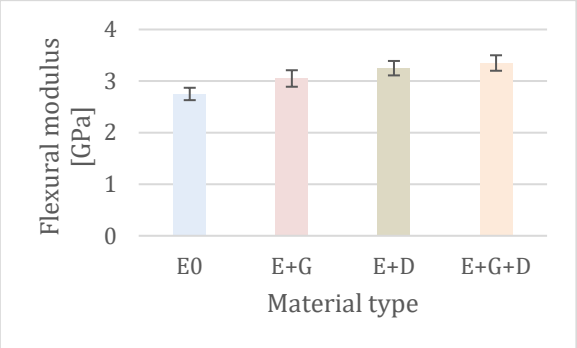

Fig. 4. Flexural modulus test results

The greatest changes were observed in the case of impact strength (Fig. 5). The E0 material obtained a value of 15.5 ± 1.2 kJ/m². For E+G, the impact strength rose by approximately 38.7%. For E+D 18.0 ± 1.5 kJ/m² was achieved. The highest impact strength was obtained for E+G+D, where the value was 23.0 ± 2.0 kJ/m², i.e. about 48.4% more than for the matrix. This effect may indicate a beneficial effect of the fraction mixture on the mechanism of fracture energy absorption. It is possible to observe the crack path deflection, local blocking of crack propagation and greater energy dissipation in the composite structure [34–37].

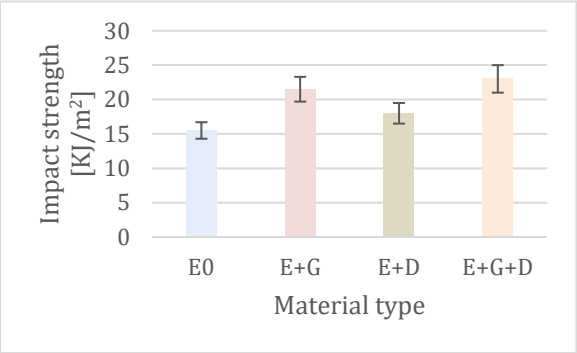

Fig. 5. Impact test results

The Shore D hardness (Fig. 6) also increased after matrix modification. For E0 it was 78.0 ± 1.1 Sh D, while for E+G it grew to 80.5 ± 1.3 Sh D, i.e. by about 3.2%. For E+D, 81.8 ± 1.0 Sh D was obtained, which corresponds to a rise of approximately 4.9%. The highest hardness was measured for E+G+D, where the value was 82.6 ± 1.2 Sh D, which is about 5.9% higher than for the matrix material. This means that the presence of the particles increased the surface resistance of the material to local deformation under the influence of the indenter [38, 39].

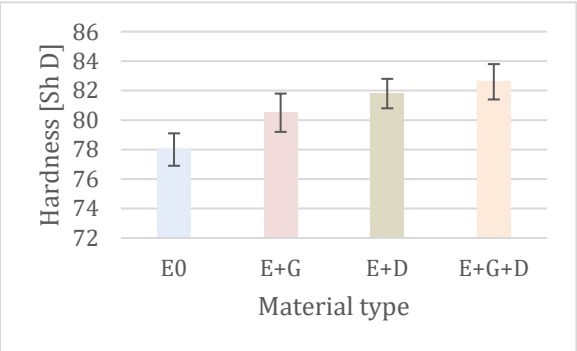

Fig. 6. Hardness test results

CONCLUSIONS

Based on the conducted research and analysis of the obtained results, the following conclusions were drawn:

- Waste composite material from wind turbine blades can be effectively utilized as a secondary reinforcing phase in epoxy composites, which is an ecological alternative to landfilling GFRP waste and fits into the assumptions of a circular economy.
- The mechanical properties of the composites are closely related to the recyclate particle size. Using only the coarse fraction (2–8 mm) reduces the flexural strength (10.6% decrease), which is due to the role of large particles as local stress concentrators.
- The most favorable mechanical parameters were obtained for the hybrid system (5% by weight of fine fraction and 5% by weight of coarse fraction). This material showed an increase in flexural strength by 9.4% and modulus of elasticity by 21.8% compared to pure resin.
- The introduction of a mixture of fractions (E+G+D) resulted in a dramatic rise in the impact strength – by 48.4% compared to the reference material. This is attributed to the ability of the recyclate particles to dissipate energy by deflecting and blocking the crack propagation path.
- The addition of recyclate increased the Shore D hardness of the material (maximum by 5.9% for E+G+D), which suggests better surface resistance of the composite to local deformations.
- The mechanical recycling of turbine blades is a low-cost and easily scalable method. Using the mixed fraction is particularly cost-effective because it eliminates the need for expensive fraction separation or energy-intensive chemical fiber recovery processes.
- In order to further optimize the material, it is advisable to conduct research on surface modification of the recyclate (e.g. silanization) in order to improve adhesion at the phase boundary and to analyze the resistance to environmental aging of the finished products.

