Employing Satellite Imagery to Identify and Assess Phosphorus in the Soil Loss Linked to Important Source Regions

G.Sivaraman1, Vijay Kumar Vinjamuri2, M.D.Raj Kamal3, V. Paranthaman4, M Ramya5,a), Vijayanandh Raja6

1 Department of Mechanical Engineering, Sona College of Technology, Salem 636005, Tamil Nadu, India.

2 Department of Civil Engineering, Aditya University, Surampalem, India.

3 Department of Mechanical Engineering, Velammal Institute of Technology, Chennai-601204. Tamil Nadu, India.

4 Department of Mechanical Engineering, Adhi College of Engineering, Chennai - 631605, Tamilnadu, India

5 Division of Research and Development, Lovely Professional University, Jalandhar - Delhi G.T.Road, Phagwara, Punjab– 144411, India.

6 Department of Aeronautical Engineering, Kumaraguru College of Technology, Coimbatore-641049, Tamil Nadu, India.

Corresponding Author: a)[ramyalpu@yahoo.com](mailto:ramyalpu@yahoo.com)

**Abstract:** The first and most important step in regulating soil P (phosphorus) degradation and avoiding long-term pollution of waterways at the regional scale is the identification of crucial sources (CASs). Nevertheless, the majority of relevant research concentrates on a local scale, making it difficult to comprehend the geographical spread of CASs for soil P depletion at the level of the region. Furthermore, there was little coverage of the ongoing, long-term fluctuation in CASs. With only the standard approaches employed at the local level, it is hard to pinpoint the causes of CSA change or gather the necessary land surface data for CSA identification. Relying upon three satellite sensors that were effectively utilized to identify CASs at a regional scale during a 15-year period, this work suggests a novel region-scale strategy. The approach included five elements that contribute to soil P loss through CASs: rainfall, gradient, soil loss, land use, and soil overall phosphorus. Results demonstrate that in a sampled, intense agriculture geographical region in India, crucial phosphorous supply areas (CPSAs) maintained an overall size of 17582 km2 throughout a fifteen-year span and made up 19.8% of the overall region, ranging from 1.3% to 33.0%.

**Keywords;** Satellite; Phosphorus loss; CPSAs detection; Eco HAT-P model; Regional scale

# Introduction

Phosphorus (P) is the main driver of the worldwide acceleration of groundwater, a condition called groundwater acceleration, and managing other sources according to P has become a typical solution. P sources other than point sources are receiving greater consideration, with a focus on creating strategies to stop agriculture's contribution to groundwater P deposition. Spatial analysis has revealed that tiny regions in a specific agricultural region account for the vast bulk of the P dumping into nearby lakes and rivers. Crucial sources (CASs) for P depletion are in such small locations. While P loss through CASs has been studied for more than ten years, it is still unknown how CASs are formed and detected. This is due to the fact that each of the interior P levels and externally motivated variables is responsible for the CASs [1]. Those CASs specify the locations on the terrain where significant P suppliers as well as elevated transport areas might meet. P loss component presence defines the creation of CASs. Despite the fact that several variables affect P loss, earlier research has identified five main ones: rainfall, geography, erosion of soil, development of land, and soil P concentrations. Surface water runoff and ground flow are two effects of rainfall that may substantially raise the amount of unresolved soluble P lost.

