



RESEARCH NEXUS

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From the Editorial Desk

“The future is not discovered by chance-it is designed through research.”

Every scientific breakthrough begins with the courage to ask a meaningful question. The answers to those questions have the power to reshape industries, protect the environment, strengthen infrastructure, improve healthcare, and ultimately transform society.

The articles presented in this edition of Research Nexus reflect this spirit of purposeful inquiry. They showcase how scientific knowledge is being translated into practical solutions-from converting biological and agricultural waste into high-value materials, to advancing intelligent computing, strengthening critical infrastructure, improving energy systems, and developing technologies that address emerging societal needs.

What unites these diverse contributions is a common vision: innovation with impact. Across disciplines, our researchers are developing solutions that are not only scientifically rigorous but also sustainable, scalable, and aligned with global priorities. Whether through circular resource utilization, intelligent engineering, resilient construction materials, quantum-secure digital systems, or next-generation diagnostic technologies, each study represents a step towards a smarter and more sustainable future.

Research today thrives at the intersection of disciplines. The convergence of engineering, computing, materials science, environmental science, biotechnology, and applied research is creating opportunities that were unimaginable only a decade ago. This interdisciplinary approach is increasingly becoming the driving force behind scientific discovery and technological advancement.

At Vignan, we believe that research finds its greatest purpose when it extends beyond publications to generate knowledge that addresses real-world challenges, fosters innovation, and contributes to national development and global sustainability. The achievements featured in this issue are a reflection of our faculty's dedication to excellence, collaboration, and societal impact.

As you explore the pages that follow, we invite you to look beyond the results and appreciate the ideas, curiosity, and perseverance that shaped them. May this edition inspire new collaborations, new questions, and new discoveries..

As you explore the pages that follow, we invite you to look beyond the results and appreciate the ideas, curiosity, and perseverance that shaped them. May this edition inspire new collaborations, new questions, and new discoveries.

Happy Reading!



RESEARCH NEXUS



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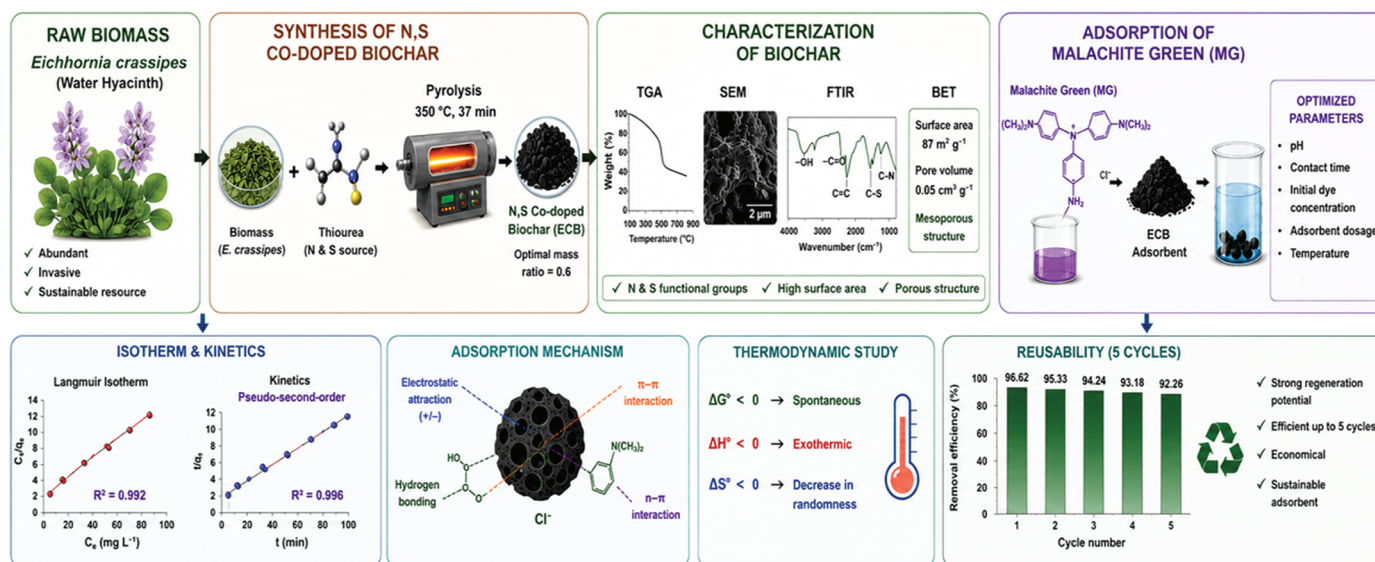
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Waste to Wealth: Transforming Water Hyacinth into Sustainable Biochar for Cleaner Water



