Influences of Silver Nanoparticles and Actions of Natural Hemp Fiber on Mechanical Behaviour of Polylactic Acid Composites

R Meenakshi Reddy1, R Karthik2, L Suriyaprakash3, M Karthick4,a), S Kalaiarasan5, S Nanthakumar6, R Anand7, Senthil Kumar Vishnu8, Gopal Kaliyaperumal9

1 Department of Mechanical Engineering, G.Pulla Reddy Engineering College, Kurnool, 518007, Andhrapradesh, India

2Dhanalakshmi Srinivasan College of Engineering, Coimbatore, 641105, Tamil Nadu, India.

3Department of Mechanical Engineering, Rathinam Technical Campus,Coimbatore, Tamilnadu 641021 India.

4 Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thuduppathi, 638057, Tamil Nadu, India.

5 Department of Chemistry, Sona College of Technology, Salem, 636005, Tamil Nadu, India.

6Department of Mechanical Engineering, PSG Institute of Technology and Applied Research Neelambur, Coimbatore, 641062, Tamilnadu, India

7Department of Aeronautical Engineering, Nehru Institute of Technology, Thirumalayampalayam, Coimbatore, 641105, Tamilnadu, India

8Centre for Sustainable Materials Research, Department of Mechanical Engineering, Academy of Maritime Education and Training (AMET)Deemed to be University, Kanathur, Chennai 603112, Tamil Nadu, India.

9Department of Mechanical Engineering, New Horizon College of Engineering, Bangalore, 560103, Karnataka, India

**Corresponding author: a)**[*mkarthickmech1992@gmail.com*](mailto:mkarthickmech1992@gmail.com)

**Abstract.** The mechanical performance of polylactic acid based hybrid bio composites reinforcement with hemp fibers of 2–4 mm treated with NaOH and silver nanoparticles (AgNPs ~50 nm) is examined in this work. Injection moulding was used to create five composite samples with different hemp fiber concentrations (5, 10 and 15 weight %) while keeping the 1 weight % AgNP loading constant. Shore D hardness, energy absorption through impact testing and tensile characteristics were all part of the mechanical characterization. AgNPs enhanced the stiffness and hardness of the surface and hemp fibers' pull out and fiber bridging processes greatly enhanced their ductility and energy absorption. By combining light weight, biodegradability, and increased toughness, the ideal formulation (PLA + 1 weight % Ag + 10 weight % hemp fibre) produced a balanced mechanical profile appropriate for non load bearing car interior trimmings.

# Introduction

In environmentally aware applications ranging from packaging to biomedical equipment polylactic acid has emerged as a top biocompatible and biodegradable thermoplastic. Notwithstanding these benefits PLA's inherentbreakability and meager impact resistance make it tough to use in structural applications therefore nano and micro scale reinforcements are required for improvement.

Silver nanoparticles, one of the most promising nanofillers have shown remarkable promise in enhancing PLA composites' mechanical and functional qualities. According to [1-4] adding AgNPs to thermally treated wood resulted in significant improvements in both mechanical strength and antibacterial activity. By incorporating collagen and nano hydroxyapatite into natural silk fibers, [4-6] made additional contributions to this field and highlighted a green modification process that has translational potential for PLA based systems.

Reinforcements made of natural fibers especially hemp have become more popular since they are affordable, renewable and work well with thermoplastic matrices. By combining hemp fibers and in situ synthesized AgNPs, [7-10] created layered composites that shown strong interfacial adhesion and notable mechanical advancements. The adaptability of these biocomposites was further illustrated [11-14] showed how well metal oxide nanoparticles could be embedded into natural fibers to create protective, antimicrobial fabrics. Such composite tactics are also supported by environmental sustainability criteria. A life cycle study of PLA-hemp-AgNP systems was carried out [15-18] confirmed their efficacy in antibacterial performance and decreased ecological footprint. Regarding processing, [19-21] used electrospinning to create nanofibers with uniform AgNP distribution, resulting in improved antibacterial activity and fiber morphology, while [22-25] confirmed the antimicrobial performance of PLA fibers modified with surface-coated AgNPs.

