Impact of Hybrid Filler Contribution on Mechanical and Energy Absorption Behaviour of Polyamide-6 (Pa6) Composites

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**Abstract:** The mechanical and impact properties of Polyamide 6 composites fabricated through injection molding are assessed in this study to determine the synergistic effect of cut basalt fibre and nano silica. 5 composite formulations were created each of which contained 10 wt% basalt fibre and progressively higher concentrations of nano silica (1–5 wt%). Tensile strength, impact resistance and flexural strength were evaluated mechanically. The results suggest that basalt fibre considerably contributes to the enhancement of strength while nano silica particularly at a concentration of 3 wt%, enhances energy absorption and matrix-filler adhesion. The PA6 + 10 wt% basalt + 3 wt% nano silica composite demonstrated optimal efficacy in all parameters. These hybrid composites are optimal for sports products that require lightweight performance, durability and strength.

# Introduction

Polyamide 6 is a semi crystalline thermoplastic highly regarded for its dimensional stability and mechanical performance with its impact strength and stiffness can be optimized for high performance applications where dynamic load resistance and strength to weight ratio are critical [1-3].

Basalt fibre which is derived from volcanic rock provides a sustainable and high strength reinforcement alternative to glass fibre. It exhibits exceptional chemical resistance and specific strength. In the meantime nano silica (SiO₂ ~20–50 nm) contributes to matrix stiffening and fracture deflection as a result of its high surface area and particle hardness [4-6]. The tensile and impact behavior of the PA6 matrix improves when these additives are used as a result of the interaction formed and hybrid reinforcements including nanofillers and fibers have been progressively integrated into the development of high performance polymer composites for structural and dynamic applications in order to satisfy some performance requirements. Polyamide-6 (PA6) is a promising candidate for hybridization strategies due to its favorable mechanical properties. They conducted an investigation into basalt fiber-reinforced systems and observed significant enhancements in dynamic performance and mechanical integrity, thereby establishing basalt as a dependable reinforcement material for structural composites [7-11]. Patel and Jain demonstrated that the tensile and flexural strength of randomly orientated short fibers was substantially improved suggesting the potential of fibre aspect ratio and orientation in composite design [12-16]. The incorporation of nanofillers such as silica is recognized to enhance matrix rigidity and fracture resistance. It examined the impact of nano silica particle size on the mechanical properties of polymer matrices concluding that the stiffness and energy absorption of the matrices are substantially enhanced by the use of smaller, well-dispersed particles [17-20]. This is consistent with the atomic-level discoveries of who conducted an investigation into the surface behavior of nanofillers and discovered that an increase in interfacial adhesion and wetting was essential for the efficient transmission of loads in polymer-filler systems [21-24]. Ray and Banerjee show the significance of sustainability and infill compatibility in biopolymer systems emphasizing the notion that hybrid composites should strike a balance between environmental considerations and performance [25-29].

They [30] studied the potential of combining mineral fibers with synthetic polymers by comparing the hybridization of basalt and glass fibers in polypropylene matrices and observing temperature dependent mechanical behavior [31]. Research [32-33] investigated PA6 & co polyester elastomer blends that were reinforced with modified silica and graphene. They reported a substantial increase in both tensile strength and energy dissipation under tension [34-36]. He emphasized the influence of natural nano clays on the dispersion behavior and dielectric properties of PA6 based nanocomposites which are also pertinent for applications that are susceptible to impact [37-39].

The impact of hybrid reinforcement of PA6 on mechanical strength and impact energy absorption by utilizing cut basalt fibers and nano silica in injection molding was studied in this work.

# Materials and Methods

## Materials

Remarkable balance of mechanical strength, thermal stability and processing ability these injection grade Polyamide 6 resin was designated as the matrix material for this study. Because of its great strength, stiffness and resilience to heat chopped basalt fibers ranging in length from 4 to 6 mm were used as reinforcement. The mechanical and impact capabilities were further enhanced by the use of nano silica particles which had an average diameter of 30 nm. These hydrophilic amorphous nanoparticles were selected because, when evenly distributed they can improve interfacial bonding and prevent fracture propagation [40-42].

