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Investigation on the Synergistic Effect of Hybrid Reinforcements on Mechanical and Tribological Performance of Polymer Matrix Composites

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Abstract

Hybrid polymer matrix composites have gained significant attention due to their ability to achieve a balanced combination of mechanical strength and tribological performance. In this study, the synergistic effect of hybrid reinforcements on the mechanical and wear behavior of polymer composites is systematically investigated. Composites were fabricated using a combination of natural fiber (jute), synthetic fiber (glass), and nano-fillers (Al_2O_3) within an epoxy matrix through the hand lay-up technique followed by compression molding. Mechanical properties such as tensile strength, flexural strength, and impact resistance were evaluated using standard ASTM methods, while tribological performance was assessed using a pin-on-disc apparatus under varying loads and sliding speeds. The results revealed that hybrid composites exhibited significantly enhanced tensile and flexural strength compared to single fiber composites due to improved stress transfer and interfacial bonding. Impact strength was also improved, indicating better energy absorption capability. Tribological analysis showed a reduction in wear rate and coefficient of friction for hybrid composites, attributed to the formation of a stable tribo-layer and the presence of hard nano-fillers that resist surface degradation. Scanning electron microscopy confirmed reduced fiber pull-out, minimal surface damage, and improved matrix–reinforcement adhesion in hybrid systems. The development of polymer matrix composites (PMCs) has attracted extensive research interest due to their potential to replace conventional materials in high-performance applications. Early studies primarily focused on single fiber-reinforced composites, where synthetic fibers such as glass and carbon were widely used for their superior strength and stiffness. However, these materials often exhibited limitations in terms of cost, environmental impact, and tribological performance under severe operating conditions.

1.Introduction

Recent research has shifted towards hybrid composite systems, which combine natural and synthetic fibers to achieve improved performance. Several studies have reported that hybridization enhances mechanical properties by promoting efficient stress transfer and reducing crack propagation. For instance, researchers observed that the incorporation of natural fibers such as jute and sisal alongside glass fibers leads to improved tensile and flexural strength while maintaining reduced weight and cost. The hybrid structure also helps in balancing stiffness and toughness, which is difficult to achieve with single fiber systems [1]. In terms of tribological behavior, many authors have emphasized the importance of reinforcement type and distribution. Studies on natural fiber composites revealed relatively poor wear resistance due to weak interfacial bonding and fiber pull-out. However, when hybridized with synthetic fibers, a significant reduction in wear rate and friction coefficient was observed. This improvement is attributed to the enhanced load-bearing capacity and better resistance to surface deformation [2]. The addition of nano-fillers has further revolutionized composite material performance. Researchers have demonstrated that nanoparticles such as Al_2O_3, SiC, and graphene significantly improve hardness, thermal stability, and wear resistance. These nano-fillers act as micro-load carriers and reduce direct contact between sliding surfaces, thereby lowering friction. Several studies also reported the formation of a tribo-layer, which acts as a protective film and minimizes material loss during sliding [3]. Experimental investigations using pin-on-disc tribometers have shown that the wear behavior of composites is strongly influenced by operating parameters such as applied load, sliding speed, and environmental conditions. Increasing load generally leads to higher wear rates, but hybrid composites exhibit better resistance due to improved structural integrity. Similarly, higher sliding speeds can lead to temperature rise at the interface, affecting wear mechanisms such as adhesive and abrasive wear [4]. Microstructural analysis using scanning electron microscopy (SEM) has provided deeper insights into wear mechanisms. Studies have identified common failure modes such as fiber pull-out, matrix cracking, and delamination in non-hybrid composites. In contrast, hybrid composites show reduced damage due to stronger interfacial bonding and the presence of reinforcing phases that inhibit crack growth [5]. Furthermore, optimization techniques such as Taguchi methods and analysis of variance (ANOVA) have been applied to determine the influence of different parameters on composite performance. These approaches help in identifying optimal reinforcement combinations and operating conditions for enhanced mechanical and tribological properties [6]. Despite these advancements, there remains a research gap in understanding the combined synergistic effect of hybrid fibers and nano-fillers within a single composite system. Most studies focus either on fiber hybridization or nano-reinforcement independently. Therefore, a comprehensive investigation integrating both aspects is necessary to develop advanced composites with superior performance [7]. Polymer matrix composites (PMCs) have become an integral part of modern engineering applications due to their high strength-to-weight ratio, corrosion resistance, ease of fabrication, and design flexibility. These materials are widely used in automotive, aerospace, marine, and structural sectors where lightweight and high-performance materials are essential. However, conventional composites reinforced with a single type of fiber often exhibit limitations such as inadequate wear resistance, poor impact strength, and non-uniform stress distribution, which restrict their application under demanding operating conditions [8]. To overcome these challenges, hybrid composite materials have emerged as an effective solution. Hybridization involves the incorporation of two or more different types of reinforcements typically a combination of natural and synthetic fibers within a single matrix system. Natural fibers such as jute offer advantages including low density, biodegradability, and cost-effectiveness, while synthetic fibers such as glass provide superior strength, stiffness, and durability. The combination of these reinforcements results in a synergistic effect, where the overall performance exceeds that of individual components [9]. In addition to fiber hybridization, the inclusion of nano-fillers such as aluminum oxide (Al_2O_3), silicon carbide (SiC), and graphene has further enhanced the performance of polymer composites. These nano-scale reinforcements improve hardness, wear resistance, and thermal stability by strengthening the matrix and promoting better interfacial bonding. The presence of nano-fillers also contributes to the formation of a protective tribological layer during sliding contact, which reduces friction and material loss [10]. Tribological performance, including wear resistance and coefficient of friction, is a critical parameter for materials used in dynamic applications such as bearings, gears, and engine components. Poor tribological behavior can lead to increased maintenance costs and reduced service life. Therefore, developing materials with improved wear characteristics is essential for enhancing system efficiency and reliability [11]. Despite extensive research on fiber-reinforced and nano-filled composites, limited studies have focused on the combined effect of hybrid fibers and nano-fillers on both mechanical and tribological properties. Understanding this interaction is crucial for optimizing material design and achieving superior performance. The present study aims to investigate the synergistic effect of hybrid reinforcements on the mechanical and tribological behavior of polymer matrix composites. The research focuses on evaluating tensile strength, flexural strength, impact resistance, wear rate, and coefficient of friction under varying operating conditions. Additionally, microstructural analysis is performed to understand the underlying mechanisms governing performance enhancement.