Studies focussing on fiber-level reinforcement also clearly demonstrate the function of nanoparticle–fiber synergy. In their comparison of organic and inorganic nanoparticles in electrospun PLA fibers, [26] found significant improvements in mechanical and thermal performance. In a related field, [27-29] examined the incorporation of graphene nanoparticles in PLA and observed that they were comparable to AgNPs in terms of reinforcing matrix strength, conductivity and functional durability. The focus of contemporary research has changed from mechanical fortification to the embedding of intelligent functions. FunctionalisedAgNPs have been shown by [30-33] to induce shape-memory behavior in PLA composites, allowing for reconfigurability and adjustable actuation. Padhy and Kandasubramanian (11) provided insightful information about nanofiller–matrix interactions in ultra high molecular weight polyethylene systems, despite their focus on a different polymer. These insights are equally applicable to PLA-based composites. Weaved and hybrid reinforcements are becoming more and more important for their structural purpose. In their engineering of woven plant-fiber hybrids, [34-36] highlighted the structural synergy that may be achieved by architecture guided design. In a similar vein, [37-40] investigated epoxy systems reinforced with natural fibers and showed their feasibility for use in automotive and construction applications, with possible crossover for PLA composites. Multifunctional PLA-based barriers have also seen recent advancements. AgNP reinforced PLA films with simultaneous increases in thermal stability and antibacterial resistance were produced by [41-45]. In order to enhance interfacial bonding and structural durability [46] synthesized existing fibre and matrix modification techniques, emphasizing the significance of alkali treatment and nanofiller integration.

Building on this framework the current study explores the combination of alkali treated hemp fibers with silver nanoparticles for PLA reinforcement. For vehicle interior trim applications, where stiffness, toughness, processability and environmental compliance must be carefully balanced, the objective is to find the finest hybrid composition that offers the highest mechanical performance.

# Materials and Methods

## Materials

This experiment utilized polylactic acid pellets specifically the Ingeo of 4032D grade supplied by Nature Works LLC, the primary matrix material and this grade of PLA is ideally suited for injection molding composite manufacture due to its remarkable mechanical strength and processability. Silver nanoparticles with a purity of 99.9% and atypical diameter of around 50 nm as the reinforcing nanomaterial were utilized and the ability of these nanoparticles to enhance the functional performance of polymer matrices and their recognized antibacterial properties. Ethanol a solvent during the mixing process was employed to disaggregate nanoparticle agglomerates and ensure uniform dispersion of the AgNPs inside the PLA matrix and chopped natural hemp fibers measuring 2 to 4 mm in length were used as an additional reinforcement measure. Prior to inclusion the hemp fibers underwent alkali treatment for four hours with a 5% NAoH solution and were thereafter dehydrated in an oven. This chemical treatment was essential for improving the interfacial union between the hydrophilic fibers and the hydrophobic PLA matrix by removing surface impurities and non-cellulosic components. Hybrid PLA mixtures with improvedmechanical and functional belongings were developed by integrating these carefully selected and pre-processed components.

## Composite Formulations

Five different formulations were used in a structured experimental design to thoroughly evaluate the impact of hybrid reinforcement on the mechanical performance of PLA-based composites. These included PLA reinforced with a fixed 1 weight % of silver nanoparticles and different additions of NaOH-treated hemp fibres at 5 weight %, 10 weight % and 15 weight %. While the addition of AgNPs was intended to provide both nanoscale reinforcement and antibacterial functions the hemp fibres were treated with alkali to improve surface roughness and interfacial bonding with the PLA matrix.

**TABLE 1.** Mechanical Composite Formulations Table

|  |  |
| --- | --- |
| **Sample** | **Description** |
| 1 | PLA (Neat) |
| 2 | PLA + 1 wt% AgNP |
| 3 | PLA + 1 wt% AgNP + 5 wt% NaOH-treated hemp fiber |
| 4 | PLA + 1 wt% AgNP + 10 wt% NaOH-treated hemp fiber |
| 5 | PLA + 1 wt% AgNP + 15 wt% NaOH-treated hemp fiber |

The individual and combined effects of natural fibre reinforcements and nanoparticles was made possible by this design to find the ideal hybrid composition that optimises mechanical performance this study will gradually increase the fibre content while keeping the AgNP loading constant. Furthermore this factorial method promotes a basic knowledge of load distribution, interfacial bonding and potential threshold effects all of which are crucial for developing high-performance sustainable biocomposites.

