Extraction and Performance Evaluation of Hydrogen from Microalgae via Hydrothermal Gasification Process

C Chinnathambi1, S Arul1, S Jeyaprakasam1, K M Senthilkumar2, M Elango3,a), R Mohan4, R Girimurugan5, S Arunkumar6, V Mohanavel7

1Department of Mechanical Engineering, K.S.Rangasamy College of Technology, Tiruchengode,

637215, Tamil Nadu, India.

2 Department of Mechanical Engineering, Kumaraguru College of Technology, Coimbatore, Tamil

Nadu 641049, India.

3 Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thuduppathi,

638057, Tamilnadu, India.

4 Department of Mechanical Engineering, Sona College of Technology, Salem,

636005, Tamil Nadu, India.

5 Department of Mechanical Engineering, Nandha College of Technology, Vailkaalmedu, Tamil

Nadu 638052, India.

6 Department of Mechanical Engineering, Vel Tech Multi Tech Dr.RangarajanDr.Sakunthala

Engineering College, Chennai, Tamil Nadu 600062, India.

7Department of Mechanical Engineering, Chandigarh University, Mohali 140413, Punjab, India

Corresponding author: a)*elango3088@gmail.com*

**Abstract.** The microalgae are familiar for hydrogen production due to their higher lipid content, carbon neutrality, and high biomass provide better hydrogen. Current research is enriching the hydrogen yield from microalgae and utilized for alternative fuel blends for CI (compression ignition) engines. With the support of the hydrothermal gasification process, the hydrogen is extracted from waste microalgae with constant gasification temperature and varied residence time of 30-90 min with 30 min intervals. Influences of gasification residence time on syngas and molar fraction performance is evaluated, and optimum hydrogen yield is used as an additive for the CI engine. The biohydrogen is mixed with diesel fuel in different ratios and evaluates the CI engine performance. Based on the investigation, the 430 ⁰C gasification temperature with 90 min residence time found maximum hydrogen yield (14.8 mol/kg), which is used for diesel blend. The compression ignition engine utilizes bio-hydrogen energy combined with a diesel blend in ratios of 10:90, 20:80, and 30:70. CI engine brake thermal efficiency/specific fuel consumptions were measured under applied electrical loads of 1 kW, 3 kW, and 5 kW. When compared to traditional diesel fuel, the 30:70 hydrogen-to-diesel fuel ratio significantly enhanced engine performance. Specifically, brake thermal efficiency improved by 34%, with fuel consumption recorded at 326 g/kW·hr.

# Introduction

Renewable energy was the prime source for maintaining a green environment secure with air, water, and natural quality. Bioenergy development was fulfilling the world energy demand [1-2]. This kind of bioenergy was derived from household waste, plastic waste, biochar, coal dust, sewage sludge, and microalgae. The trend for hydrogen energy synthesized from plastic waste material by biogas conversation technique. The thermal management system was analyzed via CFD [3]. The hydrogen energy was received from mining wastewater through the electrolysis technique and reported that the hydrogen yield was improved by 33% with 71% hydrogen purity. Biological capture of microalgae was limiting carbon capture. Hydrogen is derived from food waste through a supercritical water gasification process operated with 400 to 450º for 20 to 60 minutes. It showed a 12.73mol/kg hydrogen yield [4].

Moreover, gasification was the most prominent method for producing bioenergy [5-6]. Bio-hydrogen was synthesized using solid waste via a co-hydrothermal gasification technique to find the maximum hydrogen yield. The hydrothermal gasification technique synthesizes the Hydrogen and methane gas production from microalgae waste under 430ºC temperature for one hour in a catalyst reactor. The output behaviour showed a 43.11% molar fraction, and hydrogen and methane have 5.75mmol/g and 6.17mmol/g [7]. The nickel catalyst was adopted in thermal management and was rich in hydrogen gas. The microalgae treated at 430ºC under a 60-minute process found a superior hydrogen yield with an increased gasification efficiency of 23.55% [8].

Recently, algal biomass was recycled by hydrothermal gasification process to produce hydrogen and studied the effect of gasification process parameters. Thermodynamic equilibrium was analyzed by system simulation software [9-10]. Initially, the microalgae were treated with solar radiation [11-15]. The hydrothermal gasification process adopted hydrogen production was made by using microalgal waste under the processing temperature of 500º for one hour and was found to have a maximum hydrogen yield of 1.85 times higher than the produced gas (molar fraction) [16-19]. Aqueous phase treatment was adopted for hydrothermal liquefaction, and its economic analysis was studied. Its outcomes showed 21% economic compared to conventional techniques [20-26]. The advanced materials were found to have good thermal behaviour and reduce cost [27].

