Enhancing Mechanical and Chemical Performance of Hybrid Polymer Composites: A Study on Oil Palm and Jute Fiber Reinforcement

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Enhancing Mechanical and Chemical Performance of Hybrid Polymer Composites: A Study on Oil Palm and Jute Fiber Reinforcement

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Abstract: This work investigates the production and analysis of tri-layer hybrid polymer composites that are strengthened by including oil palm empty fruit bunches (EFBS) and jute fibres. The composites were assessed for void content, tensile strength, and chemical resistance, with a specific emphasis on a 4:1 weight ratio of oil palm empty fruit bunches (EFBS) to jute fibres. An analysis was conducted on the optimized arrangement of fibres in terms of loading and stacking patterns. The findings indicated that the hybrid composites made of Jute-fiber/EFBS/Jute-fiber demonstrated higher tensile strength (28.72 MPa) and reduced void content (3.18%) in comparison to the hybrids composed of EFBS/Jute/EFBS. The results of the chemical resistance tests indicated that both hybrid composites performed better than pure fibres. Specifically, the Jute-fiber/EFBS/Jute-fiber composites exhibited a 5% to 30% enhancement in diverse chemical environments. The research highlights the potential of these hybrid composites in applications that need improved mechanical capabilities and chemical resistance, offering a sustainable alternative to polymer composite materials.

Keywords: Polymer composites; Hybrid composites; Oil palm fibres; Jute fibres; Mechanical characterization

1. Introduction

The increasing need for high-performance, ecologically sustainable materials has resulted in notable progress in composite materials technology[1)]. Historically, the emphasis was on synthetic fibres such as carbon and glass fibres, which provided enhanced strength, rigidity, and durability[2)]. Nonetheless, these materials possess drawbacks, such as elevated manufacturing expenses, non-biodegradability, and considerable environmental repercussions. The advancement of natural fiber-reinforced polymer composites (NFRPCs) accelerated, providing an environmentally sustainable option without compromising performance[3)]. Natural fibres including jute, flax, and oil palm have been thoroughly investigated in recent decades owing to their availability, low density[4)], biodegradability, and adequate mechanical qualities. Plant-derived fibres have surfaced as sustainable alternatives to conventional synthetic fibres in several applications, including building and automotive components[5)].

With the ongoing advancement of composite materials, hybrid polymer composites have become a significant focus of study. These materials amalgamate two or more fibre types—either synthetic and natural or two distinct natural fibers—into a singular matrix, leveraging the distinctive benefits of each fibre type[6)]. Hybrid composites are engineered to improve performance beyond the capabilities of single-fiber composites, often attaining a superior equilibrium among strength, flexibility, impact resistance, and thermal stability[7)].

In recent years, composites reinforced with oil palm and jute fibre have garnered significant interest. Oil palm fibres, obtained from the by-products of the palm oil industry, are acknowledged for their flexibility, thermal insulating properties, and fatigue resistance[8,9)]. Conversely, jute fibres are among the most extensively used natural fibres worldwide, recognized for their superior tensile strength, rigidity, and economic viability. When combined in a hybrid composite, these fibres provide a combination of attributes, yielding a material that is both mechanically strong and resistant to environmental and chemical deterioration[10)]. The need for hybrid composites, such as those including oil palm and jute fibres, stems from the constraints associated with using a single natural fibre. Jute fibre composites have significant tensile strength; yet, they may experience brittleness and limited elongation at break[11)]. Conversely, oil palm fibres have enhanced flexibility and elongation, although may not attain the tensile strength of jute. When systematically joined, these fibres may provide a hybrid composite with better mechanical characteristics, such as increased tensile strength, impact resistance, flexural strength, and chemical endurance[12)].