High terrain enhances soil deterioration and runoff from the surfaces, which in turn enhances the deposition of both soluble and particle P [2]. Despite being an involved procedure, soil deterioration significantly and immediately boosts the loss of particle phosphorus. Population growth is what alters the land's usage and cover. The amount of P leakage increases as soil levels of phosphorus rise [3]. Additionally, as the amount of agricultural land increased, greater quantities of fertilizer were used, which in turn caused soil loss. Additionally, the amount of P in land used for agriculture is rising globally, which facilitates P removal. The inherent structure of the soil and exogenous anthropogenic P intake both have an impact on P concentrations [4]. Two of the five things that lead to the rise in CASs are P source variables (S variables), which include land-use type and P focus, and P transportation variables, which include rainfall, terrain, and soil erosion. P-loss research that used in situ tests to discover these five parameters was the first to do so; nevertheless, further techniques are required to pinpoint crucial phosphorous supply regions [5]. Two of the main categories of CPSA detection techniques are ecohydrological designs, P-index models, and isotopic tracer technologies. The isotopic tracing method locates CPSAs by following a P-loss route using nuclear or uncommon-earth elements. A P-index model incorporates source and transit variables to rank an area's susceptibility to P loss and, as a result, discover CPSAs. Ecohydrological designs, particularly those powered by satellite images, are more routinely utilized to identify CPSAs. Nevertheless, such methods frequently fail to identify the causes of the geographical and chronological variance in CPSAs [6]. The main causes of the rise in CPSAs cannot all be taken into consideration by ecohydrological designs, which are adept at predicting nutrients load since isotope tracer technologies and the P index models often concentrate on a fine geographical level. The long-term spatial change in CPSAs was not taken into consideration in those investigations, however. Conversely, distant sensors offer evidence that is both geographically and temporally characterized. The results of the simulations that use remote sensing may allow for a separate measurement of P accumulation and a better understanding of how P moves. This method can also broaden the study in both space and time.

These investigations are essential to the understanding of CPSAs because P-source and P-transport variables might affect their position and extent at various geographical scales. The geographic region used in the present investigation is an area bigger than 10,000 square meters, and within this size, variables including land utilization, eroding soil, and the amount of rainfall have a greater impact on the creation of CPSAs. Various research techniques may be most appropriate for different levels of space. For instance, ecohydrological methods tend to be typically employed at drainage magnitude, P-index methods function well at crop level and agricultural magnitude, and isotopic tracer technologies are better suited for plotting level. The time scale research is relevant at the regional level but less so at the plot or farm level. At the fine magnitude, the precise spot and CPSA-generating parameters are consistent, but with time, they will vary at the regional size. Regarding CPSAs, there are a pair of difficulties that are still being addressed by the study. The first step is to investigate the important, but unidentified, elements that influence CPSAs at the level of regions. The following objective is to ascertain if the position and scope of the CPSAs constitute long-term stability in the area. The current study intends to 1) determine the major variables causing these CPSAs, 2) uncover CPSAs at a regional scale using imagery from drones and each of the five variables previously discovered in studies, and 3) exhibit the geographic spread of the CPSAs, As including their regions over time.

