


Sustainable hybrid composites for wind turbine blades: Mechanical and environmental perspectives

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ABSTRACT

This study presents the results of an investigation into hybrid polymer composites with an epoxy matrix reinforced with glass and jute fibres, evaluated for potential application in wind turbine blades. The objective of the study was to combine the high mechanical strength of glass fibres with the flexibility and environmental advantages of natural fibres. Three types of laminated composites were fabricated: a glass fibre–reinforced composite, a natural fibre–reinforced composite (jute), and a hybrid laminate with a glass–jute–glass stacking sequence. Mechanical testing was conducted in accordance with ISO 527-4 and ISO 148-1 standards. The results indicated that the glass fibre composite exhibited the highest tensile strength (390 MPa). Jute fibre composite demonstrated the greatest elongation at break (about 4%), although with lower tensile strength (198 MPa). Hybrid laminate demonstrated intermediate mechanical properties, achieving a tensile strength of 240 MPa, an elongation at break of about 3.4%, and an impact strength of 9.6 J/cm². The results indicate that hybridization of the reinforcing materials improves energy dissipation and delays the onset of failure, thereby enhancing resistance to dynamic load. These findings suggest that hybrid glass–jute composites may be a promising material solution for blades of small wind turbines, combining mechanical performance with improved environmental sustainability.

Keywords: mechanical properties, natural fiber, fiber composite, wind turbine blades

INTRODUCTION

The dynamic development of wind energy requires the search for materials characterized by high mechanical strength and low weight. Polymer composites represent a response to these demands and in the recent years, these materials have become one of the most important areas of scientific and technological research due to the fact that they exhibit a more favourable strength-to-weight ratio than conventional materials used in structural applications.

However, with the increasing production of these materials, the problem of waste

management has emerged. It is estimated that more than 40,000 tonnes of wind turbine blades per year will require recycling after 2030 [1]. The lack of efficient fibre recovery technologies and the difficulty of phase separation limit the widespread adoption of hybrid materials. Therefore, it is crucial to design composite structures with end-of-life considerations in mind (Design for Recycling, DfR). Traditional polymer composites reinforced with glass or carbon fibres, although providing high strength and low weight, are difficult to recycle, which constitutes a significant environmental challenge [1, 2]. In response to these issues, hybrid composites

receive increasing attention [3–5] and modeling methods for natural fiber-reinforced composites [6], what may provide a compromise between mechanical performance and environmental sustainability.

Further research efforts focus on the development of hybrid materials incorporating recycled fractions in order to facilitate waste utilization. For example, Mahalingam, Veeramani, and Shanmugam [7] investigated the use of abrasive particles originating from machining processes in the production of hybrid laminates based on epoxy composites reinforced with natural kenaf fibres. In their study, the influence of recycled filler (worn abrasive particles) on the flexural, tensile, and impact properties of hybrid polymer composite laminates was examined. The results confirmed an improvement in the mechanical properties of hybrid composites containing recycled abrasive particles compared with epoxy laminates reinforced solely with natural kenaf fibres.

Studies conducted by Jagadeesh Chandra and co-authors [8] were also reviewed. Their research focuses on the utilization of sawdust as a reinforcing filler in polymer matrices. The authors compared hybrid sawdust-based composites with other hybrid composites reinforced with natural fibres. They discussed the applications of hybrid composites, highlighting manufacturing methods, morphology, and preparation techniques. The study emphasized the added value of composites produced through the transformation of wood waste, demonstrating their potential contribution to circular material economy models. In another work by Chandra [8], the key characteristics and challenges related to the design of hybrid polymer materials for electromagnetic interference (EMI) shielding applications were also described. The study characterized particle-reinforced composites, multilayer polymer composites reinforced with foil layers, foam-based polymer composites, and fabric-reinforced hybrid composites.

A review of hybrid polymer composites and their selected mechanical properties was conducted by Sinha and co-authors [9]. The authors evaluated the influence of factors such as the selection, distribution, type, and material of the reinforcement in polymer composites reinforced with natural fibres (ramie, manila, coconut, and bamboo) as well as fillers such as fly ash and red mud. Their analysis indicated that such

hybrid composites possess significant application potential; however, there is still a lack of research focused on modelling, modification, prediction, and optimization of their mechanical properties, particularly tensile strength, flexural strength, and impact resistance.

Hybrid composites combining synthetic fibres (glass, carbon, basalt, and aramid) with natural fibres (flax, hemp, jute, and kenaf) in polymer matrices enable the optimization of mechanical performance while simultaneously reducing environmental impact. As a result, these materials are gaining increasing importance in the design and manufacturing of wind turbine blades.

The literature [1, 2, 6, 10–12] also reports efforts aimed at developing appropriately designed laminate structures that allow for the reduction of structural weight, improvement of durability, and enhancement of environmental performance indicators.

Baharvand et al. [13] demonstrated that hybrid composites exhibit higher tensile strength, greater rigidity, and improved fatigue resistance compared with single-fibre composites. This conclusion is also supported by the findings reported in studies [14, 15]. Optimization of the laminate stacking sequence by placing fibres with higher elongation in the outer layers and more rigid fibres in the inner layers, can limit the propagation of microcracks and improve resistance to delamination [13, 16]. Furthermore, the addition of nanoparticles (e.g., carbon nanotubes or SiC) enables further improvement in impact resistance and enhances the structural integrity of the laminate [17–20]. These observations are particularly important because, under operational conditions, wind turbine blades are exposed to variable loads, bird strikes, hail impacts, and erosion. It has been demonstrated that composite hybridization increases resistance to mechanical damage and improves fatigue performance, which ultimately extends the service life of the structure [11,21]. The stacking sequence of laminate layers is also of considerable importance. The use of synthetic fibres in the outer layers can reduce moisture absorption and mitigate mechanical degradation in hydrothermal and marine environments [22–25].