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Graphical Abstract



At a Glance

Industrial wastewater containing Malachite Green is a major environmental concern because of its toxicity, persistence, and harmful effects on aquatic ecosystems and human health. This research converts the invasive aquatic weed *Eichhornia crassipes* (water hyacinth) into a high-performance nitrogen and sulfur-doped biochar using a sustainable thiourea-assisted pyrolysis process. The optimized biochar exhibited an adsorption capacity of **133mg g⁻¹**, efficiently removing Malachite Green through electrostatic attraction, hydrogen bonding, and π - π interactions. The material retained excellent adsorption efficiency even after five regeneration cycles, demonstrating remarkable reusability. By transforming an environmental nuisance into a valuable adsorbent, this work provides an economical, sustainable, and environmentally friendly solution for wastewater treatment while promoting biomass valorization and circular bioeconomy.

Why This Research Matters?

Water pollution caused by synthetic dyes released from textile and dye-manufacturing industries continues to threaten aquatic ecosystems, biodiversity, and public health.

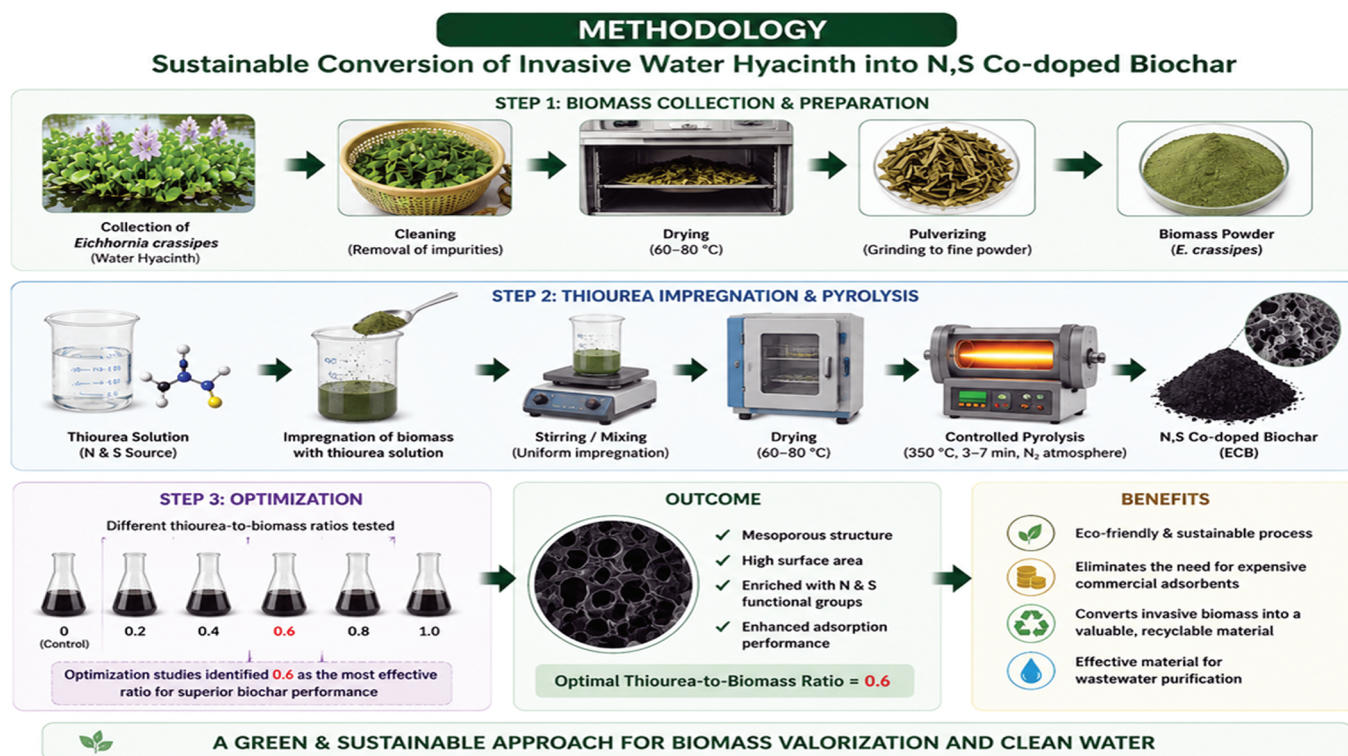
Conventional wastewater treatment technologies are often expensive, energy-intensive, or produce secondary pollutants. Simultaneously, water hyacinth has become one of the world's most destructive invasive aquatic weeds, blocking waterways and disturbing aquatic ecosystems.