Due to the above literature study, the hydrothermal gasification process was found economical and efficient for hydrogen production and 430ºC temperature under 30-90 mins duration was estimated. This research enhances the hydrogen yield by using constant gasification temperature (430ºC) with varied time duration of 30-90 minutes. The impact of processing time on molar fraction and hydrogen yield was measured, produced hydrogen was mixed with diesel and the electrical energy performance was found.

# Materials and Methods

Flow process illustration for hydrogen as microalgae via hydrothermal gasification with a constant stir catalyst is presented in Figure 1.

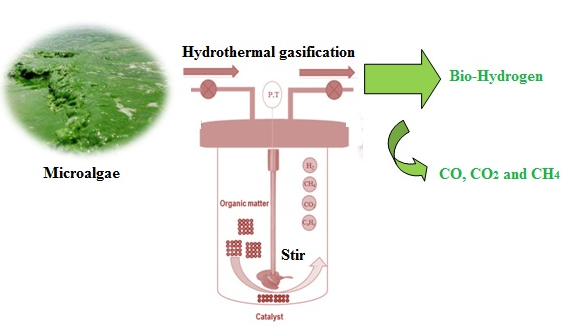
.

Fig. 1 Flow process figure for hydrogen synthesis as of waste microalgae through a hydrothermal gasification process

The waste microalgae were collected and kept in an open atmosphere with solar radiation treatment. Afterwards, it was held in a hydrothermal gasification unit with an applied temperature of 460ºC under constant stir operation made with a catalyst. The experimental setup of hydrothermal gasification is shown in Fig. 2. It was configured with a constant stir setup catalyst, heat exchanger, membrane, and gas flow pipes. The control panel limited the temperature for gasification [28-31].

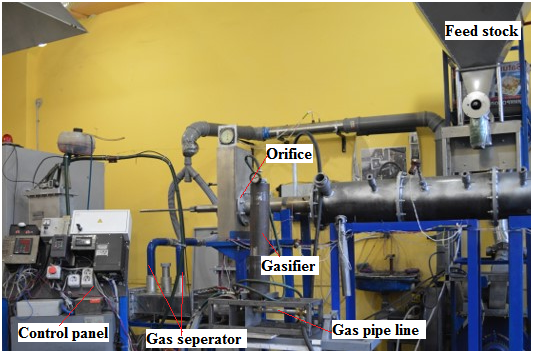


Fig. 2 Hydrothermal gasification setup

The collected microalgae were fed into a feedstock hopper and heated at 430ºC for 30, 60, and 90 minutes. It was subjected to a gasification process; the syngas were generated with CO, CO2, CH4, and H combinations. During the process, the waste heat was recovered by means of the heat exchanger and supported the gasifier unit with flow through orifice setup. The syngas were controlled and directed to the separator, and various gas concentrations were found. The maximum gas concentration was directed to storage, and other gases were directed to neutralize. The collected microalgae were fed into a feedstock hopper and heated at 460ºC for 30, 60, and 90 minutes. With the support of time duration, the molar fraction was noted. However, the 430ºC has facilitated good hydrogen yield. Finally, H gas is subjected to produce electrical energy usage [32-35]. However, hydrogen fuel has great potential for electrical application with reduced pollutants. According to the hydrogen yield, mixed by diesel and investigated the electrical energy performance for energy-holding applications. The actual setup of the CI engine with the electrical generator is indicated in Figure 3.

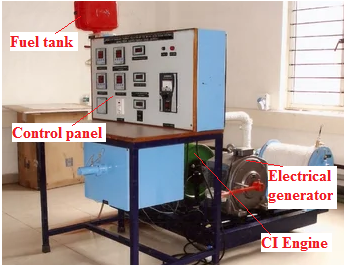


Fig. 3 Hydrogen-operated CI engine with electrical storage

# Results and Discussion

## The molar fraction of syngas

The impact of gasification time on molar fraction and gasification efficiency of microalgae recycled H production is illustrated below in Figure 4.

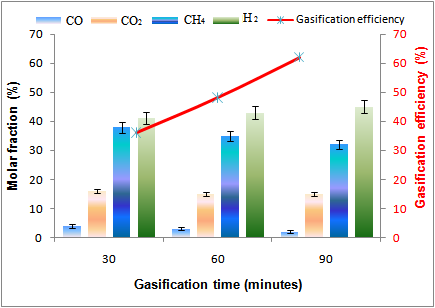


Fig. 4 Effect of gasification time on molar fraction

It was measured at 430ºC at 30, 60, and 90 minutes time duration. From Fig. 4, the CO, CO2 and CH4 concentrations decreased with increased period. It was due to the thermochemical changes at higher temperatures. Moreover, the higher gasification temperature with extended duration enhanced hydrogen yield with reduced CO and CO2. Based on the time duration, the chemical changes on biomass found variations in CO, CO2, CH4 and H2 yield. Effective temperature with higher time was superior to thermochemical reaction [12 and 19]. In addition, hydrogen yield gradually increased from 41, 43, and 45% with an improved time of 30, 60, and 90 minutes under 430ºC. The choice of catalyst and its process parameters of the gasification process fix the hydrogen yield [36-40]. However, the fraction of hydrogen was larger than the other gas. It was recorded at 45% at 90 minutes and improved by 9.7% yield compared to the 30-minute operated gasification process [50-52].