Reduction of the environmental impact of materials also received increasing attention. Life cycle assessment (LCA) analyses indicate that hybrid turbine blades containing

recycled fibres may exhibit environmental performance indicators improved by as much as 12–89% compared with conventional designs [10, 12, 26]. The most promising approaches involve hybrid recycling methods, such as low-temperature pyrolysis combined with solvolysis, which enable the recovery of high-quality fibres while reducing energy consumption [27]. However, these methods do not allow for the complete recovery of fibres in their original form, and thermal processes may generate emissions and secondary waste. For this reason, increasing attention is being directed toward the design of composites that are easier to recycle, for example through the use of natural fibres and biodegradable matrices [24]. Natural fibres such as jute, flax, and hemp are renewable, biodegradable, and facilitate the mechanical or chemical separation of composite phases [4, 21]. The literature indicates that hybrid composites incorporating natural fibres may significantly improve the recyclability of large-scale structures, reducing both the carbon footprint and the amount of generated waste [28]. Therefore, the present study focuses on the fabrication of hybrid polymer composites containing glass fibres as a conventional reinforcing material and natural fibres (jute) as a component facilitating recycling. The composites were produced in the form of laminated structures with an epoxy matrix. Selected properties of hybrid composites with a glass–jute–glass reinforcement configuration were evaluated and compared with those of glass fibre–reinforced composites and jute fibre–reinforced composites.

FABRICATION OF LAMINATED COMPOSITES

Materials

For the fabrication of the composite materials, the following components were used: an epoxy system consisting of Gurit Ampreg™ 31 resin combined with Ampreg™ 3 Slow Hardener, forming a two-component system with a weight ratio of 100:30 (resin to hardener), was applied as the matrix material, while glass fibre fabric and jute fibre fabric were used as reinforcement materials. Both fabrics exhibited a plain weave structure, with areal densities of 390 g/cm² and 380 g/cm², respectively.

The applied glass fabric was characterized by E-glass fibres with a linear density of 204 tex and an areal weight of 390 [29]. The natural fabric (jute) had a plain weave (1/1) structure [30]. The fabrics used in the study are shown in Figure 1b.

Fabrication of laminates

The fabrication of laminated composites from glass and natural (jute) fabrics was carried out in four main stages: preparation of the reinforcing fabrics, preparation of the mold and lay-up, resin impregnation, and curing.

During the fabrication of the specimens, a standardized manufacturing protocol was strictly followed in order to ensure consistency and unification of all produced samples. The protocol primarily included strict control of the resin-to-hardener ratio, curing time and temperature, as well as the ambient temperature during processing. These parameters were maintained constant for

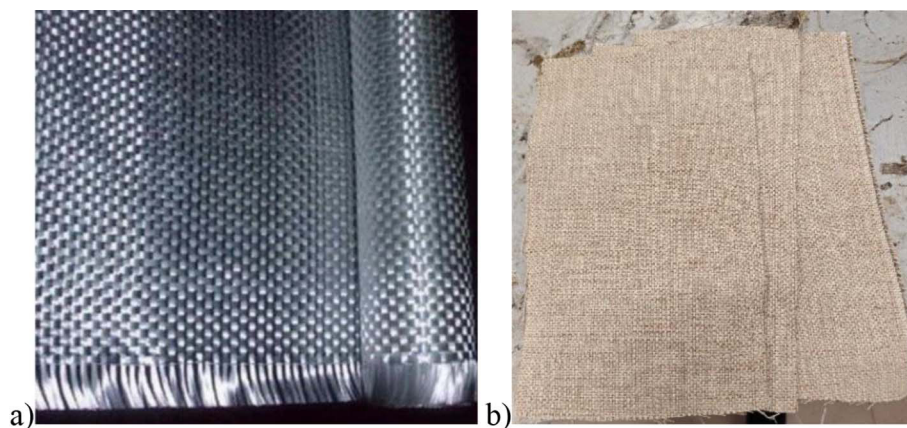


Figure 1. General view of fabrics used for the manufacturing of the hybrid composite: (a) glass fibre fabric, (b) natural fibre fabric (jute)

all specimens to minimize variability and ensure repeatability and reproducibility of the results.

Initially, raw materials were selected and subjected to quality control. A high-strength, chemically resistant glass fabric and a jute fabric, serving as a natural reinforcement, were employed. Both materials, supplied in rolls, were unrolled and inspected for mechanical damage. The fibre surfaces had been previously treated to improve adhesion to the epoxy matrix.

Next, the fabrics were cut into panels measuring 300×200 mm. Cutting was performed using technical shears to ensure uniform fibre length and minimize material waste. While cutting the glass fabric posed no particular difficulties, the jute fabric required careful handling due to the spiral arrangement of its fibres, in order to reduce edge fraying.

Subsequently, the fabric panels were dried in a chamber oven at a temperature of 70°C for 10 h. This step allows for the removal of moisture that could interfere with the impregnation process. This is particularly important in the case of jute, which is characterized by high moisture absorption.