This research addresses both environmental challenges simultaneously by converting invasive water hyacinth into a highly efficient biochar adsorbent capable of removing toxic dyes from wastewater. The study demonstrates how an unwanted biomass can be transformed into a valuable environmental remediation material, supporting sustainable water treatment, waste valorization, and circular bioeconomy principles.

Research Novelty

Unlike conventional adsorbents, this study simultaneously addresses two environmental problems by converting the invasive aquatic weed *Eichhornia crassipes* into a nitrogen- and sulfur-co-doped biochar through a simple thiourea-assisted pyrolysis process. The optimized heteroatom doping enhanced the surface chemistry and adsorption performance, enabling rapid and efficient removal of Malachite Green while providing an economical and reusable adsorbent for sustainable wastewater treatment.

Extraction Strategy



Water hyacinth biomass was cleaned, dried and powdered before impregnation with thiourea, which served as the nitrogen and sulfur source. The impregnated biomass was pyrolyzed at 350 °C to produce N, S co-doped biochar. Different thiourea-to-biomass ratios were optimized to maximize adsorption performance. The synthesized biochar was characterized using SEM, BET, FTIR and TGA analyses, followed by adsorption studies to evaluate dye removal efficiency, kinetics, isotherms and regeneration behavior.

From Laboratory Research to Practical Applications

The developed N, S co-doped biochar has excellent potential for practical implementation in textile industries, dye manufacturing units, and wastewater treatment facilities. Its high adsorption capacity, rapid dye removal, and outstanding regeneration ability make it suitable for large-scale adsorption columns and industrial effluent treatment systems. Since water hyacinth is abundantly available as an invasive aquatic weed, technology offers an economical and sustainable source of raw material. This research bridges laboratory innovation with real-world environmental applications by converting problematic biomass into a commercially valuable adsorbent for water purification.

Key Findings

- Successfully synthesized N, S co-doped biochar from invasive *Eichhornia crassipes* using thiourea-assisted pyrolysis.

- Optimized the thiourea-to-biomass ratio (0.6) to maximize adsorption performance.
- Achieved a maximum adsorption capacity of **133 mg g⁻¹** for Malachite Green.
- Adsorption followed the Langmuir isotherm, indicating monolayer adsorption.
- Adsorption kinetics followed the pseudo-second-order model, confirming chemisorption.
- Dye removal occurred through electrostatic attraction, hydrogen bonding, π - π interactions, and n - π interactions.
- Retained more than 92% adsorption efficiency after five regeneration cycles.
- Demonstrated an environmentally sustainable approach for converting invasive biomass into a high-value adsorbent.

Real-World Applications

The developed biochar can be employed in textile industries, dye manufacturing plants, municipal wastewater treatment facilities, and environmental remediation projects for the removal of Malachite Green and other cationic dyes. The technology provides a low-cost alternative to conventional adsorbents while simultaneously reducing the ecological burden caused by invasive water hyacinth. Its scalability, recyclability, and economic feasibility make it a promising solution for sustainable industrial wastewater treatment.

Future Outlook

Future studies can focus on pilot-scale production and continuous-flow wastewater treatment systems using real industrial effluents containing multiple contaminants. Further optimization of surface modification, extended regeneration

studies, and integration with membrane filtration or advanced oxidation processes may further improve treatment efficiency. Similar heteroatom-doping strategies can also be extended to other invasive plants and agricultural wastes, enabling the development of next-generation sustainable adsorbents for large-scale environmental remediation.

About the Researcher

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Reference

Boddu, S., Kumar, V., & Khan, A. A. (2026). N, S co-doped biochar derived from Eichhornia crassipes for rapid and selective removal of Malachite Green from wastewater. *International Journal of Environmental Analytical Chemistry*, 1-18. <https://doi.org/10.1080/03067319.2026.2656699>, Taylor & Francis, SCIE; Impact factor: 2.8; Q2; h-index of journal: 61

Collaborating Institutions

Department of Chemical Engineering, Haldia Institute of Technology, Haldia, West Bengal, India

Role of the Collaboration

- Collaborated in designing and optimizing the biochar synthesis methodology.
- Contributed expertise in adsorption experiments and wastewater treatment technologies.
- Assisted in characterization of biochar materials and interpretation of adsorption mechanisms.
- Supported statistical analysis, scientific validation, manuscript preparation, and critical review.
- Strengthened the research through interdisciplinary expertise in biomass valorization, materials engineering, and environmental remediation.

The collaboration combined complementary expertise to develop an efficient, reusable, and sustainable biochar adsorbent capable of addressing industrial wastewater pollution while promoting circular bioeconomy principles.