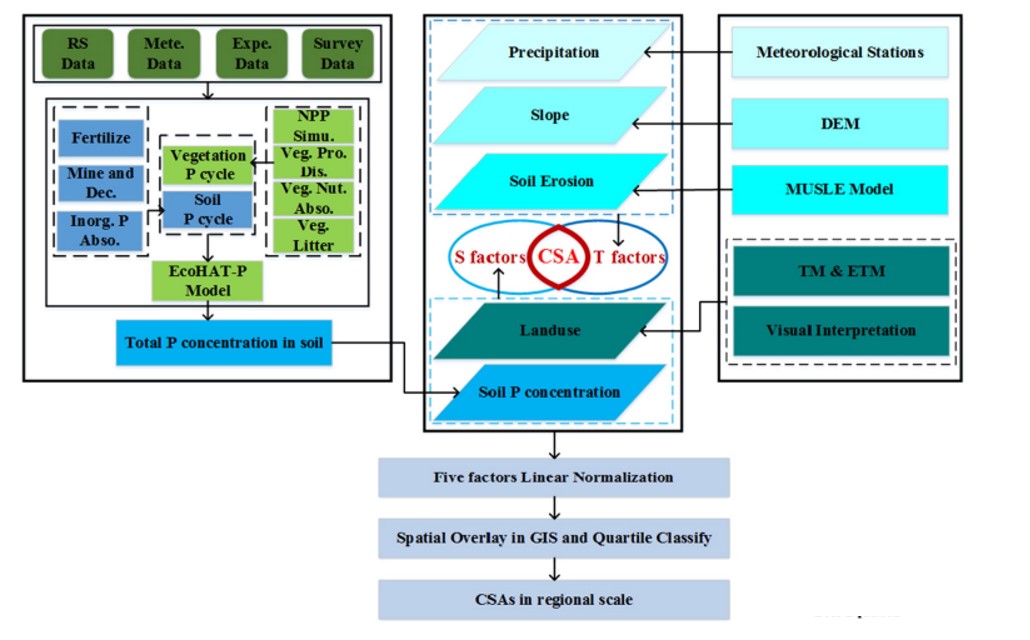
# Experimentations

## Study domain

In the northern part of China, there is a sizable region known as the Sinkiang Plain, which has low terrain. With an overall surface area of 109,700 km2, it is one of the nation's largest suppliers of agricultural products. 500–600 mm of precipitation falls annually. The arid and mid-humid desert weather has an average yearly temperature of 1.5 °C. The Zhanjiang Plateau is low in its northwestern centre, which is responsible for the abundance of sizable national farms there; mountain ranges are primarily found in the western and southern parts of the region [16-21]. Dry property, rice property, wet property, habitation land, green land, forest property, lake organisms, and undeveloped territory are the primary land-use kinds. The five predominant land-use classifications are agricultural land, woodlands, and moist property, which together make up 41.17%, 26.53%, and 9.71% of the entire surface.

## Identification of the CPSAs at regional scale

To find the CPSAs at a local level, both the source (S) and transit (T) components are merged. The geographical scale of the present investigation is an area that is more than 10,000 square miles in size; hence, the geographical resolution of the five components is 1 km. The precipitation that occurs on the slope, as well as eroded soil are among the T variables. In order to get the high-resolution images of daily precipitation information at a 1 km settlement, everyday rainfall information was collected from 13 national weather stations located in the Zhanjiang Plains. Giss was employed to determine the gradient using the DEM data at 30 m accuracy before scaling it up to 1 kilometre. The frequently employed MUSLE approach, which is powered by satellite imagery, was utilized to determine how much soil loss there is. Information on land usage and soil P content are two of the S variables. Vision interpreting was used to gather TM and ETM picture data as well as derive land-use information from the photographic data. The EcoHAT-P ecohydrological approach, influenced by satellite imagery, computed the soil's P content [22-25]. The EcoHAT-P (Ecohydrological Assessment Tool-Phosphorus) emulates individuals’ dirt, establishes P-cycle algorithms, and incorporates the P transformation and P movement in the greenery in addition to in the soil itself, the two of which are capable of exactly modelling the production and fluctuation of P in the ground. The simulation framework includes eight chemically and environmentally correlated sub-models. The inputs that are used for a simulation include data from surveys, experiments, and remote sensing, as well as weather-related information. The EcoHAT-P simulation is informed by geographical knowledge and generation, and although remotely detected pictures are used to replace the model's variables, the parameters are geographically dispersed in a rectangular pattern. Figure 1 shows the flow chart of EcoHAT-P method [26-31].



**Fig.1** EcoHAT-P model construction and research approach diagram

The outcome has a time precision of a single day and a spatial dimension of 1 km. All of the sub-models were combined and made operational using IDL. To find the CPSAs, the data from the distance sensing led modelling were integrated with those from each of the three drive elements. The exact same resolution of the space and geography location systems was subsequently applied to all five variables after they had each been analysed in photographic form. Then, in order to calculate the geographical overlay, an exponential normalizing approach was utilized to provide figures for each of these five driving variables in coefficients that ranged from 0.2 to 0.99. Atlas was applied to calculate the temporal overlaying, and its findings were then categorized using the percentile classifications approach [32-35]. It can quickly identify the regions having soil phosphorus loss at a global level; those places are referred to as P deficit CASs.