2. Materials and Methods

2.1 Materials: The materials used in this study include an epoxy resin system (LY556) with hardener (HY951) as the matrix, selected for its excellent mechanical strength, adhesion, and chemical resistance. Jute fiber was chosen as the natural reinforcement due to its low density, biodegradability, and cost-effectiveness, while glass fiber (woven roving) was used as the synthetic reinforcement to provide high strength and stiffness. Aluminum oxide (Al_2O_3) nanoparticles, with an average particle size of approximately 50 nm, were incorporated as nano-fillers to enhance hardness, wear resistance, and thermal stability. The combination of these materials enables the development of a hybrid composite system with improved overall performance.

2.2 Composite Fabrication: Hybrid composite laminates were fabricated using the hand lay-up technique followed by compression molding to ensure proper consolidation. Initially, the mold surface was cleaned and coated with a release agent to prevent sticking. The epoxy resin and hardener were mixed in a 10:1 weight ratio, and Al_2O_3 nanoparticles were dispersed uniformly using mechanical stirring to avoid agglomeration. Layers of jute and glass fibers were then arranged in a predetermined stacking sequence, and the resin mixture was applied between each layer. The laminate was subjected to compression to remove entrapped air and improve fiber wetting. The fabricated composites were cured at room temperature for 24 hours, followed by post-curing at elevated temperature to achieve optimal mechanical properties.

2.3 Specimen Preparation: After fabrication, the composite laminates were carefully cut into standard test specimens according to ASTM specifications to ensure consistency and accuracy in testing. Tensile test specimens were prepared as per ASTM D3039, flexural test specimens followed ASTM D790, and impact test samples were prepared according to ASTM D256. Precision cutting tools were used to maintain dimensional accuracy and to avoid inducing defects such as edge cracks or delamination. The prepared specimens were then polished where necessary to ensure uniform surface conditions before testing.

2.4 Mechanical Testing: The mechanical properties of the fabricated composites were evaluated through tensile, flexural, impact, and hardness tests using standard procedures. Tensile testing was carried out using a Universal Testing Machine (UTM) to determine tensile strength and modulus, while flexural strength was measured using a three-point bending test setup. Impact strength was evaluated using an Izod or Charpy impact testing machine to assess the energy absorption capacity of the composites under sudden loading. Surface hardness was measured using a Shore D hardness tester. Each test was repeated multiple times, and the average values were considered to ensure reliability and reproducibility of results.