Sustainable Development Goals (SDGs) Addressed:

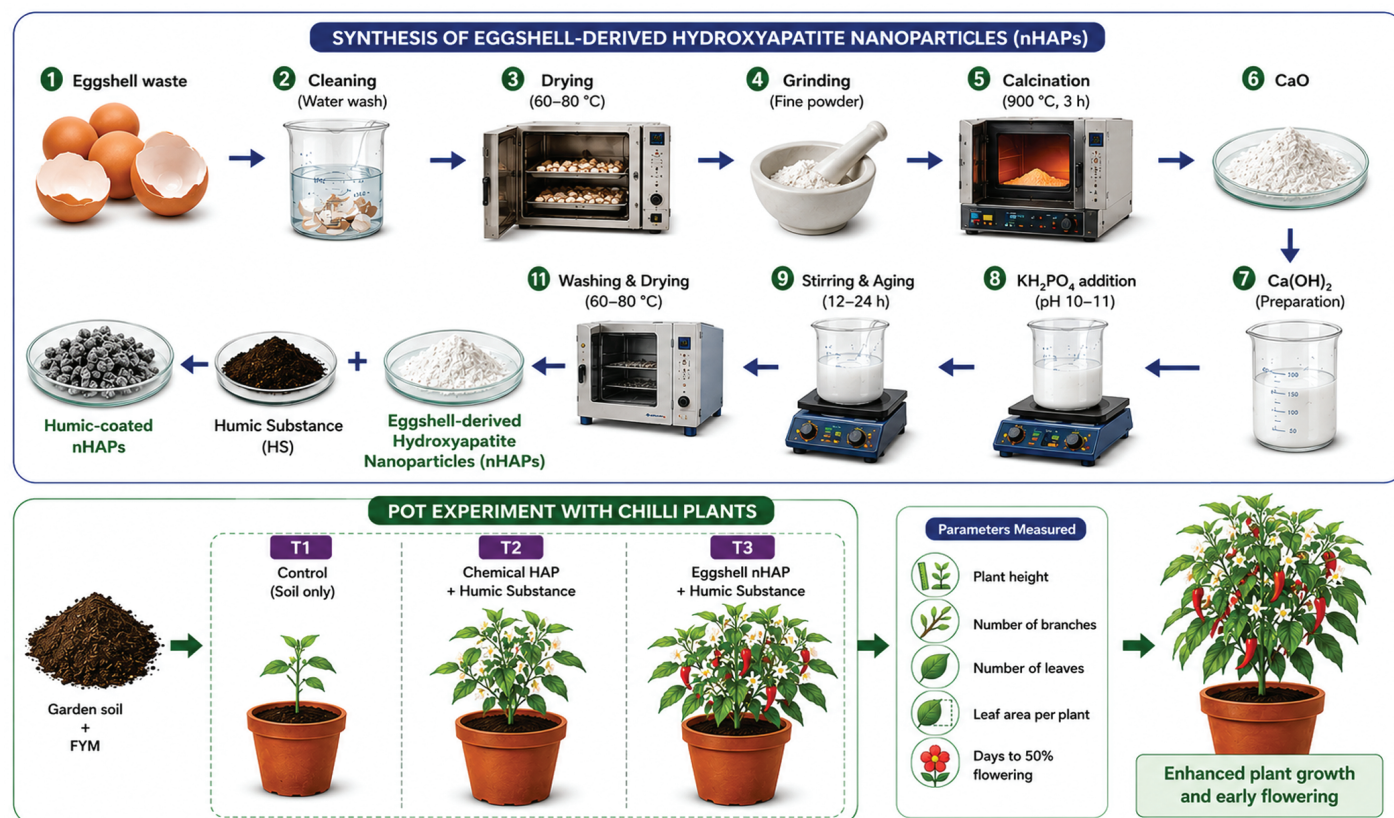
SDG	Contribution of the Research
SDG 6 - Clean Water and Sanitation	Develops an efficient biochar adsorbent for removing toxic dyes from wastewater, improving water quality.
SDG 9 - Industry, Innovation and Infrastructure	Introduces an innovative biomass-derived adsorbent for sustainable industrial wastewater treatment.
SDG 11 - Sustainable Cities and Communities	Promotes environmentally responsible management of invasive water hyacinth through resource recovery.
SDG 12 - Responsible Consumption and Production	Converts invasive biomass into a value-added product, encouraging waste valorization and circular resource utilization.
SDG 13 - Climate Action	Supports sustainable biomass utilization and eco-friendly technologies for pollution control with reduced environmental impact.
SDG 15 - Life on Land	Helps restore ecosystems by utilizing invasive aquatic weeds that threaten biodiversity and freshwater habitats.