# Results

## Validation of the input data to EcoHAT-P model

Information on surface temperatures of land using MODIS goods, interpolated data on rainfall using national weather observatories, the temperature of the air (Fig. 3C), and the velocity of the wind at 2m using GLDAS data comprised the four common input information components used by EcoHAT-P. HOBO automated meteorology sensor observations were employed to confirm the data. The validation process verified that the provided information from remote sensing complies with EcoHAT-P specifications. From the fifteenth of July 2013, to October 31, 2015, information for 487 dates was gathered from HOBO automated weather observatories in the Bawumia Ranch. At the spatial resolution of 1 km, Dams LST and GLDAS Tair exhibit excellent accuracy of the data, with R2 coefficients of 0.92 as well as 1.97 and RMSE values of 2.82 and 0.65, respectively [7, 36-40]. In contrast, the data quality for GLDASU2 as well as smoothed precipitation measurements at a spatial scale of one kilometre is less, with R2 values of 0.71 and 0.67 and an error of root mean squares (RMSE) of 0.65 and 0.57, respectively. This indicates that each of these meteorological factors can be more accurately measured using remote sensing techniques than rainfall and the speed of the wind. The coefficient of variation is reduced as a result of the accessible rainfall centre and extrapolation techniques, and the information concerning precipitation is also less sensitive to insignificant rainstorm occurrences (B). Since air flow is unpredictable and complicated, it is challenging to measure wind speed with high accuracy employing distant detection (D).

## Geographical percentage of CPSAs during a 15-year period

Although the CPSAs failed to encompass up to 20% of the study's sample territory on the local level each year, they showed a consistent upward trend throughout the course of the final six-year period of the investigation. The highest CPSA area during the fifteen years prior was in 2013, when it reached 25,129 km2, taking up 23 percent of the total Zhanjiang Plain. The most compact region in the 15-year research time frame, the CPSAs in 2008 covered 1400 km2, or about 1.5 percent of the flat. Over the course of fifteen years, there have been noticeable oscillations in each of the four soil protein loss classes, with distinct trajectories [8]. The relatively low as well as low soil P losses rating categories showed a similar variable tendency, showing notable changes in both categories during 2001 to 2010; at the exact same period of time, these two distinct categories took up the most space among the five categories [41-45]. The low, moderate, high, and extremely high classes are those with the greatest likelihood for soil P sadness, while between 2004 and 2014, those exhibited virtually identical variance trends [9].

During 2002 and 2010, both of these subgroups' inverted variance patterns showed that the categorization of one organization's soil P loss had an impact on the other's [10]. During the course of the fifteen-year span, CPSAs had an average area of 15,756 km2, accounting for 13.8 percent of the entire region. Although there is a noticeable volatility among CPSAs throughout the research time frame, this variability grows throughout the course of the entire 15 years. CPSAs grew by 24,729 km2 between 2007 and 2012, increasing by an average of 16.6 percent and 3854 km2 yearly [11]. However, 2008 marks the turning point: through 2002 to 2005, the normal CPSA was about 13,050 km2 in size and accounted for about 13.1% of the overall acreage; through 2008 to 2015, the mean CPSA had been nearly 16,190 km2 in size and made up approximately 15.9% of the entire land. The ongoing rise in CPSAs indicates that the soil P loss in the Zhanjiang Plains has reached an essential point [46-50]. The research's ability to pinpoint precise data on the quantity and distribution of CPSAs for every single year sets it apart from other research results, which only presented a hazy picture of the CPSA population over a short amount of time [12].

## Long-term spatial-temporal changes in CPSAs: Features

At the local level, CPSAs may either be pooled or scattered; their positions are not stable over the long term. At the exact same period of time, their ratio changes over obvious time. In the Chinese Zhanjiang Plain, the CPSAs constituted a median of about 12250 km2 and accounted for about 12.1% of the overall area between 2003 and 2005; from 2006 to 2015, they constituted a mean of about 17,180 km2 and made up about 18.9% of the entire territory [13, 51-52]. These contrast with the findings of earlier research at the tiny drainage or small agricultural magnitude, which concentrated on identifying CPSAs and their geographical positions at a particular period. In actuality, CPSAs don't seem geographically secure, especially at the regional level. While most of the underlying elements are controlled in certain small-scale business research, constant CPSAs over one term pose more of a worry at a plot or crop level since the investigation region is smaller and each of the five producing components is somewhat more stable than at a large scale [14]. In the future, local-size CPSA creation will be more complex. Natural occurrences and activities by humans have a greater ability to alter the factors that generate CPSAs. Experiments conducted at the level of region are unable to control the above variables, which might result in the identification of unstable areas and a variable geographical distribution of CPSAs [15].