## Fabrication Process

To ensure consistent and moisture-free processing, all PLA pellets and filler constituents were predried at 80 °C for 12 hours. The silver nanoparticles (AgNPs) were dispersed in ethanol and ultrasonicated for 20 minutes to ensure uniform distribution and prevent agglomeration. Hemp fibers, after being chemically treated in 5% NaOH solution for 4 hours, were thoroughly rinsed, dried, and then incrementally bring together into the polymer melt to achieve homogeneous mixing. Melt blending of the PLA matrix with fillers was accomplished using a corotating twinscrew extruder functioning at 190 °C and a screw speed of 100 rpm. The resulting composite strands were pelletized and subsequently processed into test specimens using injection molding at 200 °C. All specimens were arranged in accord with ASTM standards relevant to mechanical property evaluation.

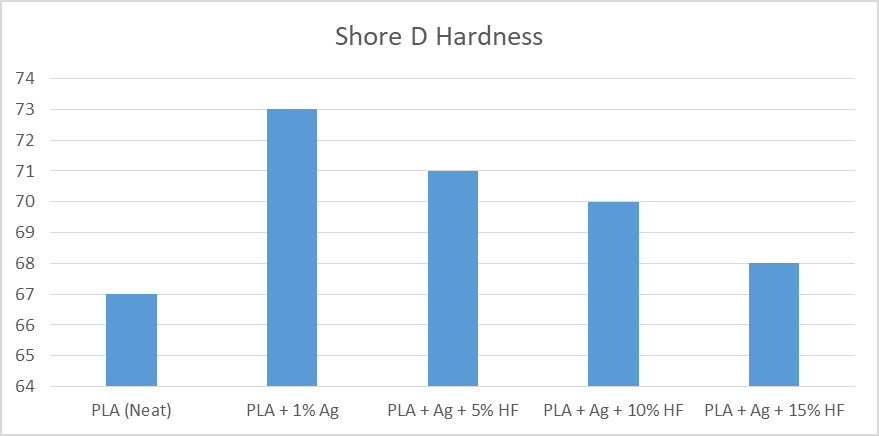
# Results and Discussion

## Shore D Hardness

The surface toughness of the developed composites was calculated using Shore D durometer measurements. The recorded values for each formulation are presented in the table below:

**TABLE 2.** Shore D Hardness

|  |  |
| --- | --- |
| **Sample** | **Shore D Hardness** |
| PLA (Neat) | 67 |
| PLA + 1% Ag | 73 |
| PLA + Ag + 5% HF | 71 |
| PLA + Ag + 10% HF | 70 |
| PLA + Ag + 15% HF | 68 |



**Figure 1.** Shore D Hardness

The incorporation of 1 wt% AgNPs led to a notable increase (~9%) in Shore D hardness compared to neat PLA, attributable to the rigid and metallic nature of silver nanoparticles which restrict polymer chain mobility. However, as the hemp fiber content increased, a slight reduction in hardness was observed. This can be linked to potential fiber agglomeration, matrix discontinuities, and weaker interfacial adhesion at higher fiber loadings.