The advancement of these hybrid composites signifies a pivotal progression in the evolution of sustainable materials. The use of fibres such as oil palm and jute enhance the mechanical qualities of the composites while also reducing the environmental impact. Industries are pursuing environmentally friendly alternatives to conventional composites, and hybrids of oil palm and jute fibres provide a viable answer, applicable in automobile parts, building materials, and consumer products[13)]. Polymer composites are widely utilized in various products, such as golf clubs, jet skis, tennis rackets, aerospace components (including aircraft, missiles, and spacecraft), marine equipment, transportation systems, chemical apparatus, electrical and electronic devices, and storage tanks. Composites are intricate solid materials formed by amalgamating two or more constituents to enhance their qualities. Lightweight, high strength-to-weight ratio and rigid polymer composites have supplanted metals and wood as the materials of choice[14)]. Fibres provide strength and stiffness, and the plastic matrix serves as an adhesive, resulting in structurally robust components. Natural fibre reinforcements for thermoplastics and thermosets are gaining prevalence. Natural fibres derived from renewable resources are more cost-effective to produce, lighter, stronger, stiffer, safer, and biodegradable. Hybrid composites, which integrate many fibres inside a single matrix, enhance the flexibility of fiber-reinforced composite materials by imparting characteristics independent of their constituents[15)]. Table 1 presents the different properties of the used fibers.

Natural fibres from renewable resources are cheaper to manufacture, lighter, stronger, stiffer, safer, and biodegradable. Hybrid composites combine many fibres in one matrix. This method increases the flexibility of fibre-reinforced composite materials by giving them properties unrelated to their components. In terms of both physical and mechanical properties, jute demonstrates superior performance compared to other natural fibres. Table 1 presents the different properties of used fibres.

Table 1. Properties of different fibres.

Material	**Density (g/cm^3)**	**Tensile Strength (MPa)**	**Modulus Elasticity (GPa)**	**Elongation (%)**
Jute Fibre	1.2	395-771	26.3	1.4-1.9
EFBS Fibre	0.6-1.52	246	2-8	7-15

Rao et al. explored different fiber ratios and found that a combination of 30% oil palm fiber and 10% jute fiber in an epoxy matrix resulted in a 32% increase in tensile strength compared to a single fiber-reinforced composite. This is primarily because oil palm fiber provides flexibility and toughness, while jute fiber contributes stiffness and load-bearing capability. In another significant study, Shah et al. highlighted that treating fibers with alkaline (NaOH) solution enhances the adhesion between the fibers and the matrix. Their research demonstrated a 20-35% improvement in tensile strength after alkali treatment due to the removal of hemicellulose and lignin, which results in better stress transfer from the matrix to the fibers[16)]. Padma Priya and colleagues studied epoxy laminates enhanced using discarded silk fabric for mechanical and chemical resistance. They also examined waste silk fabric/epoxy composites' impact strength, tensile strength, density, and weight reduction[17)]. Sidhesh Kumar and colleagues investigated the chemical durability of unsaturated polyester hybrid composites enhanced with kapok-glass fibres and kapok-sisal fabric fibres[18)]. They examined the compressive, chemical resistance, and thermal properties of polyester composites with kapok/sisal fabrics.

The current study analyses epoxy-based matrix tri-layer EFBS/Jute/EFBS hybrid fibre composite and Jute/EFBS/Jute hybrid fibre composite. The examination examines void content, tensile strength, and chemical resistance under various stacking patterns. Scanning electron microscopy examines composite fracture surfaces to study reinforcing fibre-matrix interaction.

2. Materials and methods

2.1. Materials

EFBS and Jute fibre mats (as shown in Fig. 1) were purchased from Laxmi Balaji Oil Private Limited, Andhra Pradesh, India. The Chimique Sol (Gujarat, India) supplied epoxy resin, mainly DGEBA, and epoxy hardener A062. Aldrich provided benzyl alcohol for dilution.

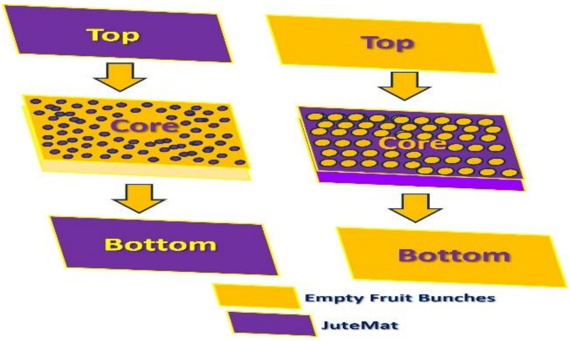

Fig. 1: Layers of Matrix and reinforcement material.