# Conclusion

Integrating five main elements impacting CPSAs at the local level, a novel technique built on satellite imagery was effectively used for identifying CPSAs during a 15-year period. For every year of the research time frame, we accurately determined the proportion and geographic distribution of the CPSAs. Additionally, we determined the primary driving forces of CPSAs at the regional level. During the course of fifteen years, the median area of CPSAs became 15,756 km2, accounting for 14.8% of the total surface area, within an assortment of 1.5 percent to 24.0%. The CPSAs' placements didn't remain consistent, and with time, their geographical dispersion became increasingly fragmented. The main element in the creation of CPSAs at a local level is rainfall. By exploring the mechanisms influencing CPSA variability on an extensive scale, this novel technique may assist in the long-term handling of phosphorous (P)) losses and avoid the depletion of nearby waterways on a local level.

# References

1. Tripathi, M. P., Panda, R. K., & Raghuwanshi, N. S. (2003). Identification and prioritisation of critical sub-watersheds for soil conservation management using the SWAT model. *Biosystems Engineering*, *85*(3), 365-379.
2. De Vente, J., & Poesen, J. (2005). Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. *Earth-science reviews*, *71*(1-2), 95-125.
3. 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
4. Easton, Z. M., Fuka, D. R., Walter, M. T., Cowan, D. M., Schneiderman, E. M., & Steenhuis, T. S. (2008). Re-conceptualizing the soil and water assessment tool (SWAT) model to predict runoff from variable source areas. *Journal of hydrology*, *348*(3-4), 279-291.
5. Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience*, *3*(5), 311-314.
6. 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
7. Fistikoglu, O., & Harmancioglu, N. B. (2002). Integration of GIS with USLE in assessment of soil erosion. *Water Resources Management*, *16*, 447-467.
8. Pionke, H. B., Gburek, W. J., & Sharpley, A. N. (2000). Critical source area controls on water quality in an agricultural watershed located in the Chesapeake Basin. *Ecological engineering*, *14*(4), 325-335.
9. Vala et al., (2024). Investigation of varying tip clearance gap and operating conditions on the fulfilment of low-speed axial flow fan. International Journal of Turbo & Jet-Engines, (0). https://doi.org/10.1515/tjj-2024-0067
10. Bhaduri, B., Harbor, J. O. N., Engel, B., & Grove, M. (2000). Assessing watershed-scale, long-term hydrologic impacts of land-use change using a GIS-NPS model. *Environmental management*, *26*, 643-658.
11. Woldesenbet, T. A., Elagib, N. A., Ribbe, L., & Heinrich, J. (2017). Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin, Ethiopia. *Science of the Total Environment*, *575*, 724-741.
12. Mehta et al., (2024). Twisted tape inserts in parabolic trough solar collectors: Assessment of Energy, Exergy, and Environmental impacts. *Applied Thermal* Engineering, 250, 123566.
13. R, Rajarajan et al. (2025). Improving Tribological Performance and Structural Analysis of Aluminium Hybrid Nanocomposites with Nano ZrO2/SiC Reinforcement via Stir Casting Assisted with Ultrasonic Vibration. International Journal of Cast Metals Research, February, 1–14. https://doi.org/10.1080/13640461.2025.2467611
14. P. K. Singh et al. Enhancement of silicon nitride layer performance by Gallium–Copper–Zinc tri-layer thin films structure via plasma featured chemical vapour deposition route. J Mater Sci: Mater Electron 36, 243 (2025). https://doi.org/10.1007/s10854-025-14326-9
15. V.V. Upadhyay et al. Trapezoidal fin featured heat exchanger performance enriched by using alumina/GNP hybrid nanofluid: thermal characteristics study. J Therm Anal Calorim (2025). https://doi.org/10.1007/s10973-025-13997-0