From Eggshell Waste to Green Growth: Nano-Hydroxyapatite for Sustainable Agriculture



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Graphical Abstract



At a Glance

The excessive use of conventional chemical fertilizers has increased agricultural productivity but has also contributed to soil degradation, nutrient loss, and environmental pollution. Simultaneously, millions of tonnes of eggshell waste generated by households and food industries remain underutilized. This research transforms discarded eggshells into value-added nano-hydroxyapatite (nHAP), providing an environmentally friendly solution that addresses both waste management and sustainable agriculture.

Eggshells were converted into hydroxyapatite nanoparticles through a controlled synthesis process and compared with chemically synthesized nanoparticles. Advanced analytical techniques including Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), Fourier Transform Infrared Spectroscopy (FTIR), and X-ray

Diffraction (XRD) confirmed the successful formation of high-quality nano-hydroxyapatite. The eggshell-derived nanoparticles exhibited a more uniform morphology and substantially higher calcium content than chemically synthesized nanoparticles.

To enhance nutrient delivery, the nanoparticles were functionalized with natural humic substances and evaluated as nano-fertilizers using chilli plants. Plants treated with eggshell-derived nano-hydroxyapatite showed superior vegetative growth, increased plant height, more branches and leaves, larger leaf area, and significantly earlier flowering than plants receiving chemically synthesized hydroxyapatite or no fertilizer. Fifty percent flowering was achieved within approximately 40 days compared with about 50 days for chemical hydroxyapatite and nearly 90 days in untreated plants.

This study demonstrates that agricultural waste can be transformed into an efficient nanofertilizer that improves crop productivity while promoting circular economy principles and sustainable farming practices.

Why Does This Research Matter?

Modern agriculture depends heavily on chemical fertilizers, yet much of the applied nutrients are lost before being absorbed by plants, reducing fertilizer efficiency and causing environmental pollution. At the same time, eggshells generated by homes and food industries are commonly discarded as waste. This research addresses both challenges by converting eggshell waste into nutrient-rich nano-hydroxyapatite capable of improving nutrient availability, plant growth, and agricultural sustainability while supporting circular bioeconomy principles.

Turning Waste into a Smart Nano-Fertilizer

Waste eggshells were cleaned, calcined, and chemically transformed into nano-hydroxyapatite particles. The nanoparticles were subsequently coated with natural humic substances to improve nutrient delivery efficiency. Comprehensive characterization using SEM, EDX, FTIR, and XRD confirmed the formation of highly crystalline hydroxyapatite with desirable nanoscale properties. Finally, the nano-fertilizer was evaluated on chilli plants under controlled pot experiments and compared with chemically synthesized hydroxyapatite.

From Laboratory Innovation to Improved Crop Growth

The synthesized nano-hydroxyapatite significantly enhanced multiple growth parameters of chilli plants. Compared with conventional hydroxyapatite and untreated controls, eggshell-derived nanoparticles promoted greater plant height, increased branching, higher leaf numbers, larger leaf area, and accelerated flowering. Plants treated with eggshell-derived nano-hydroxyapatite achieved approximately 50% flowering within 40 days, demonstrating its potential as an efficient and sustainable nano-fertilizer.

Key Discoveries Driving Sustainable Agriculture

The study confirmed that eggshell-derived nano-hydroxyapatite provides superior agricultural performance owing to its uniform nanoscale structure, higher calcium content, and enhanced nutrient delivery. The integration of humic substances further improved fertilizer performance, while utilizing eggshell waste contributed to waste valorization and reduced dependence on synthetic fertilizer production.

Key Findings

- Successfully synthesized nano-hydroxyapatite from discarded eggshell waste.
- SEM revealed more uniform nanoparticle morphology (50–200 nm).
- Eggshell-derived nanoparticles contained substantially higher calcium (52.36 wt%) than chemically synthesized nanoparticles (15.51 wt%).
- XRD and FTIR confirmed highly crystalline hydroxyapatite formation.
- Functionalization with humic substances improved fertilizer performance.
- Eggshell-derived nano-fertilizer significantly increased plant height, branches, leaves, and leaf area.
- Chilli plants reached approximately 50% flowering within 40 days, much earlier than untreated plants (~90 days).
- Demonstrated an eco-friendly strategy that simultaneously supports sustainable agriculture and waste management.

Real-World Applications

The developed eggshell-derived nano-hydroxyapatite fertilizer has promising applications in sustainable agriculture by improving nutrient-use efficiency, reducing dependence on conventional chemical fertilizers, and enhancing crop productivity. The technology can be utilized in vegetable cultivation, horticulture, greenhouse farming, and precision agriculture. Beyond agriculture, it offers an environmentally friendly approach to recycling food waste into high-value agricultural inputs, contributing to circular economy initiatives and reducing landfill waste. The synthesis strategy may also inspire future development of bio-based nanomaterials for environmental remediation, soil health improvement, and advanced nutrient delivery systems.