## Composite Formulations

**TABLE 1.** Composite Formulations Table

| **Group ID** | **Composition** | **Remarks** |
| --- | --- | --- |
| G1 | PA6 (neat polymer) | Control group |
| G2 | PA6 + 10 wt% chopped basalt fiber | Fiber-reinforced |
| G3 | PA6 + 10 wt% basalt fiber + 1 wt% nano-silica | Hybrid composite – low nano-silica loading |
| G4 | PA6 + 10 wt% basalt fiber + 3 wt% nano-silica | Hybrid composite – optimal reinforcement |
| G5 | PA6 + 10 wt% basalt fiber + 5 wt% nano-silica | Hybrid composite – possible agglomeration |

To comprehensively investigate the effects of basalt fibre and different concentrations of nano silica on the mechanical properties of Polyamide 6 five distinct composite formulations were created. As the control the base group G1 was made up of clean PA6 without any reinforcement [43-45]. To assess the reinforcing effect of fibre alone Group G2 added 10 weight % chopped basalt fibre. The hybrid composites in groups G3, G4 and G5 had the same 10 weight % basalt fibre in addition to increasing nano silica concentrations of 1 weight %, 3 weight % and 5 weight % respectively. This made it possible to compare the influence of nano silica loading on the performance of the composite and assisted in determining the ideal concentration for improved mechanical qualities.

## Fabrication Process

To prevent moisture from affecting the melt blending process all raw components were carefully dried. A co rotating twin screw extruder working in the temperature ranging from 230 to 250°C was used to melt compact the composites in order to guarantee consistent dispersion of the nano silica and basalt fibers within the PA6 matrix. To prepare test specimens for assessing tensile, flexural and impact properties in compliance with conventional ASTM testing procedures the extrudates were pelletised and then injection moulded using standard moulds.

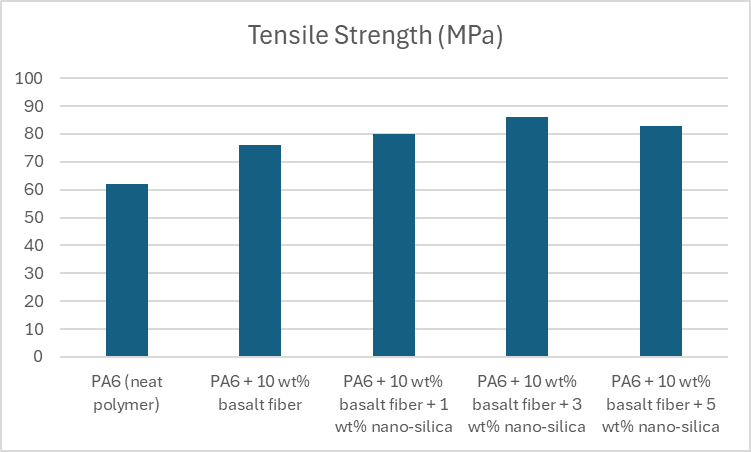
# Results and Discussion

## Tensile Strength

Tensile tests demonstrated a considerable improvement in mechanical performance due to reinforcement and Neat PA6 (G1) had a tensile strength of 62 MPa but the addition of 10 wt% chopped basalt fibre (G2) boosted it to 76 MPa representing a 22% improvement. The accumulation of nano-silica improved the tensile properties G3 (1 wt%) reached 80 MPa, while G4 (3 wt%) peaked at 86 MPa, representing a 39% increase over the unreinforced matrix. A modest reduction to 83 MPa in G5 (5 wt%) was observed most likely due to nanoparticle agglomeration which impaired interfacial bonding and stress transfer. Thus, 3 wt% nano-silica (G4) was shown to be ideal for increasing tensile strength [46-48].

**TABLE 2.** Tensile Strength of PA6 Composites

| **Formulation (Group ID)** | **Composition** | **Tensile Strength (MPa)** | **% Increase from Neat PA6** |
| --- | --- | --- | --- |
| G1 | PA6 (neat polymer) | 62 | — |
| G2 | PA6 + 10 wt% basalt fiber | 76 | +22.6% |
| G3 | PA6 + 10 wt% basalt fiber + 1 wt% nano-silica | 80 | +29.0% |
| G4 | PA6 + 10 wt% basalt fiber + 3 wt% nano-silica | 86 | **+38.7%** |
| G5 | PA6 + 10 wt% basalt fiber + 5 wt% nano-silica | 83 | +33.9% |