 All rights reserved

– It should be noted that the present study was focused on the evaluation of selected mechanical properties of epoxy composites containing recycled wind turbine blade waste. Microstructural observations were not included in the current experimental scope. Therefore, further research should include microstructural analysis of the composites, especially assessment of the recycled fraction distribution in the epoxy matrix, matrix–filler interfacial adhesion, porosity, and fracture surface morphology after mechanical testing.

REFERENCES

[1] Rahimizadeh, A.; Kalman, J.; Henri, R.; Fayazbakhsh, K.; Lessard, L. Recycled Glass Fiber Composites from Wind Turbine Waste for 3D Printing Feedstock: Effects of Fiber Content and Interface on Mechanical Performance. *Materials* **2019**, *12*, DOI:10.3390/ma12233929.

[2] Rani, M.; Choudhary, P.; Krishnan, V.; Zafar, S. A Review on Recycling and Reuse Methods for Carbon Fiber/Glass Fiber Composites Waste from Wind Turbine Blades. *Composites Part B-engineering* **2021**, *215*, 108768, DOI:10.1016/j.compositesb.2021.108768.

[3] Beauson, J.; Lilholt, H.; Brøndsted, P. Recycling Solid Residues Recovered from Glass Fibre-Reinforced Composites – A Review Applied to Wind Turbine Blade Materials. *Journal of Reinforced Plastics and Composites* **2014**, *33*, 1542–1556, DOI:10.1177/0731684414537131.

[4] Kalpokaitė-Dičkuvienė, R.; Snapkauskienė, V. Prospects for the Valorization of Wind Turbine Blade Waste: Fiber Recovery and Recycling. *Sustainability* **2025**, *17*, 4202, DOI:10.3390/su17094202.

[5] Khalid, M.Y.; Arif, Z.U.; Hossain, M.; Umer, R. Recycling of Wind Turbine Blades through Modern Recycling Technologies: A Road to Zero Waste. *Renewable Energy Focus* **2023**, *44*, 373–389, DOI:10.1016/j.ref.2023.02.001.

[6] Rozylo, P.; Rogala, M.; Pasnik, J. Load-Carrying Capacity of Thin-Walled Composite Columns with Rectangular Cross-Section under Axial Compression. *Materials* **2024**, *17*, 1615, DOI:10.3390/ma17071615.

[7] Paulsen, E.B.; Enevoldsen, P. A Multidisciplinary Review of Recycling Methods for End-of-Life Wind Turbine Blades. *Energies (Basel).* **2021**, *14*, 4247, doi:10.3390/en14144247.

[8] Pender, K.; Yang, L. Regenerating Performance of Glass Fibre Recycled from Wind Turbine Blade. *Compos. B Eng.* **2020**, *198*, 108230, DOI:10.1016/j.compositesb.2020.108230.

[9] Fonte, R.; Xydis, G. Wind Turbine Blade Recycling: An Evaluation of the European Market Potential for Recycled Composite Materials. *J. Environ. Manage.* **2021**, *287*, 112269, DOI:10.1016/j.jenvman.2021.112269.

[10] Zhang, H.; Zheng, N.; Xing, T.; Zhang, G.; Cao, D.; Bai, Y.; Wang, S.; Zuo, D.; Liu, H.; Li, L.; et al. Study on the Characteristics of Glass Fiber-reinforced Polymers from Recycled Wind Turbine Blades as Reinforcement in Particleboard. *Polym. Compos.* **2024**, DOI:10.1002/pc.28514.

[11] Pu, Z.; Yang, S.; Wang, Q. Recycling of Waste Wind Turbine Blades for High-performance Polypropylene Composites. *J. Appl. Polym. Sci.* **2024**, DOI:10.1002/app.55474.

[12] Li, A.; Zhang, H.; Zhang, H.; Wu, Y.; Mu, Y.; Luo, B.; Li, L.; Liu, H.; Liu, J. Preparation of High-Strength, Multifunctional Wood-Plastic Composites Using Recycled GFRP From Decommissioned Wind Turbine Blades. *Polym. Compos.* **2025**, *46*, 16349–16365, DOI:10.1002/pc.70051.