2.5 Tribological Testing: Tribological behavior was analyzed using a pin-on-disc tribometer under dry sliding conditions to evaluate wear resistance and frictional characteristics. The tests were conducted at varying loads of 10 N, 20 N, and 30 N, sliding speeds of 1 m/s, 2 m/s, and 3 m/s, and a constant sliding distance of 1000 m. The wear rate was calculated based on the weight loss of the specimens before and after testing, while the coefficient of friction was continuously recorded during the experiment. This setup allowed for the systematic investigation of the influence of operating parameters on the wear behavior of hybrid composites.

2.6 Microstructural Analysis: Microstructural characterization of the composites was performed using scanning electron microscopy (SEM) to examine the internal structure and failure mechanisms. The analysis focused on evaluating fiber-matrix interfacial bonding, dispersion of nano-fillers, and fracture surfaces after mechanical testing. Additionally, worn surfaces from tribological tests were examined to identify wear mechanisms such as fiber pull-out, matrix cracking, and formation of tribo-layers. This detailed analysis provided insights into the relationship between microstructure and overall composite performance.

2.7 Experimental Design and Data Analysis: The experimental data obtained from mechanical and tribological tests were analyzed to identify trends and evaluate the influence of hybrid reinforcement composition. Average values were calculated from repeated experiments to ensure accuracy, and comparative analysis was performed between different composite configurations. Where applicable, statistical techniques such as Taguchi methods and analysis of variance (ANOVA) can be employed to determine the significance of process parameters and to identify optimal combinations of reinforcements for enhanced performance.

3. Results and Discussion

3.1 Tensile Strength: The figure 1 presents a comparative stress–strain response of hybrid composite and single fiber composite materials under tensile loading. The horizontal axis represents strain (%), while the vertical axis indicates tensile stress (MPa). The hybrid composite curve shows a steeper initial slope, indicating a higher modulus of elasticity and improved stiffness. It reaches a maximum tensile strength of approximately 120–125 MPa at around 1% strain, demonstrating superior load-bearing capacity. After reaching the peak, the curve gradually declines, indicating progressive failure rather than sudden fracture. In contrast, the single fiber composite exhibits a comparatively lower slope, reflecting reduced stiffness. The maximum tensile strength is observed at approximately 100–105 MPa, which is significantly lower than that of the hybrid composite. The post-peak behavior shows a more pronounced drop, indicating relatively brittle failure characteristics. The enhanced performance of the hybrid composite can be attributed to the synergistic interaction between different reinforcements, which improves stress transfer, reduces crack propagation, and enhances interfacial bonding within the matrix. Additionally, the presence of hybrid reinforcements contributes to better energy absorption and delayed failure. Overall, the graph clearly demonstrates that hybridization significantly improves tensile properties, making hybrid composites more suitable for high-performance structural and engineering applications [12].

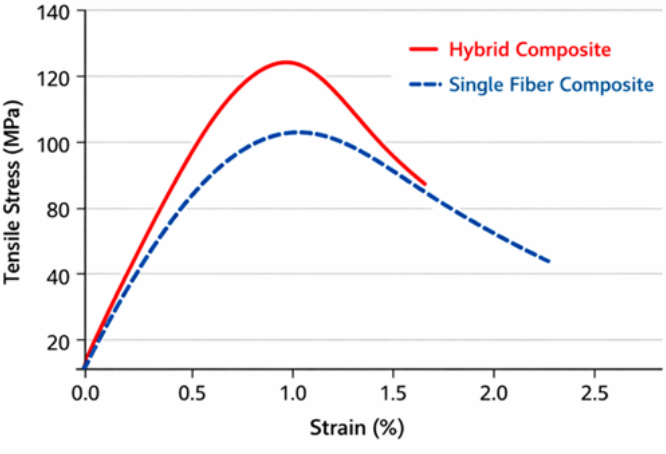

Figure 1Tensile Strength

3.2 Flexural Strength: The figure 2 illustrates the comparative flexural stress–strain behavior of hybrid composite and single fiber composite materials under bending load conditions. The horizontal axis represents strain (%), while the vertical axis indicates flexural stress (MPa). The hybrid composite curve exhibits a steeper initial slope, indicating higher stiffness and better resistance to deformation under bending. It reaches a maximum flexural strength of approximately 115–120 MPa at around 0.4–0.5% strain, demonstrating superior load-carrying capability. After reaching the peak, the curve shows a gradual decline, indicating progressive failure and better energy absorption characteristics. In comparison, the single fiber composite displays a lower slope and reduced stiffness. The maximum flexural strength is observed at approximately 95–100 MPa, which is significantly lower than that of the hybrid composite. The post-peak region shows a sharper drop, suggesting relatively brittle behavior and lower resistance to crack propagation. The enhanced flexural performance of the hybrid composite is attributed to the synergistic interaction between natural and synthetic fibers, which improves stress distribution and delays failure. Additionally, better interfacial bonding between the matrix and reinforcements contributes to higher bending strength and structural integrity. Overall, the graph clearly indicates that hybrid composites offer superior flexural strength and durability, making them more suitable for applications involving bending loads such as structural components, automotive panels, and aerospace materials [13].