2.2. Fabrication Route

The composites were produced from oil palm EFBS and jute-chopped fibre matting as shown in Fig. 2. A 304 mm by 203 mm stainless-steel mould was employed with a thin silicone oil solution coating as a release agent. The composite was created by blending epoxy resin and polyamide with the addition of benzyl alcohol. The mixture was mechanically stirred for 15 minutes. In the mould, EFBS and jute fibre mats were layered and soaked with epoxy resin.

Figure 2 shows several steps involved in fabrication process of polymer composites. A control sample with an ordered epoxy matrix without fillers and composites with EFBS and jute fibres was made. ASTM criteria were followed to obtain composite samples for void content, tensile strength, and chemical resistance[19].

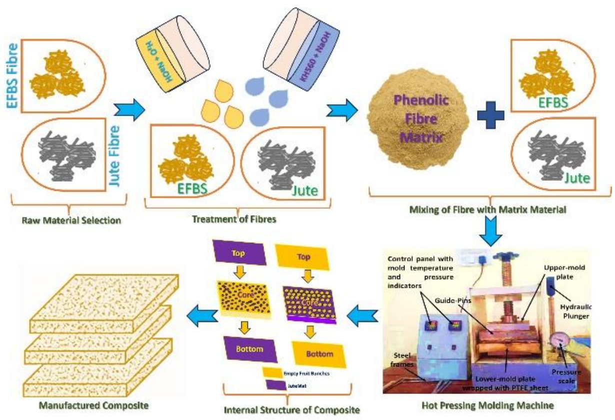

Fig. 2: Graphical representation for fabrication of polymer composites.

3. Composites Characterization

3.1 Void Content

Composite void content was assessed using ASTM D 2734-94[25]. Equation (2) factors in composites' theoretical and experimental densities to calculate void content

$$\text{Void Content (\%)} = \left(1 - \frac{\text{Experimental Density}}{\text{Theoretical Density}}\right) \times 100$$

This method helped calculate composite material air gap ratios. The predicted and experimental densities indicated the composite structure's void content, with a greater percentage indicating more voids.

3.2 Tensile Strength

The capacity of a substance to resist tugging or stretching without breaking. Tensile properties of both the matrix and composites, reinforced with EFBS/Jute/EFBS hybrid composite and Jute/EFBS/Jute fibres hybrid composite, were evaluated using an INSTRON 5582 Universal Testing Machine. The testing procedures adhered to the ASTM D 3039 standard[20]. Each circumstance was examined with five specimens, and the average findings were reported. This method helped analyse the materials' tensile strength, modulus, and other properties, revealing the composite's stress performance[21].

3.3 Chemical resistance

Hybrid composites, reinforced with EFBS/Jute/EFBS hybrid composite and Jute/EFBS/Jute fibres hybrid composite and utilizing epoxy resin, underwent chemical resistance testing according to ASTM D 543-87[22]. The study studied the effects of solvents like toluene, benzene, and carbon tetrachloride, acids like nitric acid and hydrochloric acid, and alkalies like NaOH, Na_2CO_3, and NH_4OH on matrix and hybrid composites[23-25].

$$\text{Percentage Weight Loss/Gain} = \left(\frac{\text{Final Weight} - \text{Initial Weight}}{\text{Initial Weight}}\right) \times 100$$

Five pre-weighed samples were in each chemical reagent for 24 hours. The samples were then extracted, washed with distilled water, and dried by pressing both sides with filter paper at room temperature[26]. Desiccated specimens were remeasured and the % weight change was determined. By measuring the % weight change after exposure to several chemical reagents, this method assessed composite materials' durability[27-29].