16. Malladi et al., (2024). Effectiveness of thermal and mechanical properties of jute fibers under different chemical treatment for automotive interior trim (No. 2024-01-5008). SAE Technical Paper. https://doi.org/10.4271/2024-01-5008
17. A. Sharma et al. Hybrid Reinforcement Actions on Microstructural, Physical and Mechanical Properties of Magnesium Alloy Composite by Two-Step Stir Casting Process. Inter Metalcast (2025). https://doi.org/10.1007/s40962-024-01537-9
18. 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
19. 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
20. 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.
21. 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
22. Ashok et al., (2024). Effect of Stacking Sequence on Mechanical Properties of Bamboo/Bagasse Composite Fiber for Automobile Seat Cushions and Upholstery Application (No. 2024-01-5013). SAE Technical Paper. https://doi.org/10.4271/2024-01-5013
23. Chaturvedi, Abhay, Mudit Mittal, Swapnil Uttamrao Deokar, Rachit Adhvaryu, and G. Satish. Dual Active Bridge Converter Output Current Ripple Prediction in EV Battery Chargers Through Multimodal Adaptive Spatio-Temporal Graph Neural Network. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 32-37. IEEE, 2025.
24. Al-Safi, JehanKadhim Shareef, Tanusha Mittal, Najmuddin Aamer, and Harshal Patil. Smart Grids: AI-Enabled Energy Management and Demand Forecasting. In 2025 International Conference on Frontier Technologies and Solutions (ICFTS), pp. 1-6. IEEE, 2025.
25. Pandian et al., (2024). Analyzing the Moisture and Chemical Retention Behavior of Flax Fiber–Ceramic Hybrid Composites for Automotive Underbody Shields (No. 2024-01-5006). SAE Technical Paper. https://doi.org/10.4271/2024-01-5006
26. Seeniappan et al., (2024). Surface Modification of Henequen Fibers with Catalyst for Improving Mechanical and Thermal Properties in Phenolic Composites for Automotive Uses (No. 2024-01-5029). SAE Technical Paper. https://doi.org/10.4271/2024-01-5029
27. Mariya Louis et al., Multiresponse optimization and network-based prediction modelling for the WEDM of AM60B biomedical material. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 238(20), 10045-10066. https://doi.org/10.1177/09544062241264
28. 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>
29. Muda et al., (2024). Innovative Blockchain Protocol for Enhancing Transaction Security and Integrity in Decentralized Financial Ecosystems. In 2024 International Conference on Data Science and Network Security (ICDSNS)(pp. 1-6). IEEE. https://doi.org/10.1109/ICDSNS62112.2024.10691288
30. Lakshmaiya et al., (2024). Mechanical and thermal characteristics of coir powder-filled epoxy composites for industrial application. Engineering Proceedings, 61(1), 13. https://doi.org/10.3390/engproc2024061013
31. Prasad, P. Venkata, and Chrispin Jiji. Spiking Deep Residual Network Optimized Using Pied Kingfisher Optimizer for Renewable Energy Forecasting in Microgrids. In 2025 International Conference on Inventive Computation Technologies (ICICT), pp. 1-7. IEEE, 2025.
32. 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.
33. 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
34. 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
35. M. Aruna et al. Vacuum Die Casting Process and Microstructure/Mechanical Characteristics Study of Magnesium Alloy Composite Hybridize with Zirconium Dioxide and Silicon Nitride. Inter Metalcast (2025). https://doi.org/10.1007/s40962-025-01550-6
36. Soudagar, M. Manzoore Elahi et al. Effect of electron transport layer thickness and characteristics behaviour of hybrid copper indium gallium selenide thin film solar cells, Journal of Power Sources (2025). Volume 639, 2025,236657, https://doi.org/10.1016/j.jpowsour.2025.236657