At the same time, the technological mold was prepared. After cleaning, its surface was coated with a release agent. The fabric layers were then arranged in the mold according to the designed stacking sequence. In the glass composite, six layers of glass fibre fabric were used, while the natural composite consisted of six layers of jute fabric. In the hybrid composite, four layers of glass fibre fabric and two layers of jute fabric were applied in a glass–jute–glass sequence. Such a configuration enables improved mechanical and



Figure 2. Application of epoxy resin in the hybrid composite

environmental resistance while simultaneously reducing the structural weight [31,32].

The preparation of the matrix involved mixing the epoxy resin with a hardener at a mass ratio of 100:30, in accordance with the manufacturer's recommendations. The mixture was applied using a manual hand lay-up impregnation method (Figure 2), with particular attention given to the uniform distribution of the resin and complete coverage of the fibres. In the case of jute, it was important to control the absorption of the resin and to limit fibre swelling. During the impregnation process, successive layers were pressed to remove entrapped air and prevent the formation of air bubbles.

For each material configuration, six specimens were manufactured and tested for statistical evaluation. According to the relevant standards, a minimum of five specimens is required; however, an additional specimen was included to improve the reliability of the statistical analysis. This approach was particularly important due to the use of natural fibres, where the lack of controlled fibre orientation and inherent material variability may influence the uniformity of the mechanical response. Therefore, increasing the number of samples allowed for a more representative assessment of the material behaviour.

The final stage involved curing the laminate at a temperature of 23°C for a period of 7 days. This process enabled full polymerization of the resin, providing the composite with its final mechanical, chemical, and service properties.

Test specimens for composite materials were cut from the obtained laminate sheets (Figure 3) using waterjet cutting technology (Figure 4).

This process involves the use of a very high-pressure water jet enriched with an abrasive material, which increases the cutting capability for materials characterized by high hardness. Water pressurized to approximately 350 MPa is directed through a small-diameter nozzle (1.6 mm), enabling precise and rapid cutting of specimens with the required shapes and dimensions. The materials used in the study are characterized in Table 1.

Analysis of Table 1 indicates that the glass fibre composite exhibits the highest reinforcement weight fraction, amounting to 61%, which confirms the dominance of glass fibres in the structure. The average laminate thickness was 2.94 mm.

For the jute (natural) composite, the reinforcement weight fraction was 42%, indicating that the matrix constitutes the majority of the structure with a weight fraction of 58%. The

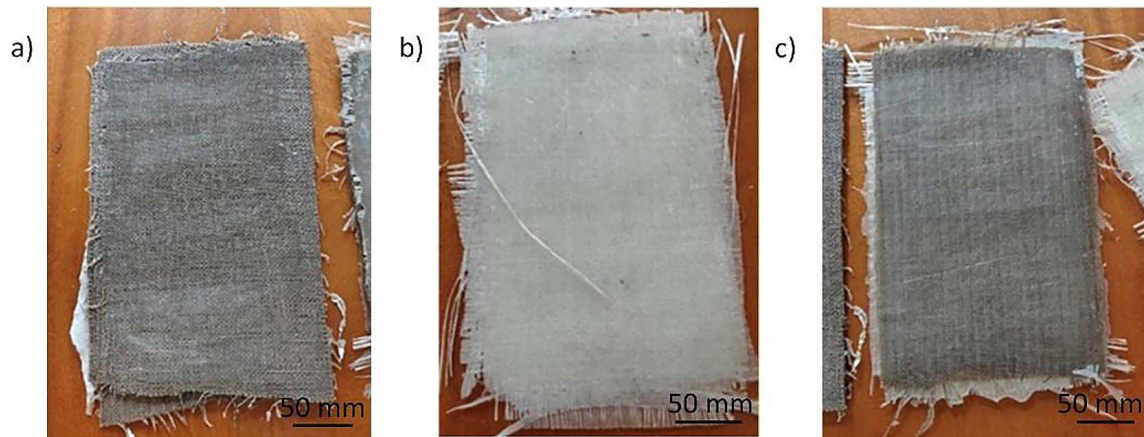


Figure 3. Composites: (a) natural, (b) glass fibre-reinforced, (c) hybrid

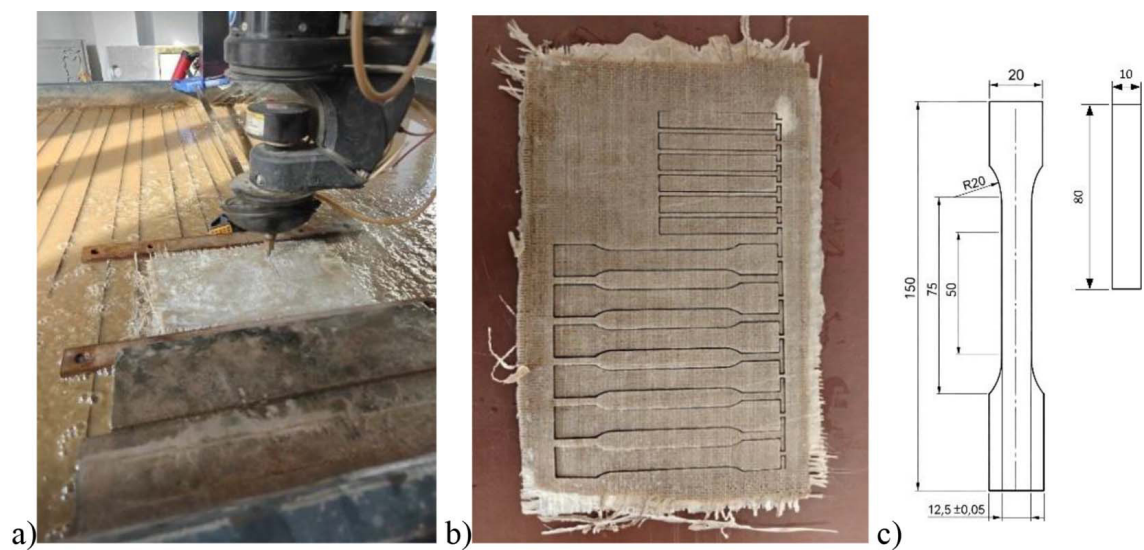


Figure 4. Preparation of test specimens: (a) waterjet cutting process; (b) specimens obtained from the hybrid composite; (c) dimension of physical sample