## Syngas yield

Fig. 5 indicates the bar chart illustration for syngas synthesized for the gasification process at 430ºC temperature for 30, 60, and 90 minutes. It was noted from Fig. 5 that the hydrogen yield munch is larger compared to others. The increased time duration facilitates an increase in the chemical reaction. It results in a maximum volume of H gas yield. At 430ºC for 60 minutes, the gasification process recorded 5.75m mol/g of hydrogen yield [41-45].

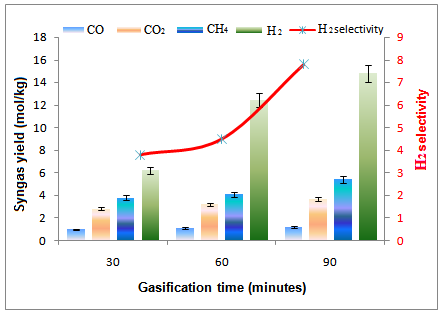


Fig. 5 Effect of gasification time on hydrogen gas yield

In addition, maximum gasification time and 460ºC showed the least CO, CO2, and CH4 volume compared to hydrogen. The maximum hydrogen, 14.8mol/kg, was noted at 90 minutes of gasification time with 7.8 hydrogen sensitivity. The main reason for improved hydrogen yield was the efficient thermal reaction between the microalgae under a constant stir catalyst. The effective selection of catalysts was found to enhance performance [22-23]. Supercritical temperature leads to enhancing the quality of the process [46-47].

## Brake-specific fuel consumption (different blends with electrical loading)

Fig. 6 illustrates the impact of the blending of diesel: hydrogen ratio by the varied electrical loading on BSFC of the CI engine. While 1kW loading with varied fuel blend ratio recorded a gradual decrease in fuel consumption due to hydrogen gas having great thermal behaviour related to diesel. An impact of 0, 10, 20, and 30% hydrogen blended by diesel was found to be 348, 338, 320, and 300g/ kW.hr. While improving the electrical energy as 3kW and 5kW showed increased fuel consumption compared to 1kW electrical load [48].

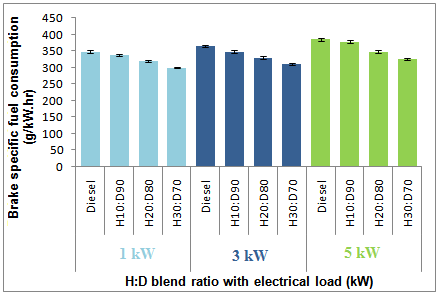


Fig. 6 Brake-specific fuel consumption (varied diesel/hydrogen blend and electrical loading)

The engine operated with a 30:70 hydrogen/diesel blend ratio under 5kW, and electrical loading recorded 326g/kW.hr BSFC, and related to diesel fuel operated under a 5kW electrical load, an 18% fuel save was found.

## Brake thermal efficiency (different blends with electrical loading)

Fig. 7 bar chart indicates an effect of the diesel: hydrogen fuel blend ratio with varied electrical loading on CI engine brake thermal efficiency. In the fuel blend ratio and electrical loading, the brake thermal efficiency progressively increased & was found to be maximum efficiency [26]. While 1kW electrical loading, the engine's brake thermal efficiency (BTE) with an electrical storage system was raised by 22, 25, 27, and 32% by the blending ratio 0:100, 10:90, 20:80, and 30:70, respectively.

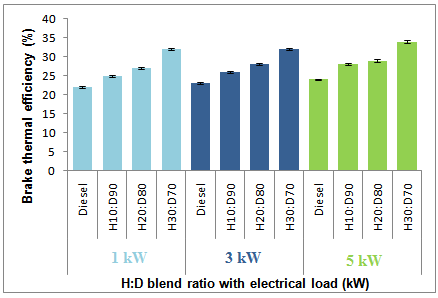


Fig. 7 BTE (varied diesel/hydrogen blend and electrical loading)

In addition, the BTE of the CI engine was evaluated by 3kW electrical power and found increased thermal efficiency compared to 1Kw electrical power. Similarly, 3kW electrical power showed significant improvement in BTE & a 30:70 blend ratio offered 34% BTE, raised by 42% related to diesel fuel. The enhancement of BTE was the hydrogen gas facilitating high thermal properties related to diesel engines [12 and 49]. In past decades, CI engines utilized by diesel fuel have been found to have low BTE.