4. Results and discussions

4.1 Void Content

Composites' mechanical and physical properties are affected by voids, reducing performance. In the process of incorporating fibres into the matrix or producing fibre-reinforced composites, these empty spaces have the potential to harbour air or other volatile substances. If the matrix fails to extract all the air from the woven or chopped fibres during impregnation, voids commonly form. Table 2 shows composite samples with different stacking patterns' empty content percentages. Oil palm EFBS fibre composites contained 8.52 % voids compared to 2.65 % for jute fibre composites. The mismatch between the epoxy resin and the oil palm EFBS fibres may be traced to the fact that the two materials are incompatible with one another. Previous research conducted by a variety of researchers has shown that the creation of voids may occur when the matrix does not adequately moisten the fibres[30-32]. The porous nature and loose arrangement of oil palm EFBS fibres lead to the extrusion of resin from the mat during the moulding process. In the case of Jute/EFBS/Jute hybrid composites, positioning the EFBS fibre layer between two jute fibre skins reduces the exposure of oil palm fibres. The denser and more compatible nature of jute fibre mats with epoxy resin contributes to Jute-fibre/EFBS/Jute-fibre hybrid composites having fewer voids compared to EFBS/Jute/EFBS hybrid composites. Layer layout reduces vacant space and strengthens composite structure.

Table 2. Void (%) of different fabricated composites.

S.No.	Composites	Void (%)
1	Pure Jute	2.65
2	Pure EFBS	8.52
3	Jute/EFBS/Jute	3.18
4	EFBS/Jute/EFBS	4.86

4.2 Tensile Strength

Park and Jang found that hybrid laminated composites' mechanical properties depended on component arrangement. Research conducted by various researchers underscores the influence of hybrid composite fibre arrangement on tensile strength and modulus[33]. While studies on synthetic-natural fibre composites have been extensive for environmental considerations, hybrid composites with natural fibres are relatively recent. Research on the tensile strengths of hybrid composites made of sisal and another natural fibre, such as silk or banana, shows that this combination improves the mechanical qualities of the final product. Hybrid composites that use various fibres allow for one kind of fibre to substitute for the limits of another type of fibre, reaching an appropriate equilibrium between cost and performance via the design of the material.

Table 3. Tensile properties of different fabricated composites.

S. No.	Composites	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
1	Pure Jute	47.54	3.86
2	Pure EFBS	23.87	2.21
3	Epoxy	19.83	1.95
4	Jute/EFBS/Jute	28.49	2.48
5	EFBS/Jute/EFBS	26.25	2.36

Table 3 illustrates the tensile properties of EFBS/Jute-fiber/EFBS hybrid composites and Jute-fibre/EFBS/Jute-fibre hybrid composites, revealing that employing jute fibre as the matrix and oil palm EFBS fibre as the reinforcement enhances tensile properties of the fabricated composites. This supports the assumption that the skin, which supports the load in tensile measurements, should be strong. Due to the outer layer's low-strength EFBS fibre composite, the EFBS/Jute/EFBS hybrid composite has a lower tensile strength. Satish et al., Afzail et. al., and Omrani et. al. obtained comparable findings with sisal-banana composites[34–36]. Tensile strength data demonstrate that the pure jute fibre composite has the highest strength (45.55 MPa), indicating a strong bond between the fibre and epoxy matrix. However, the pure EFBS composite has a much lower tensile strength of 22.61 MPa, suggesting extensive porosity. Porosity in oil palm EFBS fibre composites may be due to air entrapment. The fiber-matrix interface, which affects mechanical properties, contributes to the tensile strength differences between the two pure composites.

Rahman et al. examined the effects of hybridization on the tensile and flexural properties of oil palm and jute fiber-reinforced epoxy composites. The study found that a hybrid combination of 30% oil palm fibers and 20% jute fibers increased the composite’s tensile strength by 28% compared to a jute-only composite. The flexural strength also saw a significant improvement of 24%, showing the synergistic effects of using two different natural fibers. The study emphasized that alkaline treatment of fibers played a crucial role in enhancing fiber-matrix adhesion, leading to improved stress transfer and mechanical performance[37]. Singh et al. further investigated fiber surface modification using silane coupling agents, which improved the interfacial bonding between the polymer matrix and fibers. This treatment resulted in a 35% increase in tensile strength and a 22% improvement in flexural modulus, demonstrating that chemical treatments could significantly enhance the performance of hybrid composites[38]. Verma and Singh investigated hybrid oil palm and jute composites for automotive applications. They found that a hybrid composite with 25% jute and 15% oil palm fibers exhibited a 40% improvement in impact resistance compared to single-fiber composites. This improvement was attributed to oil palm fibers' higher elongation at break, which absorbed more energy during impact. This makes such composites ideal for applications where energy absorption and toughness are critical[39].