Table 1. Characteristics of the tested composite materials

Material	Matrix	Reinforcement	Reinforcement weight fraction (%)	Matrix weight fraction (%)	Laminate thickness (mm)
Glass composite	Epoxy resin	Glass fabric x 6	61	39	2.94 ± 0.26
Jute/natural composite	Epoxy resin	Jute fabric x6	42	58	7.01 ± 0.18
Hybrid composite	Epoxy resin	Glass fabric x2, jute fabric x2, glass fabric x2	54	46	3.93 ± 0.39

average laminate thickness, 7.01 mm, is greater than that of the glass fibre composite, which can be attributed to the higher volume and porosity of the jute fabric.

The hybrid composite, with a stacking sequence consisting of two layers of glass fabric, two layers of jute fabric, and two additional layers

of glass fabric, exhibits a reinforcement weight fraction of 54%, which is intermediate between that of the glass fibre and jute fibre composites. The average laminate thickness is 3.93 mm, also falling between the values of the other composites. This layer configuration is expected to provide a combination of high mechanical strength

provided by the glass fibres, and the elasticity and damping capacity characteristic of jute fibres.

EXPERIMENTAL METHODOLOGY

The methodology adopted in this study was designed to comprehensively evaluate the mechanical performance of fiber-reinforced composite materials under both static and dynamic loading conditions. To achieve this, two complementary experimental approaches were employed: uniaxial tensile testing of paddle-shaped specimens and impact testing using the Charpy method. The tensile tests enabled the determination of fundamental material properties, such as stiffness and load-carrying capacity under quasi-static conditions, while the Charpy impact tests provided insight into the energy absorption capability and damage tolerance of the composites under high strain-rate loading. Together, these methods allowed for a multidimensional characterization of the material behaviour, supporting a more complete assessment of their applicability in load-bearing and impact-resistant structures.

Tensile testing

Tensile properties of the investigated composite laminates were determined through uniaxial tensile testing carried out in accordance with ISO 527-4 (Figure 5). The tests were designed to obtain stress–strain characteristics, enabling the evaluation of the tensile modulus of elasticity. All

specimens were tested along the warp direction of the reinforcing fabric to capture the primary load-bearing response of the composites. Paddle-shaped specimens were prepared following the standard requirements, with a total length of 250 mm, a gauge section width of 25 mm, and a thickness corresponding to the laminate configuration. The gauge length for strain measurement was set to 50 mm using an extensometer. For each material variant, six specimens were tested to ensure repeatability and statistical relevance of the results.

The experiments were performed using a universal testing machine Cometech QC-50 equipped with a servo-driven actuator and computerized data acquisition system. The machine enables precise control of crosshead displacement within a wide range of loading speeds and provides high measurement accuracy of approximately $\pm 1\%$ within the operational range of the load cell. The applied force and displacement were recorded continuously with a high sampling frequency, allowing for accurate determination of stress–strain curves. The system was also equipped with safety features such as overload protection and automatic test termination upon specimen failure, ensuring reliable and repeatable test conditions.

Charpy impact testing

The impact resistance of the investigated composite materials was evaluated using the Charpy impact test in accordance with ISO 148-1 (Figure 6). The tests were performed to assess the energy absorption capability of the materials under

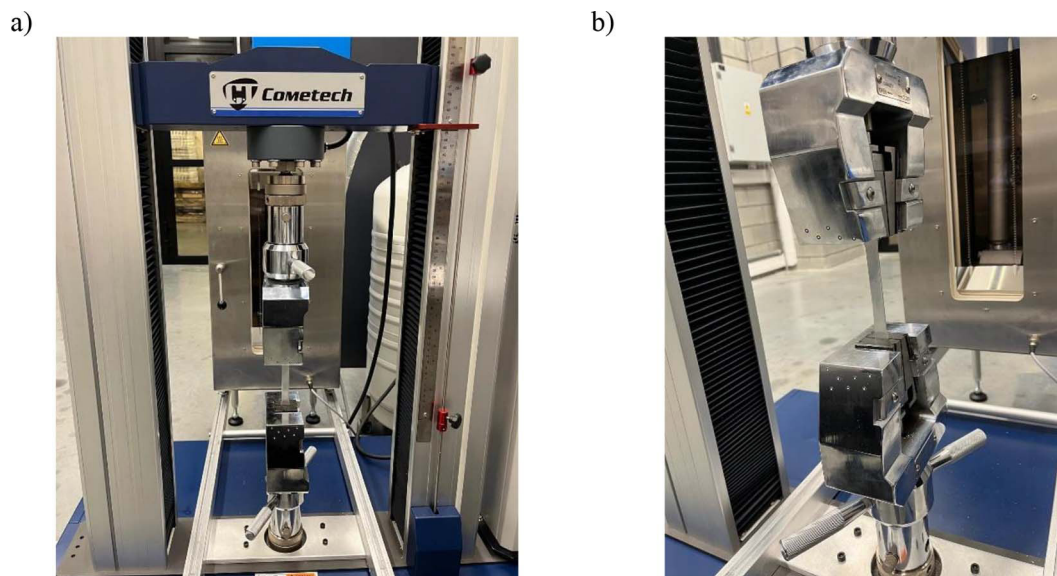


Figure 5. Uniaxial tensile machine: (a) general view, (b) specimen mount close-up