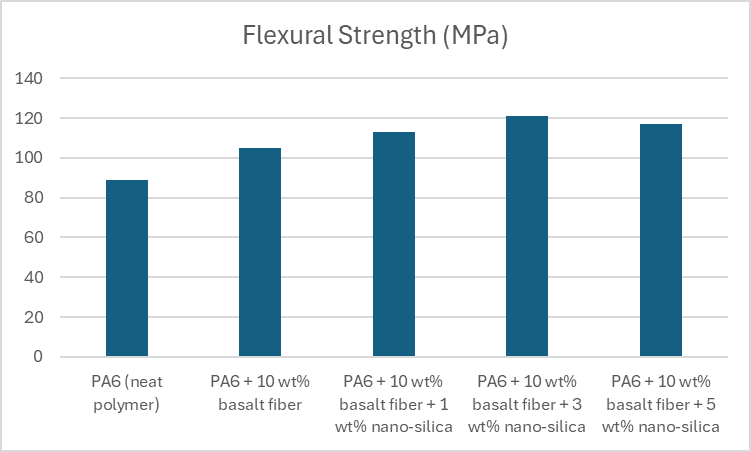
**FIGURE 1.**Tensile Strength of PA6 Composites

## Flexural Strength

Flexural performance followed a similar pattern to the tensile results. The clean PA6 has a baseline flexural strength of 89 MPa. The addition of 10 wt% basalt fibre boosted it to 105 MPa demonstrating greater matrix stiffness. With the addition of nano silica the values climbed further 113 MPa for G3 (1 wt%) and 121 MPa for G4 (3%). The minor decrease to 117 MPa in V5 (5 wt%) is related to particle clustering [49-51], which may disturb uniform stress distribution. Thus 3 wt% nano-silica appeared as the best loading for increasing flexural strength.

**TABLE 3.** Flexural Strength of PA6 Composites

| **Variant (ID)** | **Composition** | **Flexural Strength (MPa)** | **% Increase from Neat PA6** |
| --- | --- | --- | --- |
| G1 | PA6 (neat polymer) | 89 | — |
| G2 | PA6 + 10 wt% basalt fiber | 105 | +18.0% |
| G3 | PA6 + 10 wt% basalt fiber + 1 wt% nano-silica | 113 | +26.9% |
| G4 | PA6 + 10 wt% basalt fiber + 3 wt% nano-silica | 121 | **+36.0%** |
| G5 | PA6 + 10 wt% basalt fiber + 5 wt% nano-silica | 117 | +31.5% |



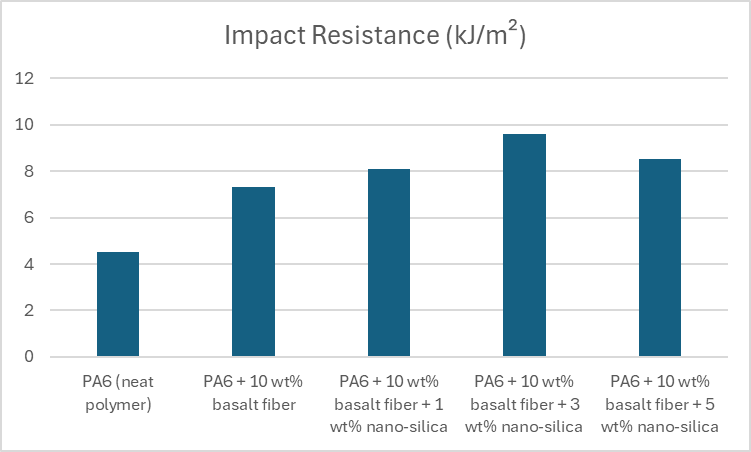
**FIGURE 2.** Flexural Strength of PA6 Composites

# Impact Resistance

**TABLE 4.**Impact Resistance of PA6 Composites

| **Blend (ID)** | **Composition** | **Impact Resistance (kJ/m²)** | **% Increase from Neat PA6** |
| --- | --- | --- | --- |
| G1 | PA6 (neat polymer) | 4.5 | — |
| G2 | PA6 + 10 wt% basalt fiber | 7.3 | +62.2% |
| G3 | PA6 + 10 wt% basalt fiber + 1 wt% nano-silica | 8.1 | +80.0% |
| G4 | PA6 + 10 wt% basalt fiber + 3 wt% nano-silica | 9.6 | **+113.3%** |
| G5 | PA6 + 10 wt% basalt fiber + 5 wt% nano-silica | 8.5 | +88.9% |