[13] Moslehi, A.; Ajji, A.; Heuzey, M.; Rahimizadeh, A.; Lessard, L. Polylactic Acid/Recycled Wind Turbine Glass Fiber Composites with Enhanced Mechanical Properties and Toughness. *J. Appl. Polym. Sci.* **2022**, *139*, DOI:10.1002/app.51934.

[14] Cousins, D.S.; Suzuki, Y.; Murray, R.E.; Samaniuk, J.R.; Stebner, A.P. Recycling Glass Fiber Thermoplastic Composites from Wind Turbine Blades. *J. Clean. Prod.* **2019**, *209*, 1252–1263, DOI:10.1016/j.jclepro.2018.10.286.

[15] Menna, C.; De Simone, L.; Capozzi, V. Mechanical Recycling of GFRP Wind Turbine Blades: Evaluating the Sustainability and Economic Potential of Recycled Fibers. *Developments in the Built Environment* **2025**, *23*, 100710, DOI:10.1016/j.dibe.2025.100710.

[16] Upadhyayula, V.K.K.; Gadhamshetty, V.; Athanassiadis, D.; Tysklind, M.; Meng, F.; Pan, Q.; Cullen, J.M.; Yacout, D.M.M. Wind Turbine Blades Using Recycled Carbon Fibers: An Environmental Assessment. *Environ. Sci. Technol.* **2022**, *56*, 1267–1277, DOI:10.1021/acs.est.1c05462.

[17] Bulińska, S.; Sujak, A.; Pyzalski, M. From Waste to Renewables: Challenges and Opportunities in Recycling Glass Fibre Composite Products from Wind Turbine Blades for Sustainable Cement Production. *Sustainability* **2024**, *16*, 5150, doi:10.3390/su16125150.

[18] Beauson, J.; Madsen, B.; Toncelli, C.; Brøndsted, P.; Ilsted Bech, J. Recycling of Shredded Composites from Wind Turbine Blades in New Thermoset Polymer Composites. *Compos. Part A Appl. Sci. Manuf.* **2016**, *90*, 390–399, DOI:10.1016/j.compositesa.2016.07.009.

[19] Thippanna, V.; Ramanathan, A.; Ravichandran, D.; Chavali, A.; Sundaravadivelan, B.; Kumar, A.S.; Patil, D.; Zhu, Y.; Buch, R.; Al-Ejji, M.; et al. Coaxial Layered Fiber Spinning for Wind Turbine Blade Recycling. *ACS Sustain. Chem. Eng.* **2024**, *12*, 3243–3255, DOI:10.1021/acssuschemeng.3c07484.

[20] Ginder, R.S.; Ozcan, S. Recycling of Commercial E-Glass Reinforced Thermoset Composites via Two Temperature Step Pyrolysis to Improve Recovered Fiber Tensile Strength and Failure Strain. *Recycling* **2019**, *4*, 24, DOI:10.3390/recycling4020024.

[21] Tao, Y.; Hadigheh, S.; Wei, Y. Recycling of Glass Fibre Reinforced Polymer (GFRP) Composite Wastes in Concrete: A Critical Review and Cost Benefit Analysis. *Structures* **2023**, DOI:10.1016/j.istruc.2023.05.018.

[22] Mamanpush, S.H.; Li, H.; Englund, K.; Tabatabaei, A.T. Recycled Wind Turbine Blades as a Feedstock for Second Generation Composites. *Waste management* **2018**, *76*, 708–714, DOI:10.1016/j.wasman.2018.02.050.

[23] Thippanna, V.; Sun, X.; Sobczak, M.; Ramanathan, A.; Theobald, T.; Doran, I.; Were, J.; Yang, L.; Jaraczewski, J.; Casey, J.; et al. Turbine-to-Textile: Upcycling Wind

Turbine Blade Waste into High-Performance PAN Composite Fibers. *ACS Appl. Polym. Mater.* **2025**, *7*, 14188–14200, DOI:10.1021/acsapm.5c02466.

[24] Rudawska, A. Mechanical Properties of Selected Epoxy Adhesive and Adhesive Joints of Steel Sheets. *Applied Mechanics* **2021**, *2*, 108–126, DOI:10.3390/applmech2010007.

[25] Jayaseelan, C.; Padmanabhan, P.; Athijayamani, A.; Ramanathan, K. Comparative Investigation of Mechanical Properties of Epoxy Composites Reinforced with Short Fibers, Macro Particles, and Micro Particles. *BioRes* **2017**, *12(2)*, 2864–2871.