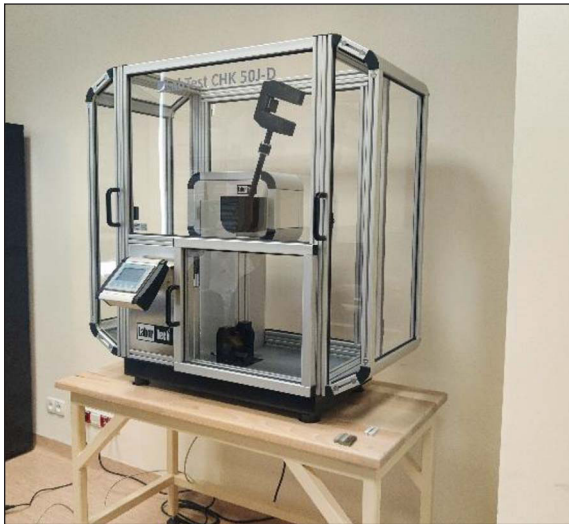


Figure 6. Impact testers LabTest CHK used for research

dynamic loading conditions. Rectangular specimens with dimensions of $80 \times 10 \times$ laminate thickness [mm] were prepared and tested without additional notching, reflecting the structural response of the laminates. For each material variant, six specimens were examined to ensure the reliability and repeatability of the results. The impact tests were carried out using a Charpy pendulum hammer, in which the absorbed energy was determined based on the difference between the initial and residual potential energy of the pendulum after fracture of the specimen. This approach enabled a comparative assessment of the toughness and failure behaviour of the analysed composite structures. The impact tests were carried out using a pendulum impact tester of the LabTest CHK series, designed for the determination of material resistance to dynamic loading conditions. The

system enables precise measurement of impact energy in the range up to 50 J, with high resolution and accuracy ensured by advanced measuring electronics and digital data acquisition. The impact velocity is maintained within a controlled range of approximately 2.9–3.8 m/s, allowing reproducible test conditions consistent with standardized procedures. The apparatus is characterized by a highly rigid frame construction, minimizing energy losses due to structural deformation and ensuring excellent repeatability of results.

RESULTS AND DISCUSSION

Figure 7 presents the tensile strength results of the tested composites, while Figure 7 shows the corresponding strain (elongation) of the composites.

Based on the results, the glass fibre composite exhibited the highest tensile strength, with an average value of approximately 390 MPa. This value was significantly higher than those of the other tested materials, indicating the dominant role of glass fibres in carrying mechanical loads. The hybrid composite showed a tensile strength of around 240 MPa, representing an intermediate value between the glass and natural composites. The lowest tensile strength was observed for the natural (jute) composite, with an average of 198 MPa, reflecting the limited ability of jute fibres to carry tensile loads.

Statistical analysis revealed significant tensile strength differences among the composites. The standard deviations, shown on the chart as error bars, indicate low variability within each material group, confirming the high repeatability of the measurements. The smallest deviation was

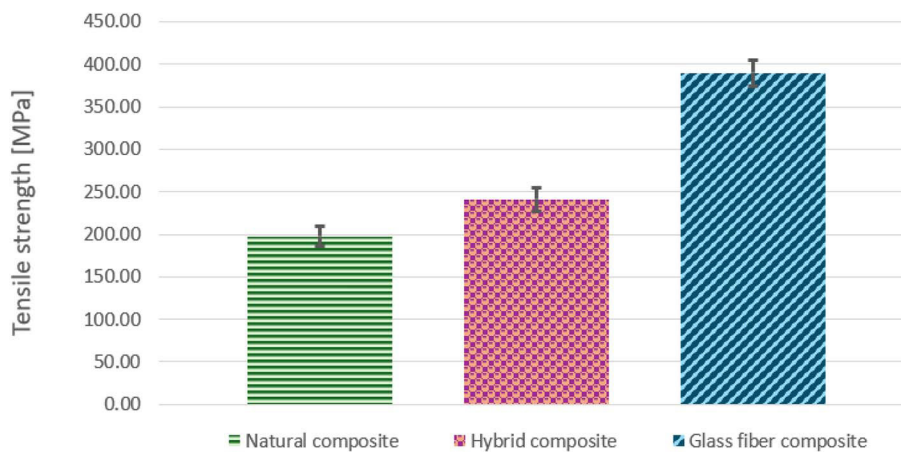


Figure 7. Tensile strength of the tested composites

observed for the glass fibre composite, suggesting a homogeneous structure and stable mechanical properties. For the hybrid composite, the deviation was slightly higher, which may result from variations in the distribution of glass and jute fibres within the material structure. The natural (jute) composite exhibited the highest standard deviation, likely due to greater heterogeneity of the jute fibres and their lower adhesion to the polymer matrix.