4.3 Chemical resistance

In evaluating their chemical resistance, hybrid composites underwent exposure to various chemicals, aiming to assess their suitability for chemical-resistant applications. Table 4 outlines the weight changes, either in loss or gain, observed in epoxy, pure EFBS composite, pure jute, EFBS/Jute/EFBS hybrid composites, and Jute-fibre/EFBS/Jute-fibre reinforced hybrid composites when subjected to various pollutants.

Table 4. Chemical resistance of different composites under various chemicals.

Chemical	Pure Jute	Pure EFBS	Epoxy	Jute-/EFBS/ Jute	EFBS /Jute/ EFBS
CCl_4	0.325	5.09	0.368	3.697	1.82
HCl	0.125	15.98	1.926	10.12	7.58
NaOH	0.087	15.78	5.264	20.10	15.78
NH_4OH	0.305	20.98	4.026	13.39	3.96
Na_2CO_3	0.198	10.06	0.887	5.26	3.82
Benzene	0.415	8.265	0.492	3.46	3.34

The table provides insights into the chemical resistance characteristics of 100% EFBS reinforced with jute fibre composites. The results indicate an overall weight gain in all cases, suggesting that the composites did not experience weight loss and, consequently, did not undergo significant erosion. Notably, when oil palm EFBS fibre was utilized as the matrix material and jute fibre as reinforcement, the fabricated composites exhibited higher weight. This tendency was not always followed, indicating it is not universal. OH, groups in oil palm EFBS fibre cellulose may have increased hydrophilicity in certain circumstances. Compared to pure systems, tri-layered hybrid composites have better chemical resistance. This shows that adding jute fibre to polymers boosts chemical resistance. The matrix and composites were superior chemically resistant to all studied substances, indicating their potential usage in chemical-resistant applications.

Ahmad et al. conducted a comparative study on the chemical resistance of hybrid composites reinforced with oil palm and jute fibers. Their experiments exposed the composites to acidic (pH 4) and alkaline (pH 10) environments for 30 days. The hybrid composites exhibited a 25% higher resistance to acid attack compared to composites made with only jute fibers. The alkali resistance was improved by 30%, with hybrid composites retaining 88% of their tensile strength after prolonged exposure to basic environments. The researchers attributed this increased chemical stability to the denser fiber packing and enhanced matrix-fiber bonding in hybrid structures[40)]. Singh et al. focused on the role of fiber treatment in chemical resistance. By applying an alkaline and silane treatment to the fibers, the composite's resistance to acid and alkali solutions was significantly improved. After treatment, the hybrid composite retained 95% of its initial mechanical properties after 60 days of exposure to acidic environments, compared to just 75% for untreated fibers[41)].

5. Conclusions

In conclusion, the study investigated epoxy-based tri-layer composites reinforced with EFBS/Jute/EFBS hybrid composite and Jute/EFBS/Jute hybrid composite. The key findings and conclusions drawn from the research are as follows:

1. The use of natural fibres, such as jute and oil palm EFBS, in the composites aligns with environmental concerns, offering a sustainable alternative to synthetic fibres.
2. Hybridization with jute fibres significantly reduced the void content in the composites compared to Pure EFBS and EFBS/Jute/EFBS hybrid composites. The densely packed and epoxy resin-compatible nature of jute fibre mats contributed to this reduction.
3. Hybrid composite also demonstrated a lower void content of 3.18, signifying improved structural integrity and denser packing compared to EFBS/Jute-fiber/EFBS hybrid composites
4. The hybrid composites exhibited enhanced tensile strength and modulus, with the arrangement of jute fibres as the matrix material and oil palm EFBS fibres as the reinforcement.
5. Jute-fibre/EFBS/Jute-fibre hybrid composites exhibited the highest tensile strength at 28.72 MPa, indicating superior mechanical performance.
6. The hybrid composites demonstrated strong resistance to a variety of chemicals, including acids, alkalis, solvents, and pollutants. This indicates their potential for use in chemical-resistant applications.
7. Jute-fiber/EFBS/Jute-fiber hybrid composites outperformed EFBS/Jute-fiber/EFBS hybrid composites across different chemical conditions, showing an improvement ranging from 5% to 30%.
8. The study underscores the potential of these hybrid composites for applications requiring chemical resistance and superior mechanical properties.
9. The findings open avenues for further research in optimizing the layering patterns and exploring additional properties of hybrid composites for diverse applications.