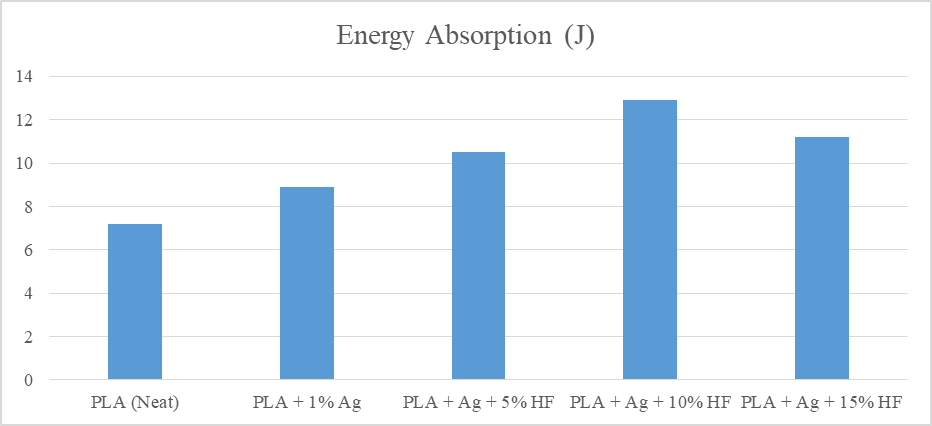
## Energy Absorption

The energy absorption ability of the composites was assessed using notched Izod impact testing. The results are summarized below:

**TABLE 3.** Energy Absorption

|  |  |
| --- | --- |
| **Sample** | **Energy Absorption (J)** |
| PLA (Neat) | 7.2 |
| PLA + 1% Ag | 8.9 |
| PLA + Ag + 5% HF | 10.5 |
| PLA + Ag + 10% HF | 12.9 |
| PLA + Ag + 15% HF | 11.2 |

Improvement in impact confrontation was observed with the accumulation of hemp fibers peaking at 10 wt % fiber loading and this enhancement is primarily used to fiber related toughening mechanisms, including fiber bridging and crack deflection. But a decline in performance at 15 wt % fiber content suggests increased chances of fiber entanglement or poor dispersion can reduce stress transfer efficiency and compromise impact resistance.



**Figure 2.**Energy Absorption (J)

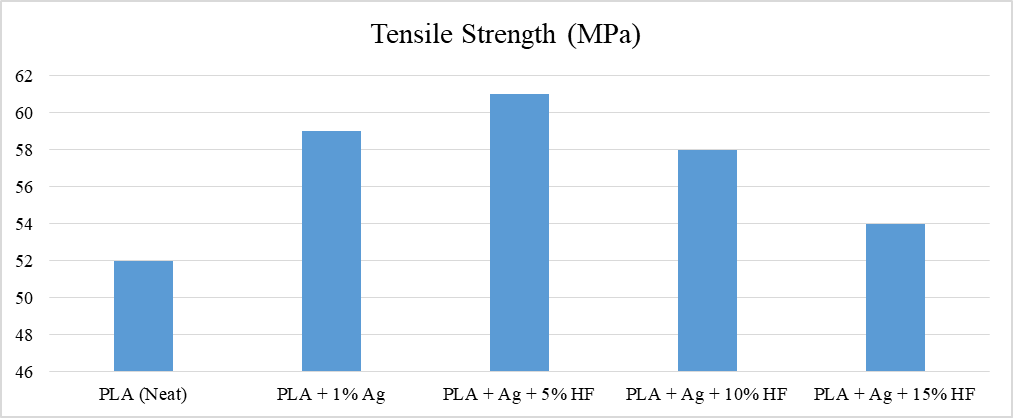
However, at 7.5 wt% n-SiC, the flexural strength decreased marginally to 45 MPa. This drop was most likely caused by the commencement of particle agglomeration at increasing filler concentrations. Clustering of n-SiC disrupted matrix homogeneity resulting in local stress concentrations and reduced reinforcing efficiency. Despite this all reinforced composites outperformed pure HDPE in terms of flexural performance [47-48].

## Stress–Strain Behavior

To comprehend the stress strain performance of the created PLA based composites under uniaxial tensile loading, their tensile characteristics were methodically assessed. The metrics examined include elongation at break (%) and tensile strength in MPa provide information about the materials' ductility and strength and table 4 provides a summary of the findings and figure 3 shows the associated stress-strain curves.