Based on the analysis of the results, the glass fibre composite exhibited the highest tensile strength (Figure 8), which can be attributed to the intrinsic properties of glass fibres, such as high rigidity and mechanical strength [33,34]. The hybrid composite, due to the combination of glass and natural fibres, demonstrated balanced properties, combining strength with elasticity. Although the natural (jute) composite exhibited considerable elasticity, it also showed the lowest tensile strength, which limits its applicability under conditions requiring high resistance to mechanical loads.

Based on the presented results, the natural (jute) composite exhibited the highest elongation, with an average value of approximately 4%. This value was significantly higher compared with the other tested materials, indicating the high elasticity of natural (jute) fibres and their ability to undergo deformation before failure. The hybrid composite showed an elongation of approximately 3%, representing an intermediate value between the natural and glass fibre composites. The lowest elongation at break was observed for the glass fibre composite, with an average value of about 2%, indicating its limited ability to undergo plastic deformation.

Statistical analysis revealed significant differences in elongation among the composites. The

standard deviations, shown on the chart as error bars, indicate low variability within each material group, confirming the high repeatability of the measurements. The smallest deviation was observed for the glass fibre composite, suggesting a homogeneous structure and stable mechanical properties. For the hybrid composite, the deviation was slightly higher, which may result from variations in the distribution of glass and jute fibres within the material structure. The natural (jute) composite exhibited the highest standard deviation, likely due to greater heterogeneity of the jute fibres and their variable adhesion to the polymer matrix.

Based on the analysis of the results, the natural (jute) composite exhibited the highest deformability, which can be attributed to the elasticity of the jute fibres. The hybrid composite, due to the combination of glass and natural fibres, demonstrated balanced properties, combining moderate elasticity with strength. The glass fibre composite, despite its high strength, showed the lowest elongation, limiting its ability to deform before failure.

Figure 9 presents representative stress–strain curves for the three types of composites: glass fibre (red), natural (jute) fibre (blue), and hybrid (green), confirming the above observations.

The stress–strain curve of the glass fibre composite indicates that high stress values are achieved at relatively low elongation. This means that the material is highly resistant to tensile forces, but its ability to undergo plastic deformation is limited. After reaching the maximum stress, the material fails abruptly, which is typical for materials with high rigidity and low elasticity. Such behaviour is characteristic of rigid materials that are less prone to deformation. Similar results have been reported in studies showing that placing glass fibres in the

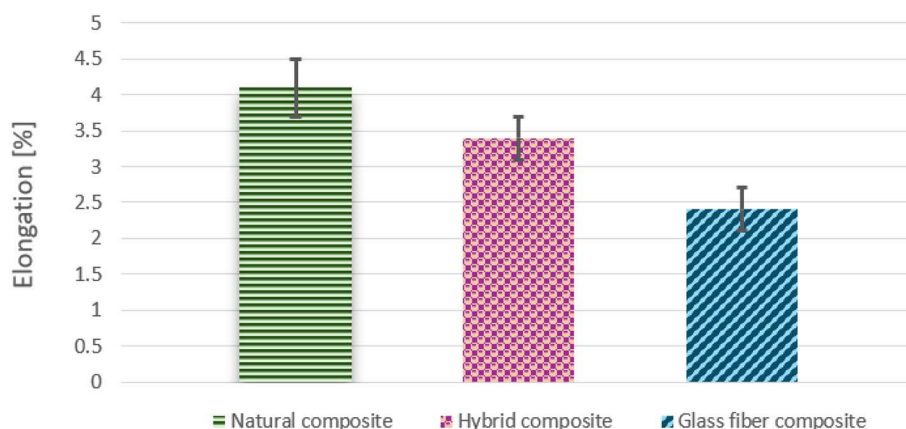


Figure 8. Elongation at break of the tested composites

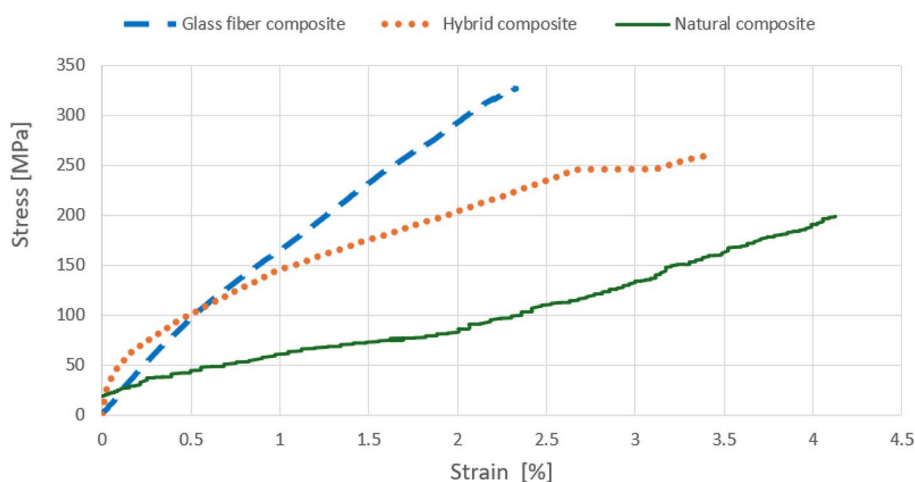


Figure 9. Stress–strain curves of all tested composites: glass fibre (blue), natural (jute) fibre (green), and hybrid (red)

outer layers of composites significantly enhances their mechanical strength [35,36].