6. Future Scope

Several areas of future research are critical for advancing the understanding and application of hybrid composites in the industry:

1. Investigating the long-term performance of these composites under various environmental conditions, including moisture absorption, UV exposure, and thermal cycling.
2. Further studies on the effects of different fiber ratios and stacking arrangements on mechanical properties and performance in specific applications.
3. Exploring the recyclability of these composites and their environmental impact at the end of their life cycle.
4. Conducting tests tailored to specific industries (e.g., automotive, construction) to evaluate the performance of these composites under real-world conditions.

5. Development of Hybrid Composites with Other Natural Fibers: Investigating the potential of combining EFBS and jute with other natural fibers to enhance properties and broaden application areas.

References

1) D. Kumar, S. Singh, and S. Angra, 'Morphology and corrosion behavior of stir-cast al6061- ceo 2 nanocomposite immersed in nacl and h 2 so 4 solutions', EVERGREEN, 10 (01) 94–104 (2023). doi:10.5109/6781054
2) S.A. Pardeep Kumar, Vipin Sharma, Dinesh Kumar, 'Morphology and mechanical behavior of friction stirred aluminum surface composite reinforced with graphene', EVERGREEN, 10 (01) 105–110 (2023). doi:10.5109/6781056
3) H. Kumar, V. Kumar, D. Kumar, and S. Singh, 'Wear behavior of friction stir processed copper-cerium oxide surface composites', EVERGREEN, 10 (01) 78–84 (2023). doi:10.5109/6781043
4) D. Kumar, S. Singh, and S. Angra, 'Dry sliding wear and microstructural behavior of stir-cast al6061-based composite reinforced with cerium oxide and graphene nanoplatelets', Wear, 516–517 (September 2022) 204615 (2023). doi:10.1016/j.wear.2022.204615.
5) N.M. Ramezani, and B. Davoodi, 'Evaluating the influence of various friction stir processing strategies on surface integrity of hybrid nanocomposite al6061', Scientific Reports, 1–15 (2024). doi:10.1038/s41598-024-58714-3.
6) M.P. Muthuraj, and K. Nithyapriya, 'Experimental studies on multicellular gfrp bridge deck panels under static and fatigue loading', Sadhana, 42 (12) 2171–2181 (2017). doi:10.1007/s12046-017-0747-0.
7) Nihad AlFuraiji, W. Atallah, and Syed Saad B Qasim, 'Evaluation of flexure strength of heat cure acrylic resin reinforcement with nano al2o3 after polishing with different abrasive materials', Journal of Techniques, 5 (2) 134–140 (2023). doi:10.51173/jt.v5i2.1358.
8) T.S. Sadagoapan, and P. Ravindran, 'A continuum model for predicting strain evolution in carbon fiber-reinforced composites subjected to cyclic loading', Sādhanā, 0123456789 (2022). doi:10.1007/s12046-021-01728-8.