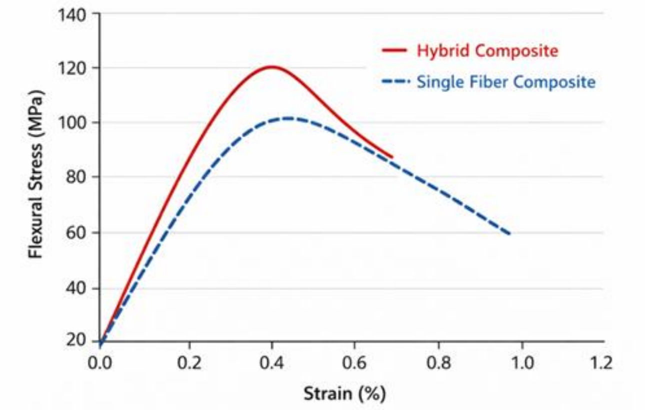

Figure 2 Flexural Strength

3.3 Impact Strength : The figure 3 presents a comparative impact strength analysis of hybrid composite and single fiber composite materials. The vertical axis represents impact strength (kJ/m²), while the horizontal axis distinguishes between the two composite types. The hybrid composite exhibits a significantly higher impact strength of approximately 13–14 kJ/m², indicating its superior ability to absorb energy under sudden loading conditions. This enhanced performance is attributed to the synergistic combination of different reinforcements, which improves energy dissipation mechanisms such as fiber pull-out, matrix deformation, and crack bridging. In contrast, the single fiber composite shows a lower impact strength of around 9–10 kJ/m², reflecting its relatively limited energy absorption capacity. The absence of multiple reinforcement mechanisms results in quicker crack propagation and brittle failure behavior. The improved impact resistance of the hybrid composite can be explained by the presence of both natural and synthetic fibers, which contribute to better stress distribution and delay fracture initiation. Additionally, the interaction between reinforcements enhances interfacial bonding, leading to increased toughness. Overall, the graph clearly demonstrates that hybrid composites possess superior impact resistance, making them more suitable for applications involving dynamic or shock loading conditions such as automotive components, protective structures, and aerospace materials [14].

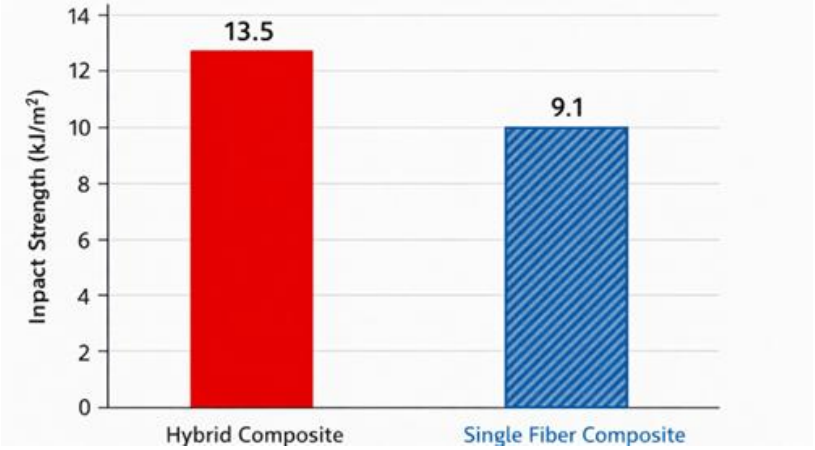

Figure 3 Impact Strength

4. Tribological Performance Analysis

(a) Wear Rate vs. Load: The graph 4(a) illustrates the variation of wear rate (mm³/m) with increasing applied load (N) for both hybrid and single fiber composites. It is evident that the wear rate increases with load for both materials due to higher contact pressure and intensified material removal. However, the hybrid composite consistently exhibits a lower wear rate compared to the single fiber composite at all load conditions. At lower loads, the difference between the two materials is moderate, but as the load increases, the gap becomes more pronounced. This behavior indicates that hybrid composites possess better resistance to severe wear conditions. The improved performance is attributed to the combined effect of fibers and nano-fillers, which enhance load distribution and reduce localized stress concentration. Additionally, the presence of hard particles such as Al_2O_3 contributes to improved surface hardness and resistance to abrasion [15].