**TABLE 4.** Energy Absorption

|  |  |  |
| --- | --- | --- |
| **Sample** | **Tensile Strength (MPa)** | **Elongation at Break (%)** |
| PLA (Neat) | 52 | 4.1 |
| PLA + 1% Ag | 59 | 4.4 |
| PLA + Ag + 5% HF | 61 | 5.8 |
| PLA + Ag + 10% HF | 58 | 6.7 |
| PLA + Ag + 15% HF | 54 | 5.2 |



**Figure 3.**Stress–Strain Behavior

When compared to pure PLA the addition of 1 weight % silver nanoparticles ensued in a noteworthyenhancement in tensile strength suggesting better stress transfer and interfacial bonding. Energy absorption and ductility were enhanced by further reinforcement using hemp fibre treated with NaOH. The composite containing 10 weight % HF showed the maximum elongation at break (6.7%) indicating a more compliant failure mechanism. Tensile strength however somewhat declined at 15 weight % HF presumably as a result of matrix disruption or fibre aggregation at greater fibrecontent.AgNP and hemp fibres work in concert to customise strength and toughness, as seen in Figure 3, which clearly shows the progressive improvement in stress-strain behaviour with optimised hybrid reinforcement [49-51].

# Application in Automotive Interior Trims

For vehicle interior applications that require materials that are strong, lightweight and eco friendly the designed PLA based hybrid composites hold great potential. Their appropriateness for such applications is supported by several important characteristics:

Lightweight design: Using natural hemp fibres lowers the composite's total density helps vehicles weigh less and consume less fuel.

The integration of natural hemp fibres decreases composite density, hence reducing vehicle weight and improving fuel efficiency. The 10 wt% hemp fibre reinforced composite exhibited improved energy absorption making it appropriate for interior components subjected to mechanical stress. The use of silver nanoparticles improves surface hardness and thermal stability.

This biodegradable PLA matrix when reinforced with renewable natural fibres makes the material environmentally compatible and alternative to petroleum based plastic materials.

The PLA composite reinforced with 1 wt % AgNP and 10 wt % hemp fibre had the most favorable balance of mechanical strength and ductility. This makes it an optimal candidate for use in automotive components such as dashboard panels, door trims and seatback shells.

# Conclusion

This work effectively illustrates the use of melt compounding and injection molding in the plan, production and testing of hybrid polylactic acid composites reinforced with silver nanoparticles and natural hemp fibers treated with NaOH whose results show that the synergistic effects of fibre reinforcement and nanoparticles result in notable increases in mechanical properties especially impact resistance and surface hardness. For example, adding 1 weight % silver nanoparticles raised Shore D hardness by about 9%, whereas adding 10 weight % hemp fibre produced the best energy absorption and elongation at break, indicating higher toughness and ductility. However performance declined when the fibre content was exceeded due to problems such inadequate dispersion and fibre aggregation which had an adverse effect on matrix continuity and stress transmission.

These findings emphasize the importance of balancing strength, stiffness and toughness in hybrid bio composites through filler ratio optimization as they meet the increasing demand for sustainable material solutions in modern engineering applications the materials developed in this study have important environmental benefits including biodegradability and the use of renewable resources. Particularly in the consumer goods and automotive interior industries, the optimized formulation PLA with 1 weight % AgNP and 10 weight percent hemp fiber emerges as a strong contender for lightweight, impact-resistant, and environmentally friendly materials. To verify the composites for practical use future research should concentrate on assessing long-term durability, thermal ageing, weathering resistance and biodegradation behavior under service like settings. Furthermore adding compatibilizers or surface treatments could improve fiber-matrix adhesion even furthe, creating opportunities for even better performance in cutting-edge applications.