37. N. Nagarajan. et al. Thermal performance assessment of dish collector-integrated cooking application using TiO2/SiO2 hybrid nano-enhanced coated receiver. J Braz. Soc. Mech. Sci. Eng. 47, 148 (2025). https://doi.org/10.1007/s40430-025-05454-8
38. Manzoore Elahi M. Soudagar, et al. Enrichment of Solar Heat Exchanger Thermal Performance by the Integration of Beeswax and Hybrid Nanofluid (ZnO/MgO). ASME. J. Thermal Sci. Eng. Appl. (2025) https://doi.org/10.1115/1.4067929
39. N. Nagabhooshanam et al. Influences of Potassium Fluoride and Ultrasonic Vibration on Functional Performance of AZ91 Alloy Hybrid Nanocomposite with Nano-SiC/TiO2. Inter Metalcast (2025). https://doi.org/10.1007/s40962-025-01552-4
40. I. Hossain et al. (2025). Enriching performance of Al-Mg composites by incorporating nano-alumina and SiC via semi-solid stir processing. International Journal of Cast Metals Research, 1–11. https://doi.org/10.1080/13640461.2025.2476826
41. Balaji, N., & Mahesh, V. (2024). Dynamic Mechanical and Thermal Properties of Polymer-Coated Jute Fibers for Enhanced Automotive Parts (No. 2024-01-5019). SAE Technical Paper. https://doi.org/10.4271/2024-01-5019
42. Surakasi, R., Muthu, G., Paramasivam, P., & Shanmugam, K. (2024). Effectiveness of natural dye adsorption on ILSS and optical properties of bio synthesised TiO2 nano particles and reinforced with flax seed fiber/epoxy based hybrid composites. Discover Applied Sciences, 6(3), 125. https://doi.org/10.1007/s42452-024-05758-9
43. Karthick, M., Bhaskar, K., Chukka, N. D. K. R. (2025). Development of eco friendly hybrid nanocomposites with improved antibacterial and mechanical properties through NaOH treated natural fibers. Results in Engineering, 104996.
44. Dutt, Sudershan, et al. Emerging EM wave sensors for non-invasive glucose monitoring: review, techniques and developments. Sensors and Actuators Reports 9 (2025): 100282.
45. Matharu et al., (2024). Developing an AI-Driven Personalization Engine for Real-Time Content Marketing in E-commerce Platforms. In 2024 15th International Conference on Computing Communication and Networking Technologies (ICCCNT) (pp. 1-6). IEEE. https://doi.org/10.1109/ICCCNT61001.2024.10725400
46. Kaliappan et al., (2024). Polypropylene Composite Materials with Natural Fiber Reinforcement: An Acoustic and Mechanical Analysis for Automotive Implementations (No. 2023-01-5130). SAE Technical Paper. https://doi.org/10.4271/2023-01-5130
47. Anitha, Cuddapah, G. Vipashi Kansal, Swapnil Uttamrao Deokar, Kamal Sutaria, and Ravi Kumar. Bi-Directional Power Control in Grid-Connected Electric Vehicle On-Board Chargers using Spider Wasp Optimization. In 2025 5th International Conference on Trends in Material Science and Inventive Materials (ICTMIM), pp. 517-522. IEEE, 2025.
48. Stalin et al., (2024). Innovative cinque rib-roughened stimulators on performance improvement in triangular channel solar air heater. International Journal of Low-Carbon Technologies, 19, 227-235. https://doi.org/10.1093/ijlct/ctae002
49. 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
50. 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
51. Anand et al., (2024). A comprehensive analysis of small-scale building integrated photovoltaic system for residential buildings: Techno-economic benefits and greenhouse gas mitigation potential. Journal of Building Engineering, 82, 108232. https://doi.org/10.1016/j.jobe.2023.108232
52. Mehta et al., (2024). Twisted tape inserts in parabolic trough solar collectors: Assessment of Energy, Exergy, and Environmental impacts. Applied Thermal Engineering, 250, 123566. https://doi.org/10.1016/j.applthermaleng.2024.123566