The impact strength showed the most significant improvement. Neat PA6 had an impact resistance of 4.5 kJ/m². The addition of 10 wt% basalt fibre improved the value to 7.3 kJ/m². The addition of nano-silica resulted in 8.1 kJ/m² and 9.6 kJ/m² at 1 and 3 wt% silica respectively. The hybrid with 3 wt% nano silica has more than double the energy absorption of pure PA6. B5 (5 wt%) showed a modest decrease to 8.5 kJ/m² most likely due to stress from silica agglomerates. This demonstrates that 3 wt% nano silica provides the most effective synergy for impact resistance [52-53].



**FIGURE 3.**Impact Resistance of PA6 Composites

# Application in Sports Goods

The increased mechanical and impact capabilities of PA6 composites make them great choices for sporting goods particularly components that must withstand high dynamic loads while remaining lightweight. Such applications include bicycle parts, protective gear shells, skate frames and paddles all of which require materials that can tolerate repeated bending, flexural fatigue, and accidental impacts. The hybrid composite formulation of PA6 + 10 wt% basalt fibre + 3 wt% nano silica improves all essential mechanical characteristics in a balanced manner comprising a 39% rise in tensile strength a 36% development in flexural strength and an astonishing 113% increase in impact resistance over neat PA6. These performance advantages together with the material moldability and low weight make it suitable for application in next generation sports equipment that prioritizes durability, energy return and user safety.

# Conclusion

This study indicates that hybrid reinforcement of Polyamide-6 with chopped basalt fibers and nano silica improves the composite's mechanical and impact properties. The formulation with the best performance was PA6 + 10 wt% basalt fibre + 3 wt% nano-silica which demonstrated:

* Tensile strength is 86 MPa,
* Flexural strength is 121 MPa and
* Impact resistance is 9.6 kJ/m².

These advances are the result of macro- and nano-scale reinforcements working together. While basalt fibers improve stiffness and load-bearing capacity nano silica particles improve interfacial bonding and energy dissipation mechanisms when suitably dispersed. The findings highlight the composite's applicability for injection-molded sports equipment where strength, durability and toughness are required without sacrificing lightweight design and processing ability.