# References

1. Ayrilmis, N., Yurttaş, E., Durmus, A., Özdemir, F., Nagarajan, R., Kalimuthu, M., &Kitek Kuzman, M. Properties of biocomposite films from PLA and thermally treated wood modified with silver nanoparticles using leaf extracts of oriental sweetgum. J. Polym. Environ. 29, 2409–2420 (2021).
2. Guo, Z., Chi, Y., Xie, W., Lu, J., Wang, D., Gao, F., Zhang, G., Feng, Q., Wu, H., & Zhao, L. Synergetic enhancement of mechanical properties for silk fibers by a green feeding approach with nano-hydroxyapatite/collagen composite additive. J. Nat. Fibers 19(13), 5310–5320 (2022).
3. P. B. Sethupathi, (2020). Liquid state stir cast processing and characteristics study of AZ91D/SiCp composites. In Materials Today: Proceedings (Vol. 45, pp. 6507–6511). Elsevier Ltd. https://doi.org/10.1016/j.matpr.2020.11.450
4. Hasan, K. M. F., Horváth, P. G., Zsolt, K., Kóczán, Z., Bak, M., Horváth, A., & Alpár, T. Hemp/glass woven fabric reinforced laminated nanocomposites via in-situ synthesized silver nanoparticles from Tilia cordata leaf extract. Compos. Interfaces 29(5), 503–521 (2022).
5. Araujo, J. C., Fangueiro, R., & Ferreira, D. P. Protective multifunctional fibrous systems based on natural fibers and metal oxide nanoparticles. Polymers 13(16), 2654 (2021).
6. Raue, T., Spierling, S., Fischer, K., Venkatachalam, V., Endres, H.-J., Chevali, V., & Wang, H. Life Cycle Assessment of Novel Antibacterial Polylactide-Hemp-Nanosilver-Biocomposites. J. Polym. Environ. (2025), 1–19.
7. Ranjbar Mohammadi, M., Naghashzargar, E., Moghaddam, M. K., & Khorshidi, R. Production of PLA fibers with surface modifications and silver nanoparticle coating to impart antibacterial activity. Polym. Bull. 81(7), 6055–6072 (2024).
8. Supriya et al., (2024). Securing loT Systems with AI-Infused Software and Virtual Replica Models. In 2024 International Conference on Integrated Intelligence and Communication Systems (ICIICS) (pp. 1-6). IEEE. https://doi.org/10.1109/ICIICS63763.2024.10860178
9. Chaudhary et al., (2024). AI-Driven Digital Mirror Technology for Securing IoT-Enabled Smart Infrastructures. In 2024 International Conference on Integrated Intelligence and Communication Systems (ICIICS) (pp. 01-08). IEEE. https://doi.org/10.1109/ICIICS63763.2024.10859436
10. Nikalje et al., (2024). Detecting Cancer through Analysis of Histopathological Images. In 2024 International Conference on Expert Clouds and Applications (ICOECA) (pp. 579-585). IEEE. https://doi.org/10.1109/ICOECA62351.2024.00107
11. Munirathnam, Rajesh, Rohit P. Jadhav, Nilesh M. Mahajan, Amit Barve, and ME Shashi Kumar. Electric Vehicle Charging Demand Prediction using Multiresolution Sinusoidal Neural Network Optimized with Addax Optimization. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 604-609. IEEE, 2025.
12. Lakshmaiya, N. (2024). Short review of partial flow dilution systems for very low PM mass measurements. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 359-367). SPIE. https://doi.org/10.1117/12.3030836
13. Saygılı, T., Kahraman, H. T., Aydın, G., Avcı, A., & Pehlivan, E. Production of PLA-based AgNPs-containing nanofibers by electrospinning method and antibacterial application. Polym. Bull. 81(6), 5459–5476 (2024).
14. Lakshmaiya, N. (2024). Perovskite photovoltaic cells with freezone zone carbon-based instruments: state of review. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 351-358). SPIE. <https://doi.org/10.1117/12.3030837>
15. Almatrafi et al., (2024). Reducing metastasis ability of gastric cancer cell line by targeting MMP16 using miR-193a-5p and 5-FU. Advances in Medical Sciences, 69(2), 463-473. https://doi.org/10.1016/j.advms.2024.09.008
16. Kumar et al., (2024). Cognitive Digital Twin Systems for Predictive Security in AI-Enhanced IoT Environments. In 2024 First International Conference on Software, Systems and Information Technology (SSITCON) (pp. 1-6). IEEE. https://doi.org/10.1109/SSITCON62437.2024.10796449