Future Outlook

Future research can optimize nano-hydroxyapatite formulations for different crops and soil conditions while evaluating long-term field performance under diverse agricultural environments. Integration with smart agriculture technologies and controlled nutrient-release systems could further improve fertilizer efficiency. Large-scale production from food-processing waste could provide an economical and sustainable alternative to conventional fertilizers, supporting food security, waste valorization, and climate-resilient agriculture.

About the Researcher

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Reference

Syam Babu, D., Jeevana, G., Madhu Babu, Y., Yaswanth, P., & Indira, M. (2026). Characterization and utilization of eggshell-derived nano-hydroxyapatite for improved plant growth as a fertilizer. Journal of Material Cycles and Waste Management, 28, 465–478. Springer Nature. <https://doi.org/10.1007/s10163-025-02432-z>

Indexed in: SCIE / Web of Science

Publisher: Springer Nature

Journal: Journal of Material Cycles and Waste Management

Collaborating Institutions

This research was conducted by faculty members of the Department of Biotechnology, who combined expertise in nanobiotechnology, biomaterials, sustainable agriculture, waste valorization, and plant sciences. The multidisciplinary team integrated material synthesis, physicochemical characterization, and plant growth evaluation to develop an eco-friendly nano-fertilizer from waste eggshells, demonstrating a sustainable approach to agricultural waste utilization and enhanced crop productivity.

Sustainable Development Goals (SDGs) Addressed:

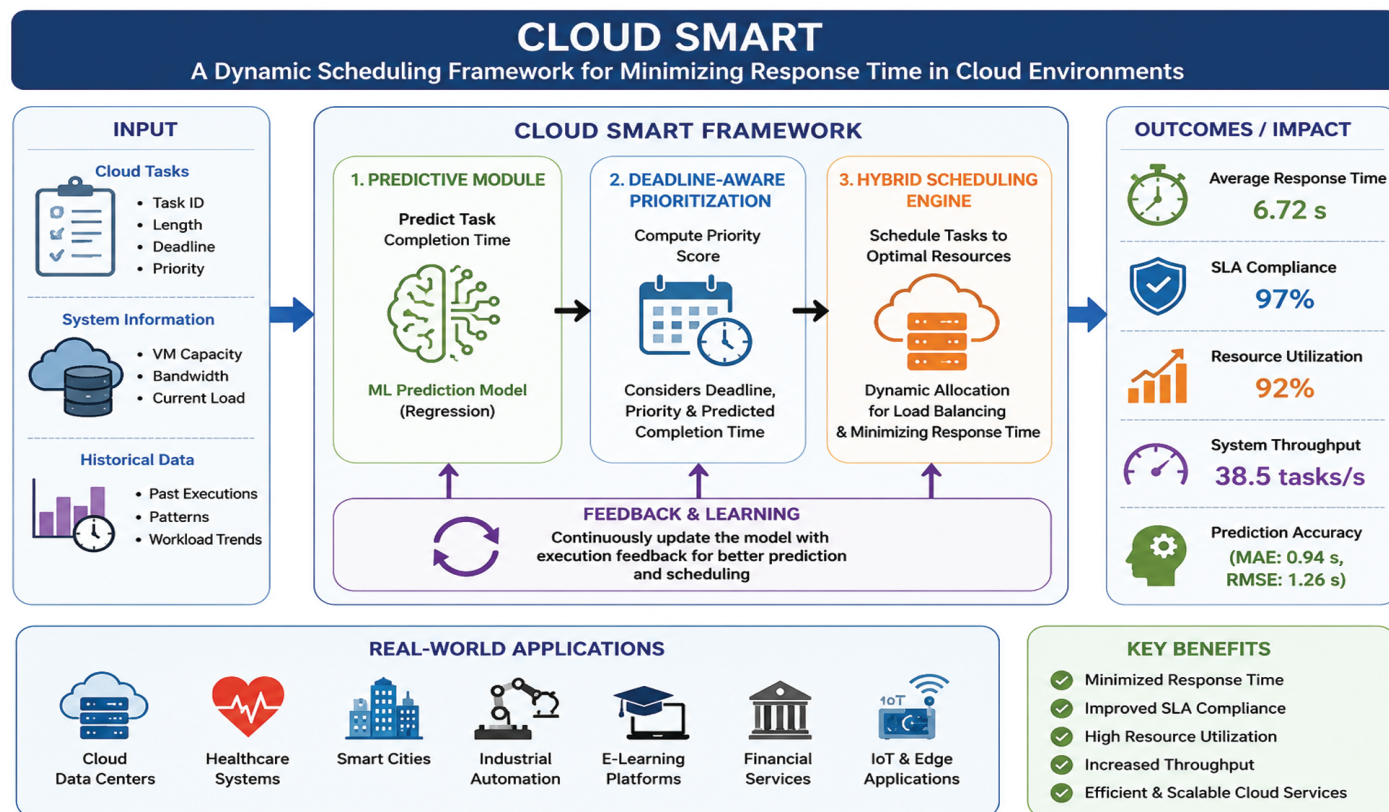
SDG	Contribution of the Research
SDG 2 Zero Hunger	Supports sustainable crop production by enhancing plant growth, nutrient-use efficiency, and fertilizer performance through eggshell-derived nano-hydroxyapatite.
SDG 11 Sustainable Cities and Communities	Demonstrates an innovative nanotechnology-based approach that converts agricultural waste into a value-added nano-fertilizer for sustainable farming.
SDG 12 Responsible Consumption and Production	Promotes waste valorization by converting discarded eggshells into high-value nano-hydroxyapatite, supporting resource recovery and circular economy practices.
SDG 13 Climate Action	Encourages environmentally friendly alternatives to conventional chemical fertilizers, contributing to more sustainable and climate-resilient agricultural practices.
SDG 15 Life on Land	Promotes sustainable soil nutrient management and environmentally responsible crop production through efficient, bio-based nano-fertilizer technology.