9) P. Phani Prasanthi, K. Sivaji babu, and A. Eswar Kumar, 'Waviness effect of fiber on buckling behavior of sisal/carbon nanotube reinforced composites using experimental finite element method', International Journal of Engineering, Transactions B: Applications, 34 (12) 2617–2623 (2021). doi:10.5829/IJE.2021.34.12C.06.
10) Q.B. Nguyen, M.L. Sharon Nai, A.S. Nguyen, S. Seetharaman, E.W. Wai Leong, and M. Gupta, 'Synthesis and properties of light weight magnesium-cenosphere composite', Materials Science and Technology (United Kingdom), 32 (9) 923–929 (2016). doi:10.1080/02670836.2015.1104017.
11) W. Xu, S. Zhang, W. Liu, and Y. Yu, 'Highly tough 3d woven composite materials: fracture characterization and toughening mechanisms', Theoretical and Applied Fracture Mechanics, 124 (December 2022) 29–35 (2023). doi:10.1016/j.tafmec.2022.103734.
12) D.K. Rajak, D.D. Pagar, P.L. Menezes, and E. Linul, 'Fiber-reinforced polymer composites: manufacturing, properties, and applications', Polymers, 11 (10) (2019). doi:10.3390/polym11101667.
13) S. Singh, and S. Angra, 'Experimental evaluation of hygrothermal degradation of stainless steel fibre metal laminate', Engineering Science and Technology, an International Journal, 21 (1) 170–179 (2018). doi:10.1016/j.jestch.2018.01.002.
14) S. Gao, W. Hou, J. Xing, and L. Sang, 'Numerical and experimental investigation of flexural properties and damage behavior of cfrtp/al laminates with different stacking sequence', Applied Sciences (Switzerland), 13 (3) (2023). doi:10.3390/app13031667.
15) A.K. Sharma, R. Bhandari, A. Aherwar, and R. Rimašauskiene, 'Matrix materials used in composites: a comprehensive study', Materials Today: Proceedings, 21 1559–1562 (2020). doi:10.1016/j.matpr.2019.11.086.
16) P.C. Gope, 'Maximum tangential stress coupled with probabilistic aspect of fracture toughness of hybrid bio-composite', Engineering Science and Technology, an International Journal, 21 (2) 201–214 (2018). doi:10.1016/j.jestch.2018.03.008.
17) N.M. Siddesh Kumar, M. Sadashiva, J. Monica, and S. Praveen Kumar, 'Investigation on corrosion behaviour of hybrid aluminium metal matrix composite welded by friction stir welding', Materials Today: Proceedings, 52 2339–2344 (2021). doi:10.1016/j.matpr.2022.01.362.
18) S.P. Venkatesan, G. Muthuswamy, R. Shyam Sundar, S. Ganesan, and J. Hemanandh, 'Investigation of mechanical properties of aluminum metal matrix composites with nanomaterial reinforcement', Materials Today: Proceedings, 62 572–582 (2022). doi:10.1016/j.matpr.2022.03.594.
19) S. Singh, and S. Angra, 'Flexural and impact properties of stainless steel based glass fibre reinforced fibre metal laminate under hygrothermal conditioning', 31 (1) 164–172 (2018).
20) S.P. Dwivedi, S.P. Dwivedi, N.K. Maurya, and M. Maurya, 'Assessment of hardness on aa2014 / eggshell composite produced via electromagnetic stir casting method assessment of hardness on aa2014 / eggshell composite produced via electromagnetic stir casting method', EVERGREEN, 6 (4) 285–294 (2019). doi:10.5109/2547354