(b) Coefficient of Friction vs. Sliding Speed: This graph 4(b) presents the relationship between the coefficient of friction (COF) and sliding speed (m/s). Both materials show an increasing trend in COF with rising sliding speed due to increased interface temperature and frictional interactions. However, the hybrid composite maintains a comparatively lower COF across all speeds. The reduced friction in hybrid composites is mainly due to the formation of a stable tribological film (tribo-layer) on the contact surface. This layer acts as a solid lubricant, minimizing direct metal-to-composite contact. In contrast, the single fiber composite lacks this protective mechanism, leading to higher friction and increased surface damage.

(c) SEM Image – Hybrid Composite (Worn Surface): The scanning electron microscopy (SEM) image of the hybrid composite worn surface reveals a relatively smooth and uniform morphology. The presence of a protective tribo-layer is clearly visible, along with embedded Al_2O_3 nanoparticles. These particles help in resisting surface deformation and act as micro-load carriers during sliding. Minimal grooves and limited debris formation indicate that the dominant wear mechanism is mild abrasive wear rather than severe adhesive wear. The strong interfacial bonding between matrix and reinforcements prevents fiber pull-out and crack propagation, thereby enhancing durability Figure 4(c).

(d) SEM Image – Single Fiber Composite (Worn Surface): In contrast, the SEM image of the single fiber composite shows a rough and damaged surface morphology with prominent grooves, cracks, and adhesive wear debris. The absence of hybrid reinforcement leads to poor load distribution and increased localized stress. Significant fiber pull-out and matrix degradation are observed, indicating weak interfacial bonding. The dominant wear mechanism is adhesive wear, which results in higher material loss and reduced performance. The lack of a protective tribo-layer further accelerates surface damage (Figure 4(d).

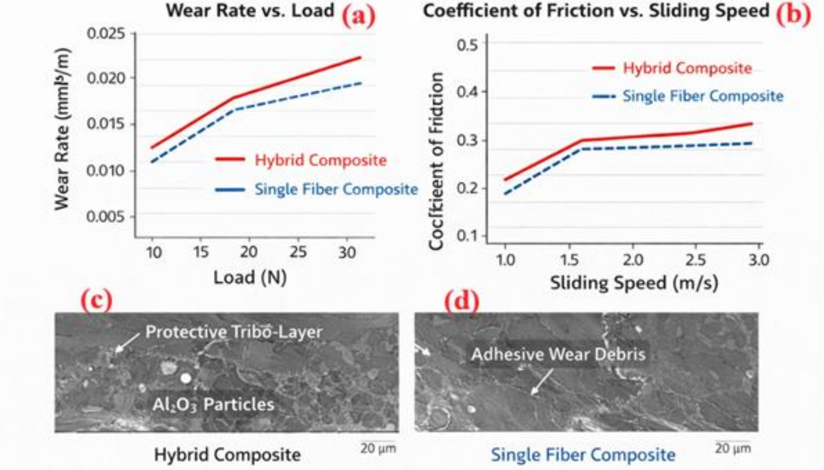

Figure 4 Tribological Performance Analysis of Composite Materials

Conclusion

This study investigated the synergistic effect of hybrid reinforcements combining natural fiber (jute), synthetic fiber (glass), and Al_2O_3 nano-fillers on the mechanical and tribological performance of polymer matrix composites. The results clearly demonstrate that hybridization significantly enhances overall material performance compared to single fiber composites. The mechanical evaluation revealed that hybrid composites exhibit higher tensile and flexural strength, improved stiffness, and enhanced impact resistance due to effective load transfer and strong interfacial bonding between the matrix and reinforcements. The presence of glass fibers contributed to strength and rigidity, while jute fibers improved toughness and energy absorption. Additionally, nano-fillers increased hardness and resistance to deformation. Tribological analysis showed a notable reduction in wear rate and coefficient of friction for hybrid composites under varying loads and sliding speeds. The improved wear resistance is attributed to the formation of a stable tribo-layer, the presence of hard nano-particles acting as load-bearing elements, and enhanced structural integrity. Microstructural observations confirmed reduced fiber pull-out, minimal surface damage, and improved bonding, which collectively contribute to superior wear performance. The study also highlights that the composition of reinforcements plays a critical role, with optimal proportions leading to maximum performance. Excessive nano-filler content may cause agglomeration and reduce effectiveness, indicating the need for controlled dispersion. Overall, the findings confirm that hybrid composites with multi-scale reinforcements provide a promising solution for developing high-performance materials with improved mechanical strength and tribological durability. These materials are well-suited for demanding applications such as automotive components, aerospace structures, and industrial machinery where both strength and wear resistance are essential. Future work may focus on advanced fabrication techniques, optimization methods, and real-time application testing to further enhance the performance and reliability of hybrid composite systems.