# References

1. Wu, Han, Xia Qin, Xu Huang, and SakdiratKaewunruen. "Engineering, mechanical and dynamic properties of basalt fiber reinforced concrete." Materials 16, no. 2 (2023): 623.
2. Patel, Nikunj, and Piyush Jain. "An investigation on mechanical properties in randomly oriented short natural fiber reinforced composites." Materials Today: Proceedings 37 (2021): 469-479.
3. Siraj, Sidra, Ali H. Al-Marzouqi, Muhammad Z. Iqbal, and Waleed Ahmed. "Impact of micro silica filler particle size on mechanical properties of polymeric based composite material." Polymers 14, no. 22 (2022): 4830.
4. Fame, Cheikh Makhfouss, Tamon Ueda, Marc A. Minkeng, Eskinder Desta Shumuye, Yi Wang, and Chao Wu. "Atomic-Level Insights into Epoxy-Modified Nanofiller Adsorption and Wetting on Calcium Silicate Hydrates: Principles for Optimizing Interfacial Properties." Ntjam and Shumuye, Eskinder Desta and Wang, Yi and Wu, Chao, Atomic-Level Insights into Epoxy-Modified Nanofiller Adsorption and Wetting on Calcium Silicate Hydrates: Principles for Optimizing Interfacial Properties (February 27, 2025) (2025).
5. Ray, Suprakas Sinha, and Ritima Banerjee. Sustainable Polylactide-Based Composites. Elsevier, 2023.
6. Kufel, Anna, Slawomir Para, and Stanisław Kuciel. "Basalt/glass fiber polypropylene hybrid composites: Mechanical properties at different temperatures and under cyclic loading and micromechanical modelling." Materials 14, no. 19 (2021): 5574.
7. Srinivas, S., G. S. Ananthapadmanabha, B. Suresha, Rajini Nagarajan, Faruq Mohammad, Kumar Krishnan, MP Indira Devi, and Shafiq Ahmad. "Experimental studies on the physical and mechanical properties of modified silica/graphene reinforced polyamide6/copolyester elastomer blend nanocomposites." Polymer Engineering & Science 65, no. 2 (2025): 605-619.
8. Hussein, Labiba I., Dalia S. Fathy, Salwa M. Elmesallamy, Nahla A. Mansour, Onsy IH Dimitry, and Azima LG Saad. "Exploring the phenomena of dispersion and electrical properties of natural montmorillonite particles in polyamide 6 as a nanocomposite material." Pigment & Resin Technology (2025).
9. Thongchom, Chanachai, Nima Refahati, Pouyan Roodgar Saffari, Peyman Roudgar Saffari, Meysam Nouri Niyaraki, Sayan Sirimontree, and Suraparb Keawsawasvong. "An experimental study on the effect of nanomaterials and fibers on the mechanical properties of polymer composites." Buildings 12, no. 1 (2021): 7.
10. Ali, Alamry, Seyed Saeid Rahimian Koloor, Abdullah H. Alshehri, and A. Arockiarajan. "Carbon nanotube characteristics and enhancement effects on the mechanical features of polymer-based materials and structures–A review." Journal of Materials Research and Technology 24 (2023): 6495-6521.
11. M. E. M. Soudagar et al. (2026). Effect of lithium nitride/potassium nitride and hybrid nanofluid actions on thermal performance of solar-based heat exchanger featured with linear fresnel reflector. Chemical Engineering Science, 319(122261), 122261. https://doi.org/10.1016/j.ces.2025.122261
12. A. Sharma et al. Structural Modification and Enhancement of Optoelectronic Behaviour of ZnO Nanofilms Featuring Cu and Ti Particles. J. Electron. Mater. (2025). https://doi.org/10.1007/s11664-025-11951-2
13. N. Nagarajan et al. Hybrid Stir Cast Featured with Wettability Agent and Ultrasonic Action of Magnesium Alloy Composite Composed with Nanofiller: Study Characteristics. Inter Metalcast (2025). https://doi.org/10.1007/s40962-025-01603-w
14. P. K. Singh et al. Integration of phase change material for enriching the solar collector featured with dryer configuration enhanced via alumina/titanium dioxide nanoparticle: performance study. J Therm Anal Calorim (2025). https://doi.org/10.1007/s10973-025-14302-9
15. Karthick et al., (2025). Experimental investigation of photocatalytic degradation and antioxidant activities of biosynthesized gold nanoparticles from royal poinciana tree leaves. Discover Applied Sciences, 7(8), 838.
16. Vinodh et al., (2025). Integration of ceramic reinforcements in AA5083 composites for enhanced mechanical and thermal properties in friction stir welding. Engineering Research Express, 7(3), 035519.
17. K. Vijetha, Arockia Selvakumar Arockia Doss, KJN Sai Nitesh, Nimel Sworna Ross, Dual-Scale Evaluation of Hybrid Al-SiC/Graphene Composites: Mechanical Properties and Deep Learning-Driven Machinability Insights. Results in Engineering (2025): 105742.