21) S. Kashyap, H. Tripathi, and N. Kumar, 'MECHANICAL properties of marble dust reinforced aluminum matrix structural composites fabricated', 48 (2) 282–288 (2022). doi:10.18149/MPM.4822022.
22) M. Mobin, R. Aslam, R. Salim, and S. Kaya, 'An investigation on the synthesis, characterization and anti-corrosion properties of choline based ionic liquids as novel and environmentally friendly inhibitors for mild steel corrosion in 5% hcl', Journal of Colloid and Interface Science, 620 293–312 (2022). doi:10.1016/j.jcis.2022.04.036.
23) E.O. Opare, E. Struhs, and A. Mirkouei, 'A comparative state-of-technology review and future directions for rare earth element separation', Renewable and Sustainable Energy Reviews, 143 (February) 110917 (2021). doi:10.1016/j.rser.2021.110917.
24) P.F. Tortorelli, and K. Natesan, 'Critical factors affecting the high-temperature corrosion performance of iron aluminides', Materials Science and Engineering: A, 258 (1–2) 115–125 (1998). doi:10.1016/S0921-5093(98)00924-1.
25) V.K.A. H.P.Khairnar, 'Experimental & analytical investigation for optimization of disc brake heat dissipation using cfd', EVERGREEN, 09 (04) 1076-1089 (2022). doi:10.5109/6625720
26) D. Choudhari, 'Characterization and analysis of mechanical properties of short carbon fiber reinforced polyamide66 composites characterization and analysis of mechanical properties of short carbon fiber reinforced polyamide66 composites', EVERGREEN, 8 (4) 768–776 (2021). doi:10.5109/4742120
27) S. Stankovich, D.A. Dikin, G.H.B. Dommett, K.M. Kohlhaas, E.J. Zimney, E.A. Stach, R.D. Piner, S.B.T. Nguyen, and R.S. Ruoff, 'Graphene-based composite materials', Nature, 442 (7100) 282–286 (2006). doi:10.1038/nature04969.
28) B. Radovan, F. Mária, K. Peter, and J. Füzer, 'Preparation and properties of fe-based composite materials', Proceedings of the World Powder Metallurgy Congress and Exhibition, World PM 2010, 5 (August 2017) (2010).
29) A.H. Abdalsalam, E. Şakar, K.M. Kaky, M.H.A. Mhareb, B. Ceviz Şakar, M.I. Sayyed, and A. Gürol, 'Investigation of gamma ray attenuation features of bismuth oxide nano powder reinforced high-density polyethylene matrix composites', Radiation Physics and Chemistry, 168 108537 (2020). doi:10.1016/j.radphyschem.2019.108537.
30) A.T. Abbas, A.J. Al-obaidi, and S.J. Ahmed, 'SYNTHESIS and study of the mechanical properties of biodegradable polyvinyl alcohol / eggshell composites', 16 (4) 3084–3093 (2021).
31) A. Kubit, 'The effect of adhesive type on strength of inter-layer joints in fiber metal laminate composites', Composites Theory and Practice, 17 (3) 162–168 (2017).
32) R.V.S. Manivannan, and P.S. V Vijayan, 'The investigation on newly developed of hydrophobic coating on cast az91d magnesium alloy under 3 . 5 wt % nacl solutions', Journal of Inorganic and Organometallic Polymers and Materials, 32 (4) 1246–1258 (2022). doi:10.1007/s10904-021-02174-z.
33) S. Sathish, K. Kumaresan, L. Prabhu, and N. Vigneshkumar, 'Experimental investigation on volume fraction of mechanical and physical properties of flax and bamboo fibers reinforced hybrid epoxy composites', Polymers and Polymer Composites, 25 (3) 229–236 (2017). doi:10.1177/096739111702500309.
34) M. Afzali, and V. Asghari, 'Analyzing mechanical behavior of abs-sio2 polymer-based nanocomposite based on anova method', Composites Theory and Practice, 2021 (3) 61–69 (2021).
35) E. Omrani, P.L. Menezes, and P.K. Rohatgi, 'State of the art on tribological behavior of polymer matrix composites reinforced with natural fibers in the green materials world', Engineering Science and Technology, an International Journal, 19 (2) 717–736 (2016). doi:10.1016/j.jestch.2015.10.007.
36) F.O. Edoziuno, C.C. Nwaeju, A.A. Adediran, B.U. Odoni, and V.R. Arun Prakash, 'Mechanical and microstructural characteristics of aluminium 6063 alloy/palm kernel shell composites for lightweight applications', Scientific African, 12 e00781 (2021). doi:10.1016/j.sciaf.2021.e00781.
37) D. Şimşek, D. Özyürek, and S. Salman, "Wear behaviors at different temperatures of zro2 reinforced a356 matrix composites produced by mechanical alloying method," Ind Lubr Tribol, 74 (5) 463–471 (2022). doi:10.1108/ILT-10-2021-0416.
38) S.P. Dwivedi, S.P. Dwivedi, N.K. Maurya, and M. Maurya, "Assessment of hardness on aa2014 / eggshell composite produced via electromagnetic stir casting method assessment of hardness on aa2014 / eggshell composite produced via electromagnetic stir casting method," **6** (*4*) 285–294 (2019).
39) S. Aribo, A. Fakorede, O. Ige, and P. Olubambi, "Erosion-corrosion behaviour of aluminum alloy 6063 hybrid composite," 377 608–614 (2017).
40) S. Banerjee, S. Poria, G. Sutradhar, and P. Sahoo, "Corrosion behavior of az31-wc nano-composites," J Magnes Alloy, 7 (4) 681–695 (2019). doi:10.1016/j.jma.2019.07.004.
41) M.O. Bodunrin, K.K. Alaneme, and S.J. Olusegun, "Influence of thermomechanical processing on the corrosion behaviour of aluminium (6063) -sic p composites in nacl and h 2 so 4 environment," 2 (2) 17–25 (2011).