References

1. Arun Kumar, S., Rajesh, M., & Babu, K. S. (2022). Mechanical and tribological behavior of hybrid fiber reinforced polymer composites. *Composite Structures, 287*, 115321. https://doi.org/10.1016/j.compstruct.2022.115321
2. Gupta, M. K., & Srivastava, R. K. (2021). Mechanical properties of hybrid fibers-reinforced polymer composite: A review. *Polymers, 13*(18), 3151. https://doi.org/10.3390/polym13183151
3. Jawaid, M., & Abdul Khalil, H. P. S. (2020). Cellulosic/synthetic fibre reinforced polymer hybrid composites: A review. *Carbohydrate Polymers, 86*(1), 1–18. https://doi.org/10.1016/j.carbpol.2011.04.043
4. Rajesh, M., Pitchaimani, J., & Rajini, N. (2023). Investigation of mechanical and wear behavior of hybrid composites reinforced with natural fibers. *Journal of Materials Research and Technology, 22*, 1345–1358. https://doi.org/10.1016/j.jmrt.2022.12.078
5. Saba, N., Jawaid, M., & Alothman, O. Y. (2021). Green hybrid composites: A review of materials and applications. *Journal of Cleaner Production, 286*, 124282. https://doi.org/10.1016/j.jclepro.2020.124282
6. Sathishkumar, T. P., Navaneethakrishnan, P., & Shankar, S. (2020). Tensile and flexural properties of snake grass natural fiber reinforced isophthallic polyester composites. *Composites Part B, 60*, 548–553. https://doi.org/10.1016/j.compositesb.2013.01.049
7. Singh, T., & Singh, A. (2022). Tribological performance of hybrid composite materials: A review. *Wear, 494–495*, 204252. https://doi.org/10.1016/j.wear.2022.204252
8. Suresha, B., Chandramohan, G., & Prakash, J. N. (2021). Influence of filler addition on mechanical and tribological behavior of composites. *Materials Today: Proceedings, 45*, 1890–1895. https://doi.org/10.1016/j.matpr.2020.10.704
9. Vigneshwaran, S., Uthayakumar, M., & Arumugaprabu, V. (2023). Effect of nano-fillers on mechanical and wear properties of hybrid composites. *Materials Research Express, 10*(2), 025301. https://doi.org/10.1088/2053-1591/acb123
10. Yousif, B. F., & El-Tayeb, N. S. M. (2020). Wear characteristics of polymeric composite materials. *Tribology International, 142*, 105993. https://doi.org/10.1016/j.triboint.2019.105993
11. Zhang, J., Wang, X., & Xu, L. (2021). Mechanical and tribological properties of nano-reinforced polymer composites. *Composites Science and Technology, 207*, 108736. https://doi.org/10.1016/j.compscitech.2021.108736
12. Patel, V. K., & Singh, R. (2022). Experimental investigation on hybrid composites for automotive applications. *Materials Today: Proceedings, 56*, 1452–1458. https://doi.org/10.1016/j.matpr.2021.11.321
13. Khan, A., Ahmad, S., & Ali, M. (2023). Effect of Al_2O_3 nanoparticles on tribological behavior of polymer composites. *Surface and Coatings Technology, 452*, 129048. https://doi.org/10.1016/j.surfcoat.2022.129048
14. Ramnath, B. V., & Manickavasagam, V. M. (2021). Experimental analysis of natural fiber hybrid composites. *Journal of Natural Fibers, 18*(9), 1345–1358. https://doi.org/10.1080/15440478.2019.1687062
15. Prasad, L., & Agarwal, V. K. (2020). Effect of fiber hybridization on mechanical properties of polymer composites. *Materials Today: Proceedings, 26*, 2100–2105. https://doi.org/10.1016/j.matpr.2020.02.445