Smarter Cloud Scheduling for Faster and More Reliable Computing



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Graphical Abstract



At a Glance

Cloud computing has become the foundation of today's digital world, supporting essential services such as online banking, healthcare, e-commerce, education, smart cities, and the Internet of Things (IoT). As millions of users access these services simultaneously, cloud platforms must process enormous numbers of tasks efficiently while maintaining speed and reliability. However, conventional scheduling methods often struggle to cope with dynamic workloads, resulting in increased response times, missed deadlines, and inefficient utilization of computing resources.

To address these challenges, this research introduces CLOUD SMART, an intelligent and adaptive scheduling framework that continuously analyzes incoming workloads and dynamically allocates computing resources according to task urgency, predicted execution time, and Service Level Agreement (SLA) requirements. Unlike traditional

scheduling approaches that rely on fixed rules, CLOUD SMART adapts to changing workload conditions in real time, enabling faster and more efficient scheduling decisions.

The framework integrates workload analysis, predictive scheduling, hybrid decision-making, and continuous performance feedback to improve cloud efficiency. Experimental evaluation demonstrated that CLOUD SMART significantly reduces response time and waiting time while improving throughput, resource utilization, and SLA compliance compared with conventional scheduling methods.

By enabling intelligent resource allocation, CLOUD SMART offers a practical solution for building faster, more reliable, and scalable cloud computing environments. The framework has broad applications in healthcare, IoT, financial services, online education, smart cities, and other cloud-based systems where rapid and dependable service delivery is essential.

Why Cloud Services Need Smarter Scheduling?

Cloud computing powers nearly every aspect of modern digital life, from online transactions and telemedicine to e-learning, smart cities, and industrial automation. Behind every cloud application lies a scheduling system responsible for deciding how computing resources are allocated to thousands of incoming tasks. As cloud workloads continue to grow in volume and complexity, these scheduling decisions have become increasingly challenging.

Traditional scheduling techniques such as First Come First Served (FCFS) and Shortest Job First (SJF) operate using fixed rules and cannot effectively adapt to changing workloads or varying SLA requirements. As a result, cloud systems often experience increased waiting times, delayed responses, inefficient resource utilization, and reduced service quality.

Modern cloud platforms require intelligent scheduling systems capable of continuously analyzing workloads, predicting task execution, identifying urgent requests, and dynamically allocating resources. Such adaptive scheduling improves user experience, enhances infrastructure efficiency, reduces operational delays, and supports reliable cloud services for rapidly evolving digital applications.

The CLOUD SMART Innovation

CLOUD SMART introduces an intelligent scheduling framework that continuously adapts to changing cloud workloads in real time. Instead of relying on a single scheduling policy, the framework predicts workload behaviour before making scheduling decisions and automatically selects the most suitable scheduling strategy based on task priority, predicted completion time, and deadline urgency.

A key feature of CLOUD SMART is the Predictive Deadline-Aware Hybrid Scheduling (PDHS) model, which estimates task completion times before resource allocation. By combining prediction with adaptive scheduling, the framework ensures that urgent tasks receive priority while maintaining balanced utilization of available cloud resources.