17. Vinodh et al., (2024). Experimental analysis on surface hardness of AA5083 with SiC/eggshell powder reinforced novel metal matrix composite. In International Conference on Medical Imaging, Electronic Imaging, Information Technologies, and Sensors (MIEITS 2024) (Vol. 13188, pp. 368-377). SPIE. https://doi.org/10.1117/12.3030842
18. Meshram et al., (2024). Investigation of Mechanical and Thermal Properties of Bamboo Fiber Reinforced with Epoxidized Soybean Oil for Automotive Seat Bases (No. 2024-01-5009). SAE Technical Paper. https://doi.org/10.4271/2024-01-5009
19. Prasad et al., (2024). Deep Learning based Channel Assignment with Load Balancing in MANET for Improved Performance. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1172-1177). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544447
20. Mohan et al., (2024). Image Quality Enhancement using Deep Convolutional Network. In 2024 International Conference on Inventive Computation Technologies (ICICT) (pp. 1272-1277). IEEE. https://doi.org/10.1109/ICICT60155.2024.10544980
21. Venkatesh, R., "Synthesis and Machining Characteristics Evaluation of Silicon Nitride Made Magnesium Alloy Composites," SAE Int. J. Mater. Manf. 18(3), 2025, <https://doi.org/10.4271/05-18-03-0017>.
22. Melvin Victor De Poures et al., Processing and Characteristics Study of Hydrogen from Sewage and Waste Municipal Water via Gasification Process" SAE Technical Paper 2024-01-5257, 2024, <https://doi.org/10.4271/2024-01-5257>
23. Melvin Victor De Poures et al. Influences of Zinc Oxide Doping on Functional Characteristics Study of Thin Film Solar Cell for Hybrid Solar Electric Vehicle Utilization" SAE Technical Paper 2024-01-5256, 2024, <https://doi.org/10.4271/2024-01-5256>
24. Alamanda et al., (2024). Machine Learning-Based Fault Diagnosis for Rotating Machinery in Industrial Settings. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568891
25. Baruah et al., (2024). Artificial Intelligence Influence on Leadership Styles in Human Resource Management for Employee Engagement. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568819
26. Aslam et al., (2024). Smart Multiphase Power Converter in the Fault-Tolerant Machine Development for Aerospace Applications. In 2024 Ninth International Conference on Science Technology Engineering and Mathematics (ICONSTEM) (pp. 1-5). IEEE. https://doi.org/10.1109/ICONSTEM60960.2024.10568598
27. Selvi et al., (2024). Transfer Learning Approaches for Improved Thyroid Detection. In 2024 5th International Conference on Electronics and Sustainable Communication Systems (ICESC) (pp. 1311-1317). IEEE. <https://doi.org/10.1109/ICESC60852.2024.10689771>
28. Saadh et al., (2024). Natural killer cell-mediated immune surveillance in cancer: Role of tumor microenvironment. Pathology-Research and Practice, 254, 155120. <https://doi.org/10.1016/j.prp.2024.155120>
29. Neelakandan Aagashram et al., Computational design exploration of rocket nozzle using deep reinforcement learning. Results in Engineering 25 (2025): 104439.
30. R. Venkatesh Fabrication and Functional Behavior Studies of Polypropylene Composite Containing Hybrid Reinforcements, SAE Int. J. Mater. Manf. 18(2), 2025, <https://doi.org/10.4271/05-18-02-0015>.
31. R. Venkatasubramanian et al. Thermal characteristics and dryer performance analysis of double pass solar collector powered by copper and iron oxide. J. Thermal Sci. Eng. Appl. (2025) 1-20. https://doi.org/10.1115/1.4067258
32. Umamaheswari, D. et al. Featuring of Fiber-Ceramic Combination on Behavior Studies of High Density Polyethylene Composite: Hot Compression Mould. Mech Compos Mater (2025). <https://doi.org/10.1007/s11029-025-10305-7>
33. R.P. Singh et al. Alumina-silicon dioxide hybrid nanofluid action on functional characteristics of photovoltaic thermal collector featured with spiral coil. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-024-13973-0>
34. M.E.M. Soudagar et al. Integration and heat performance evaluation of NaNO3–KNO3 PCM and hybrid nanofluid configured solar thermal heat exchanger. J Therm Anal Calorim (2025). <https://doi.org/10.1007/s10973-024-13970-3>