The characteristics of the natural (jute) composite indicate its high elasticity and ability to undergo deformation before failure. However, the stress levels achieved by this composite were considerably lower compared to those of glass fibre composite, reflecting the lower tensile strength of the former. Natural fibres such as jute exhibit greater deformability, making the material more susceptible to elongation but less resistant to high mechanical loads. The natural composite can undergo significant deformation prior to failure due to the plastic deformability of jute fibres. These results are consistent with the literature, which reports that natural fibre composites demonstrate higher elasticity but lower strength compared to glass fibre composites [28,35].

The hybrid composite, consisting of two layers of glass fibre, two layers of jute, and two additional layers of glass fibre, exhibited intermediate properties between glass fibre and natural composites. Its tensile strength was about 31% higher than that of the natural composite, but approximately 20% lower than that of the glass fibre composite. The elongation of the hybrid composite was greater than that of the glass fibre composite, yet lower than that of the natural composite, indicating a balance of mechanical properties. The layer configuration, with glass fibres in the outer layers and natural fibres in the inner layers, enabled the combination of the advantages of both materials. As a result, the hybrid composite retained some of the elasticity characteristic of natural fibres, while simultaneously exhibiting higher tensile strength than the fully natural composite. The presence of

natural fibres in the hybrid structure enhances its elasticity, allowing for better stress distribution and delaying the onset of failure. Similar findings have been reported in studies showing that hybrid composites reinforced with glass and jute fibres combine the mechanical strength of glass fibres with the elasticity of natural fibres [28,35–38].

The failure mechanisms of the composites under tensile loading differ depending on the type of material. In the glass fibre composite, the dominant failure mechanism is fibre breakage. Glass fibres are characterized by high rigidity but low deformability. Cracks initiate at stress concentration points and then propagate through the material, leading to abrupt failure (Figure 10a). In the natural (jute) composite, failure begins with fibre deformation, as jute fibres are more compliant and capable of elongation. The fibres gradually stretch and then rupture, resulting in plastic deformation of the material. This process occurs over a longer time due to the higher elasticity of the natural fibres (Figure 10b). For the hybrid composite, the failure mechanism is a combination of the two processes described above. The glass fibres in the outer layers fracture at higher stress levels, while the jute fibres in the inner layers undergo deformation and gradual rupture. This layered arrangement allows partial stress absorption by the natural fibres, delaying total failure of the composite and providing more balanced mechanical properties (Figure 10c).

Following figure presents the results of the Charpy impact tests of the investigated composites. Based on the results presented in Figure 11, the highest impact strength was observed for the glass fibre composite, with an average value

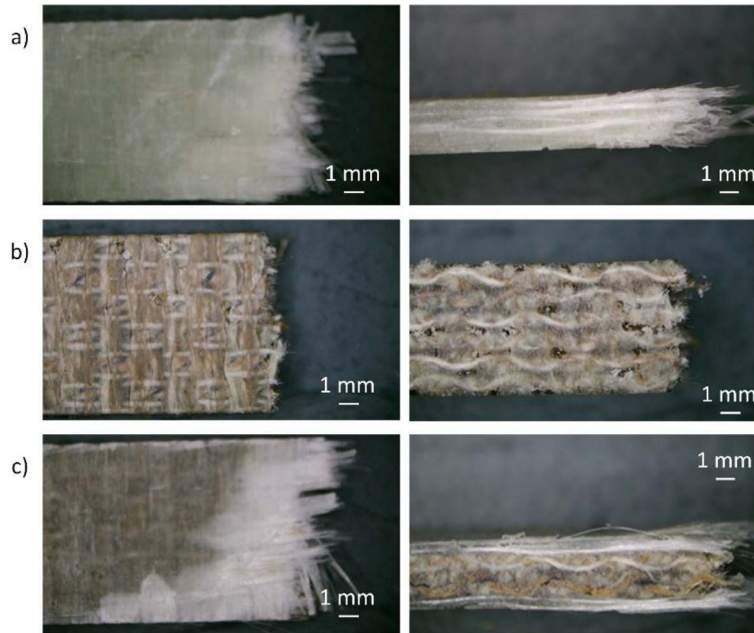


Figure 10. Fracture surfaces of the tested laminates: (a) glass fibre composite, (b) natural (jute) composite, (c) hybrid composite

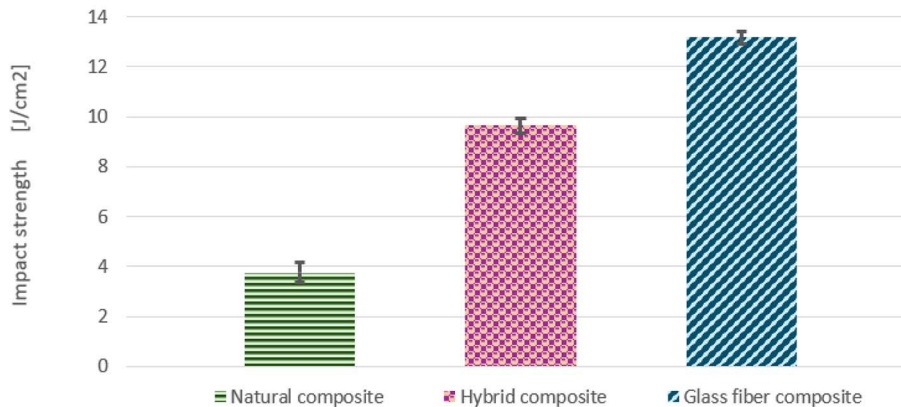


Figure 11. Impact strength of the tested composites

of 13 J/cm², indicating its greatest resistance to dynamic loading. This value was significantly higher compared to the other tested materials. The hybrid composite exhibited an impact strength of approximately 10 J/cm², representing an intermediate value between the glass and natural composites. The lowest impact strength was recorded for the natural (jute) composite, averaging 4 J/cm², reflecting its lowest resistance to dynamic loading.