18. Raja et al., (2025). Sustainable High-Strength Composites: Hybrid Bamboo and Cellulose Reinforced Polyester for Automotive Engineering. Journal of Bio-and Tribo-Corrosion, 11(3), 85.
19. Udhayakumar et al., (2025). Multi-functional natural fiber composites using flaxseed and cotton: tailoring acoustic, mechanical, and thermal properties for eco-friendly applications. Discover Applied Sciences, 7(8), 906.
20. Jain, Akshay, et al. Conversion of water hyacinth biomass to biofuel with TiO2 nanoparticle blending: Exergy and statistical analysis. Case Studies in Thermal Engineering 67 (2025): 105771.
21. Neelakandan Aagashram et al., Computational design exploration of rocket nozzle using deep reinforcement learning. Results in Engineering 25 (2025): 104439.
22. V. Mohanavel et al. Tribological characteristics and optimization of ZrB2 configured magnesium alloy composite via squeeze casting technique. J Mech Sci Technol. 39(5), 2025. https://doi.org/10.1007/s12206-025-0425-9
23. M. Aruna et al. Integration of Magnesium Fluoride and Nano Alumina–Silicon Carbide Actions on Properties of AZ91 Alloy Hybrid Nanocomposites. Inter Metalcast (2025). https://doi.org/10.1007/s40962-025-01617-4
24. Jothi Arunachalam et al. Integration of nanographene and action of fiber sequences on functional behaviour of composite laminates" International Polymer Processing, 2025. https://doi.org/10.1515/ipp-2024-0149
25. Manzoore Elahi M. Soudagar, Ravindra Pratap Singh, Nagabhooshanam Nagarajan. et al. Featuring of in-situ carbon capturing and functional performance study of hydrogen from aquaculture wastewater algae biomass via supercritical steam gasification route, Chemical Engineering Science 313 (2025) 121704. https://doi.org/10.1016/j.ces.2025.121704
26. P. Sharma et al. Effect of paraffin with salt hydrates PCM and hybrid Al2O3/Tio2 nanofluid on thermal and energy storage characteristics of solar thermal heat exchanger. J Therm Anal Calorim (2025). https://doi.org/10.1007/s10973-025-14224-6
27. Shah, Ronit, Arockia Selvakumar Arockia Doss. Advancements in AI-Enhanced Collaborative Robotics: Towards Safer, Smarter, and Human-Centric Industrial Automation. Results in Engineering (2025): 105704.
28. Neelashetty, K., et al. Energy Management for PV-Powered EV Charging With Grid Integration and Battery Energy Storage System using Dung Beetle Optimizer. 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM). IEEE, 2025.
29. Chinta, N. D., Gogulamudi, B., Swamy Nadh, V., Muthu, G., Kaliappan, S., & Srinivas, C. (2024). Investigation on mechanical properties of the green synthesis bamboo fiber/eggshell/coconut shell powder-based hybrid biocomposites under NaOH conditions. Green Processing and Synthesis, 13(1), 20230185. https://doi.org/10.1515/gps-2023-0185
30. Manzoore Elahi M. Soudagar et al. Higher performance solar air dryer functioned with palmitic acid phase change material and hybrid nanofluid: Thermal performance evaluation, Applied Thermal Engineering (2025). Volume 272, 2025,126413, https://doi.org/10.1016/j.applthermaleng.2025.126413
31. P. P. Singh et al. Hybrid Thin Film Coating Performance and Functional Characteristics of Silicon Nitride (SiNx) Layer for Solar Cell Application. J. Electron. Mater. (2025). https://doi.org/10.1007/s11664-025-11888-6
32. Kaliappan, S., Balaji, V., & Mahesh, V. (2024). Effects of Injection Molding on Linum usitatissimum Fiber Polyvinyl Chloride Composites for Automotive Underbody Shields and Floor Trays (No. 2024-01-5053). SAE Technical Paper. https://doi.org/10.4271/2024-01-5053
33. Ameen, F., Chinta, N. D., Teja, N. B., Muthu, G., Kaliappan, S., ... &Vadiveloo, A. (2024). Antibacterial and dynamical behaviour of silicon nanoparticles influenced sustainable waste flax fibre-reinforced epoxy composite for biomedical application. Green processing and synthesis, 13(1), 20230214. https://doi.org/10.1515/gps-2023-0214
34. V. Rathinavelu et al. Optimal performance of poly-hybrid nanocomposites promoted with carbon fibers and nano silicon carbide particles via compression associated with hot pressing: characterization study. International Polymer Processing, 2025. https://doi.org/10.1515/ipp-2024-0152
35. K. K. Ilavenil et al. Enrichment of monolithic aluminium alloy characteristics by nano ceramic: Solid state process. J Mech Sci Technol (2025). https://doi.org/10.1007/s12206-025-0513-x