35. R.K. Singh et al. Exposure of Cu on microstructural and functional performance of Cadmium telluride solar cell. Opt Quant Electron 57, 112 (2025). <https://doi.org/10.1007/s11082-024-08027-6>
36. V. Mohanavel et al. Investigation of Al/Mg composite behaviour by the adaptation of SiC and Al2O3 nanoparticle via electromagnetic stir cast route. Materials Science and Technology. 2025;0(0). doi:10.1177/02670836241306686
37. G. Deepana et al. (2025). Synthesis and machining characteristics study of agro-waste coconut shell powder incorporated aluminium alloy composite via the squeeze cast technique. International Journal of Cast Metals Research, 1–11. <https://doi.org/10.1080/13640461.2024.2447101>
38. K. Logesh et al. Injection mould processing and characteristics measures of hybrid epoxy composites with jute fiber/boron nitride. J Mech Sci Technol. 39(1), 2025. <https://doi.org/10.1007/s12206-024-1219-1>
39. R.P. Singh et al. Influence of a Copper Layer on the Functional Behaviour of a Cadmium Telluride Solar Cell Processed via Thermal Evaporation. J. Electron. Mater. (2024). <https://doi.org/10.1007/s11664-024-11669-7>
40. R. Venkatesh Effects of ramie fiber/boron nitride exposure on the mechanical characteristics of injection-moulded polypropylene composites for automated structural applications. International Journal of Automotive Science and Technology. 2024; 8 (4): 451-456. <http://dx.doi.org/10.29228/ijastech..1528281>
41. Singh et al. Natural fiber-ceramic filler configured polypropylene hybrid composite made via hot compression technique: Characteristics evaluation. J Mech Sci Technol. 39(1), 2025. <https://doi.org/10.1007/s12206-024-1216-4>
42. S. Prabagaran et al. Texturing of silicon nitride passivation layers on functional behaviour study of polycrystalline silicon (p-Si) made with plasma enhanced chemical vapour deposition. J Mater Sci: Mater Electron 36, 73 (2025). <https://doi.org/10.1007/s10854-024-14135-6>
43. Melvin Victor De Poures et al. Effect of Gasification Temperature on Biohydrogen Derived from Waste Agro Products for Alternative Fuel Application " SAE Technical Paper 2024-01-5260, 2024, <https://doi.org/10.4271/2024-01-5260>
44. V. Mohanvel et al. Ferric oxide nanofluid on functional properties of parabolic trough solar collector under different flow rate, Applied Thermal Engineering (2025). Volume 265, 2025,125608, <https://doi.org/10.1016/j.applthermaleng.2025.125608R>.
45. Ravindra Pratap Singh et al. Enhancement and thermal performance evaluation of parabolic trough solar collector with the integration of innovative snail porous material. ASME. J. Thermal Sci. Eng. Appl. (2025) 1-23. <https://doi.org/10.1115/1.4067588>
46. 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.
47. Logesh, K., Vinayagam, M., Kumar, A., Chaturvedi, R., Prabagaran, S., Soudagar, M. E. M., Salmen, S. H., and Al Obaid, S. (2025). "Solar collector featured dryer performance enriched by the adaptations of phase change material embedded with fin collector absorber." ASME. J. Thermal Sci. Eng. Appl. doi: <https://doi.org/10.1115/1.4067631>
48. 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.
49. Murali, J. G., Marimuthu, S., Vignesh, P., Prakash, P., Kaliyannan, G. V., & Karthikeyan, S. (2025). Influences of silicon carbide particles on tensile performance and hardness behavior of polyethylene composites made via injection mold. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020292). AIP Publishing LLC.
50. Marimuthu, S., Ashokkumar, R., Karthick, S., Karthikeyan, A., Karthikeyan, S., & Gunasekaran, R. (2025). Synthetic fiber featured epoxy composite for light weight application: Performance measures. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020293). AIP Publishing LLC.
51. Karthikeyan, S., Ganesan, S., Suresh, A., Muruganandhan, P., Jebasingh, B. E., & Manogar, K. (2025). Impact of E glass fiber on functional properties of low density polyethylene composite made via compression mold. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020243). AIP Publishing LLC.