[26] Tavadi, Ashokkumar.R.; Basheer, D.; Melese, K.G.; Kumaresan, K.; Mohan, N.; Kerur, M.R.H.; Shashidhara, L.C. Experimental Analysis of Mechanical Properties and FTIR Analysis of Areca Fiber-Reinforced Epoxy Composites Incorporating Al2O3. *Journal of Industrial Textiles* **2025**, *55*, DOI:10.1177/15280837241313217.

[27] Sathish, T.; Mohanavel, V.; Raja, T.; Djearamane, S.; Velmurugan, P.; Nasif, O.; Alfarraj, S.; Wong, L.S.; Manikandan, V.; Ravichandran, M. Influence of Compression Molding Process Parameters in Mechanical and Tribological Behavior of Hybrid Polymer Matrix Composites. *Polymers (Basel).* **2021**, *13*, 4195, DOI:10.3390/polym13234195.

[28] Shen, R.; Liu, T.; Liu, H.; Zou, X.; Gong, Y.; Guo, H. An Enhanced Vacuum-Assisted Resin Transfer Molding Process and Its Pressure Effect on Resin Infusion Behavior and Composite Material Performance. *Polymers (Basel).* **2024**, *16*, 1386, DOI:10.3390/polym16101386.

[29] Uflyand, I.E.; Irzhak, T.F.; Irzhak, V.I. Formation of Fiber Composites with an Epoxy Matrix: State-of-the-Art and Future Development. *Materials and Manufacturing Processes* **2022**, *37*, 723–747, DOI:10.1080/10426914.2021.2016820.

[30] Zhang, J.Q. Study on the Influence of Different Pressurization Times on the Mechanical Properties of Carbon Fiber Reinforced Epoxy Resin Composite Materials. *Key Eng. Mater.* **2025**, *1013*, 9–14, DOI:10.4028/p-E4rfvn.

[31] Cinar, K.; Parasiz, S.A.; Akbulut, M.; Eruslu, S.O. An Experimental and Numerical Investigation of Particle Morphology Effect on the Elasto-Plastic Behavior of Particle-Filled Composites. *Fibers and Polymers* **2022**, *23*, 2694–2711, doi:10.1007/s12221-022-4382-y.

[32] Wu, Q.; Xu, W.; Zhang, L. Microstructure-Based Modelling of Fracture of Particulate Reinforced Metal Matrix Composites. *Compos. B Eng.* **2019**, *163*, 384–392, DOI:10.1016/j.compositesb.2018.12.099.

[33] Kuan, H.T.N.; Tan, M.Y.; Shen, Y.; Yahya, Mohd.Y. Mechanical Properties of Particulate Organic Natural Filler-Reinforced Polymer Composite: A Review. *Composites and Advanced Materials* **2021**, *30*, DOI:10.1177/26349833211007502.

[34] Fu, S.-Y.; Feng, X.-Q.; Lauke, B.; Mai, Y.-W. Effects of Particle Size, Particle/Matrix Interface Adhesion and Particle Loading on Mechanical Properties of Particulate–Polymer Composites. *Compos. B Eng.* **2008**, *39*, 933–961, DOI:10.1016/j.compositesb.2008.01.002.

[35] Lauke, B. Contribution of Matrix Yielding Energy to the Crack Resistance of Particle Reinforced Composites. *Compos. Sci. Technol.* **2013**, *86*, 135–141, DOI:10.1016/j.compscitech.2013.07.004.

[36] Mohammed, R.; Badruddin, I.A.; Shaik, A.S.; Kamangar, S.; Khan, A.A. Experimental Investigation on Mechanical Characterization of Epoxy-E-Glass Fiber-Particulate Reinforced Hybrid Composites. *ACS Omega* **2024**, *9*, 24761–24773, DOI:10.1021/acsomega.4c01365.

[37] Siraj, S.; Al-Marzouqi, A.H.; Iqbal, M.Z.; Ahmed, W. Impact of Micro Silica Filler Particle Size on Mechanical Properties of Polymeric Based Composite Material. *Polymers (Basel).* **2022**, *14*, 4830, DOI:10.3390/polym14224830.

[38] Muna Noori Ismael; Hazim F. Hassan Mechanical Behaviour of Polymer Matrix Composite Reinforced by Silicon Carbide Particles. *Journal of Techniques* **2023**, *5*, 108–113, DOI:10.51173/jt.v5i2.949.

[39] Ulay, G.; Koyuncu, M. Effect of Micronised Pumice Powder Addition on Shore-D Hardness Values of Medium Density Fiber Epoxy Composite. *Journal of Novel Engineering Science and Technology* **2024**, *3*, 38–40, DOI:10.56741/jnest.v3i02.531.