36. M.E.M. Soudagar et al. Exploration and thermal characteristics analysis of hybrid TiO2/SiO2 nanofluids passing through heavy-duty automotive radiators for intensive cooling system. J Therm Anal Calorim (2025). https://doi.org/10.1007/s10973-025-14305-6
37. N. Basavegowda et al. Influence of Silver Nanowire Concentration on Electrical and Optical Properties of Polyaniline for Transparent Conductive Sensors. J. Electron. Mater. (2025). https://doi.org/10.1007/s11664-025-12174-1
38. V. V. Upadhyay et al. Hexachloroethane fluxing mechanism and actions of hybrid fillers on functional behaviour of AZ31B alloy composites. J Mech Sci Technol (2025). https://doi.org/10.1007/s12206-025-0622-6
39. A. Sharma et al. Featuring of Formamidinium lead halide and enrichment of optoelectronic behaviour of SnO2/FAPbI3/NiOx with PCBM layer. J Mater Sci: Mater Electron 36, 1124 (2025). https://doi.org/10.1007/s10854-025-15203-1
40. A. Sharma et al. Semisolid stir casting and effect of hybrid fillers on functional properties of aluminium alloy composites. J Mech Sci Technol (2025). https://doi.org/10.1007/s12206-025-0620-8
41. Seeniappan, K. (2024). Optimizing Carbon Monoxide Emission Reduction Using Rice Husk Activated Carbon in Automobile Exhaust Systems (No. 2024-01-5054). SAE Technical Paper. https://doi.org/10.4271/2024-01-5054
42. Chukka, N. D. K. R., S., Balaji, V., Ross, N. S., (2025). An integrated Artificial neural network technique to optimize the various parameters of Pineapple/SiO2/epoxy-based nanocomposites under NaOH treatment. Results in Engineering, 26, 104737.
43. Seeniappan, K. (2024). Effectiveness of titanium dioxide nano fillers on sisal fiber for enhanced mechanical properties and occupant protection in hybrid nanocomposites (No. 2023-01-5114). SAE Technical Paper. https://doi.org/10.4271/2023-01-5114
44. Mohan, G., G. Komala, K. Manikannan, Pallavi Baghel. Heart Disease Detection in Cloud Platforms: A Privacy-Driven Approach using Exponential Distribution Optimized Hopfield Networks and Blockchain Security. In 2025 International Conference on Inventive Computation Technologies (ICICT), pp. 1084-1089. IEEE, 2025.
45. Seeniappan, K., & Sree, G. V. (2024). Enhancing the mechanical and thermal properties of Kevlar composites for advanced vehicle components using montmorillonite nano clay integration (No. 2023-01-5113). SAE Technical Paper. https://doi.org/10.4271/2023-01-5113
46. S. Ravi et al. Processing and SiC content on functional behaviour of aluminium alloy composite. J Mech Sci Technol (2025). https://doi.org/10.1007/s12206-025-0723-2
47. V. Mohanavel et al. Exploration of photovoltaic thermal collector performance enhancement by the accumulations of hybrid nanofluid and phase change material. J Therm Anal Calorim (2025). https://doi.org/10.1007/s10973-025-14427-x
48. M. A. Babu et al. Effect of Surfactants and Hybrid Filler on Microstructural and Mechanical Properties of Al7075/TiC/Graphene Alloy Composite via Additive Manufacturing. J. of Materi Eng and Perform (2025). https://doi.org/10.1007/s11665-025-11873-4
49. Janardhan, G., Nadh, V. S., Srinivas, C., & Velmurugan, G. (2024). Eco-friendly zinc oxide nanoparticles from Moringa oleifera leaf extract for photocatalytic and antibacterial applications. Clean Technologies and Environmental Policy, 1-13. https://doi.org/10.1007/s10098-024-02814-1
50. Naga Dheeraj Kumar Reddy Chukka, M. Karthick, Nimel Sworna Ross. Optimization of thermal efficiency in double pass solar air heating systems with emphasis on collector design parameters and operating conditions. Results in Engineering 26 (2025): 104948.
51. Chinta, N. D., Teja, N. B., Muthu, G.., Kirubanandan, S., & Paramasivam, P. (2024). Evaluating mechanical, thermal, and water absorption properties of biocomposites with Opuntia cladode fiber and palm flower biochar for industrial applications. Discover Applied Sciences, 6(2), 30.
52. Karthikeyan, S., Karthick, M., Munipalli, M., Sankar, N., Suriyaprakash, L., & Muthugounder, P. (2025). Effect of roselle fiber on physical and thermal behaviour of polypropylene nanocomposite developed by conventional route. In *AIP Conference Proceedings* (Vol. 3252, No. 1, p. 020223). AIP Publishing LLC.
53. Karthikeyan, S., Manivannan, S., Venkatesh, R., Karthikeyan, S., Anand, R., & Sasikaran, S. V. (2024). Optimization and characteristics of multimodal binder on polymer nanocomposite for lightweight applications. *Journal of Environmental Nanotechnology, 13*(3), 207–216.