# Conclusion

Hydrothermal gasification was implemented with a constant stir catalyst for H gas synthesis as microalgae waste. Its gasification process parameters like temperature were fixed at 430ºC, and the process duration varied from 30 to 90min respectively. Action on gasification time on hydrogen yield was studied, & a maximum yield of hydrogen of 14.8 mol/kg was found with a molar fraction of 45%. The developed hydrogen gas blends with diesel as 0, 10, 20, and 30% and its performance was successfully investigated via CI engine with an electrical load setup. The 30H:70D blend ratio found significant electrical storage performance (5kW) with a saving of 12% of brake-specific fuel. The BTE of the present system with 5kW power was recorded at 34%.

# References

1. S. Rajesh et al., "Enhanced photocatalytic performance of CuO nanoparticles synthesized via surfactant assisted hydrothermal method," Appl. Phys. A Mater. Sci. Process., vol. 130, no. 9, 2024
2. J. Gayathri, V. Meenakshi, C. Malathi, G. Kanaga, S. Radhika, and V. V. Kaveri, "Generating an IOT based knowledge base to analyze the microalgae growth," in 2024 10th International Conference on Communication and Signal Processing (ICCSP), IEEE, 2024.
3. P. Raja sekaran, K. Udayakumar, and M.B. Bayu, "Adsorption and photocatalytic degradation properties of bimetallic Ag/MgO/Biochar nanocomposites", Adsorpt. Sci. Technol. vol. 2022, Article ID 3631584, pp. 14, October. 2022.
4. B. İşcan, "Optimization of process parameters of medium carbon steel joints joined by MIG welding using Taguchi method," Eur. Mech. Sci., vol. 6, no. 1, pp. 17–26, 2022, doi: 10.26701/ems.989945.
5. D. Nagarajan, C.-D. Dong, C.-Y. Chen, D.-J. Lee, and J.-S. Chang, "Biohydrogen production from microalgae-Major bottlenecks and future research perspectives," Biotechnol. J., vol. 16, no. 5, p. e2000124, 2021,
6. R. Karthik, "Influence of stir casting parameters in mechanical strength analysis of aluminium metal matrix composites (AMMCs)", Mater. Today: Proc. vol. 62, pp. 1965-1968, June. 2022.
7. X. Hao, H. Suo, H. Peng, P. Xu, X. Gao, and S. Du, "Simulation and exploration of cavitation process during microalgae oil extracting with ultrasonic-assisted for hydrogen production," Int. J. Hydrogen Energy, vol. 46, no. 3, pp. 2890–2898, 2021,
8. A. Rai et al., "Hydrogen economy and storage by nanoporous microalgae diatom: Special emphasis on designing photobioreactors," Int. J. Hydrogen Energy, vol. 47, no. 100, pp. 42099–42121, 2022
9. J. Chandradass et al. “Experimental study of wear characteristics of Al2O3 reinforced magnesium based metal matrix composites," Mater. Today, vol. 14, pp. 211–218, 2019
10. 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.
11. 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.
12. 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.
13. 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>
14. 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>
15. 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>
16. 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>
17. 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>
18. 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>
19. 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>
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. 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>
23. 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.
24. 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>
25. 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.
26. 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.
27. 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.
28. 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.
29. 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>
30. 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>
31. 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>
32. 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>
33. 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>
34. 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>
35. 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>
36. 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>
37. 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.
38. 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.
39. 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>
40. 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>
41. 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.
42. 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>
43. 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>
44. 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>
45. 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>
46. 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>
47. 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>
48. 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>
49. 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>
50. Karthikeyan, S., Jagadheeswari, A. S., Murali, J. G., Kaliannan, G., Marimuthu, S., & Kalaiarasan, S. (2025). Hot compression actions on functional behavior of polyester composite configured with basalt fiber. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020294). AIP Publishing LLC.
51. Karthikeyan, S., Karthikeyan, A., Jose, B. K., Marimuthu, S., Sathish, T., & Murali, J. G. (2025). Influences of titanium carbide on behaviour of jute fiber made epoxy composite for automotive usage. In *AIP Conference Proceedings* (Vol. 3267, No. 1, p. 020296). AIP Publishing LLC.
52. Anu, T., Gobikrishnan, U., Karthikeyan, S., Chirag, S., Vishal, S., Aravindan, N., & Swathi, S. (2025). Enhancing power conversion efficiency of polycrystalline silicon solar cells through ZnO/SiO2/Al2O3 anti-reflective coatings via spin coating. *Journal of Ovonic Research, 21*(1), 75–84.