The statistical analysis revealed significant differences in impact strength among the tested composites. The standard deviations, shown on the chart as error bars, indicate low variability within each material group, confirming the high repeatability of the measurements. The smallest deviation was observed for the glass fibre

composite, suggesting a homogeneous structure and stable mechanical properties. For the hybrid composite, the deviation was slightly higher, which may result from variations in the distribution of glass and jute fibres within the material structure. The natural (jute) composite exhibited the largest standard deviation, likely due to the greater heterogeneity of jute fibres and their lower adhesion to the polymer matrix.

The high impact strength of the glass fibre composite is attributed to the properties of the glass fibres, which exhibit high rigidity, mechanical strength, and resistance to brittle fracture. In this case, the failure mechanism primarily involves crack propagation in the polymer matrix, which is arrested by the glass fibres. These fibres

carry the dynamic loads, allowing for effective absorption of impact energy. A uniform fibre distribution within the laminate structure minimizes local stress concentrations, reducing the risk of crack initiation [35, 36].

The low impact strength of the natural (jute) composite is a result of limited mechanical strength of jute fibres and their lower rigidity as compared to glass fibres. The failure mechanism involves deformation of the jute fibres, which are more susceptible to plastic deformation, followed by fibre breakage. Additionally, poor adhesion between the jute fibres and the polymer matrix leads to delamination and weakening of the structure. The porous nature of the jute fibres and their uneven distribution within the matrix may facilitate crack initiation, contributing to faster material failure [28, 37]. Moreover, jute-reinforced laminates tend to develop higher porosity, further reducing the mechanical properties of this composite.

The hybrid composite exhibits a failure mechanism that combines processes characteristic of both glass and natural fibre composites. The glass fibres in the outer layers carry the dynamic loads, enhancing resistance to brittle fracture, while the jute fibres in the inner layers improve energy absorption due to their elasticity. The failure mechanism involves both crack propagation within the matrix and delamination between the glass and natural fibre layers. However, such layer arrangement allows for more effective dissipation of impact energy, reducing the risk of sudden material failure [36, 38].

Hybrid composites, consisting of glass and natural fibres, may find application in the construction of wind turbine blades due to their balanced mechanical properties. The high tensile strength of approximately 240 MPa, provided by the glass fibres, allows the material to withstand the substantial mechanical loads experienced during turbine operation. At the same time, the presence of natural fibres, such as jute, enhances the material's elasticity and likely its vibration-damping capacity, which is important under the dynamic loading conditions characteristic of wind turbine operation.

The thickness of the hybrid laminate, measuring 4 mm, along with a reinforcement mass fraction of 54%, indicates an optimal balance between mechanical strength and structural weight. The lower mass compared to pure glass fibre composites may contribute to reduced loads on bearings and other turbine

structural components, thereby enhancing the turbine's durability and operational efficiency.

Additionally, hybrid composites exhibit moderate resistance to dynamic loading, as evidenced by an impact strength of 9.6 J/cm². This property is crucial for wind turbine blades, which are exposed to impacts from solid particles such as dust, sand, or hail. The failure mechanism in hybrid composites, involving both crack propagation within the matrix and delamination, allows for gradual energy dissipation, thereby reducing the risk of sudden material failure.

The literature indicates that the use of hybrid composites in wind turbine structures can contribute to improvements in both efficiency and durability. Studies have shown that hybrid composites combining glass and natural fibres integrate the advantages of both materials, offering high mechanical strength, elasticity, and vibration-damping capacity [35, 36]. Moreover, the incorporation of natural fibres in hybrid composites may reduce production costs and enhance environmental sustainability, which is particularly relevant in the context of renewable energy development [28].

In addition to wind turbine applications, the proposed hybrid composites may be used in marine structures and renewable energy systems, where low weight, corrosion resistance, and sustainability are required. Furthermore, the potential for improved fire performance, particularly with the use of flame-retardant matrix systems, enhances their applicability in offshore and energy-related structures subject to strict safety regulations.

CONCLUSIONS

Hybrid polymer composites reinforced with glass and natural (jute) fibres exhibit intermediate properties compared to single-component composites, confirming their suitability for lightweight structural applications. The glass fibre composite shows the highest mechanical strength (390 MPa) and rigidity, making it suitable for applications requiring resistance to high mechanical loads.

The jute composite exhibits the greatest elasticity (elongation at break of about 4%), but its porosity and lower strength (198 MPa) limit its use in structures subjected to significant mechanical loads.

The hybrid composite combines the advantages of glass fibres (strength, rigidity) and jute fibres (lightweight, vibration damping), achieving

a tensile strength of 240 MPa and an elongation at break of around 3%.

The failure mechanisms of hybrid composites involve simultaneous fracture of glass fibres and gradual breaking of natural (jute) fibres, which enhances energy dissipation and delays material failure. The impact strength of the hybrid composite (10 J/cm²) indicates its improved resistance to dynamic loading compared to the glass fibre composite.

The results suggest that hybrid composites have potential applications in small wind turbine blades, where a combination of high strength and elasticity is required.

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