Another important innovation is its continuous feedback mechanism. The framework monitors actual execution performance and uses this information to refine future scheduling decisions, enabling the system to learn from previous executions and adapt to changing workload conditions. This intelligent decision-making process allows CLOUD SMART to consistently deliver faster, more reliable, and scalable cloud services.

How Intelligent Scheduling Works?

CLOUD SMART follows an intelligent workflow that continuously improves cloud scheduling decisions. The framework first analyzes the characteristics of incoming cloud

tasks and estimates how long each task is likely to take for execution. It then evaluates task priority and deadline requirements to determine the urgency of each request.

Based on these predictions, CLOUD SMART dynamically selects the most appropriate scheduling strategy to allocate available computing resources efficiently. Rather than following a fixed scheduling rule, the framework adapts its decisions according to real-time workload conditions, ensuring that critical tasks are processed quickly while maximizing overall system performance.

After task execution, CLOUD SMART continuously monitors system performance and compares predicted outcomes with actual results. This feedback is used to refine future scheduling decisions, allowing the framework to become increasingly accurate and efficient over time.

Turning Performance into Real-World Impact

Experimental evaluation demonstrated that CLOUD SMART substantially improves cloud computing performance compared with conventional scheduling approaches. The framework significantly reduced response and waiting times while increasing throughput, improving resource utilization, and maintaining high Service Level Agreement compliance. These improvements enable cloud platforms to process user requests more efficiently while minimizing delays and deadline violations.

The practical impact of CLOUD SMART extends across a wide range of cloud-enabled applications. Healthcare systems can process medical information more rapidly, financial institutions can support faster online transactions, IoT platforms can manage large volumes of connected devices more efficiently, and smart city services can deliver reliable real-time operations. Educational platforms, industrial automation systems, and data analytics services can also benefit from improved scalability and responsiveness.

By combining intelligent prediction with adaptive scheduling, CLOUD SMART contributes toward the development of next-generation cloud infrastructures that are faster, more reliable, and capable of meeting the increasing demands of modern digital society.

Key Findings

- CLOUD SMART significantly reduced response time compared with conventional cloud scheduling techniques, enabling faster service delivery.
- The Predictive Deadline-Aware Hybrid Scheduling approach improved Service Level Agreement compliance by intelligently prioritizing time-critical tasks and minimizing deadline violations.
- The framework enhanced resource utilization and system throughput, demonstrating its ability to improve overall cloud computing efficiency while supporting scalable and reliable cloud services.

Real-World Applications

The CLOUD SMART framework enhances cloud-based applications by reducing response time and improving resource utilization. It supports healthcare through faster processing of medical data and smart cities by enabling efficient management of real-time services. The framework also improves the performance of IoT applications by intelligently scheduling data from connected devices. It can be applied to online education, financial services, and other cloud platforms that require reliable and scalable computing. By improving SLA compliance and system efficiency, CLOUD SMART helps deliver faster and more dependable cloud services across diverse application domains.

Future Outlook

The CLOUD SMART framework provides a strong foundation for the next generation of intelligent cloud computing systems. Future research will focus on extending the framework to edge computing, hybrid cloud environments, and AI-driven autonomous resource management. Integrating CLOUD SMART with emerging technologies such as Internet of Things, digital twins, and smart city infrastructures can further improve cloud efficiency, reduce operational delays, and support sustainable digital transformation. As cloud services continue to expand globally, intelligent scheduling frameworks such as CLOUD SMART will play an increasingly important role in delivering faster, more reliable, and scalable computing environments.

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Reference

Anuradha, S., Unnikrishnan, K., Reshma, S., Bhaskaru, O., & Sharma, R. (2026). CLOUD SMART: A Dynamic Scheduling Framework for Minimizing Response Time in Cloud Environments. *Concurrency and Computation: Practice and Experience*, 38(2), e70561. Wiley. SCIE; Impact Factor: 2.2; Quartile: Q2; h-index of journal: 89.

Collaborating Institutions

This research was carried out through a collaborative partnership among researchers from SRM Institute of Science and Technology, Chennai; Rajiv Gandhi Institute of Technology (Government Engineering College), Kottayam; Dayananda Sagar College of Engineering, Bengaluru; Vignan's Foundation for Science, Technology and Research (Deemed to be University), Guntur; and Lovely Professional University, Phagwara.

The multidisciplinary collaboration combined expertise in cloud computing, artificial intelligence, intelligent task scheduling, and distributed systems to develop the CLOUD SMART framework. By integrating diverse technical perspectives, the team designed an adaptive scheduling approach that enhances cloud resource utilization, minimizes response time, improves Service Level Agreement compliance, and supports efficient, reliable, and scalable cloud computing environments.

Sustainable Development Goals (SDGs) Addressed:

This research contributes to the following United Nations Sustainable Development Goals

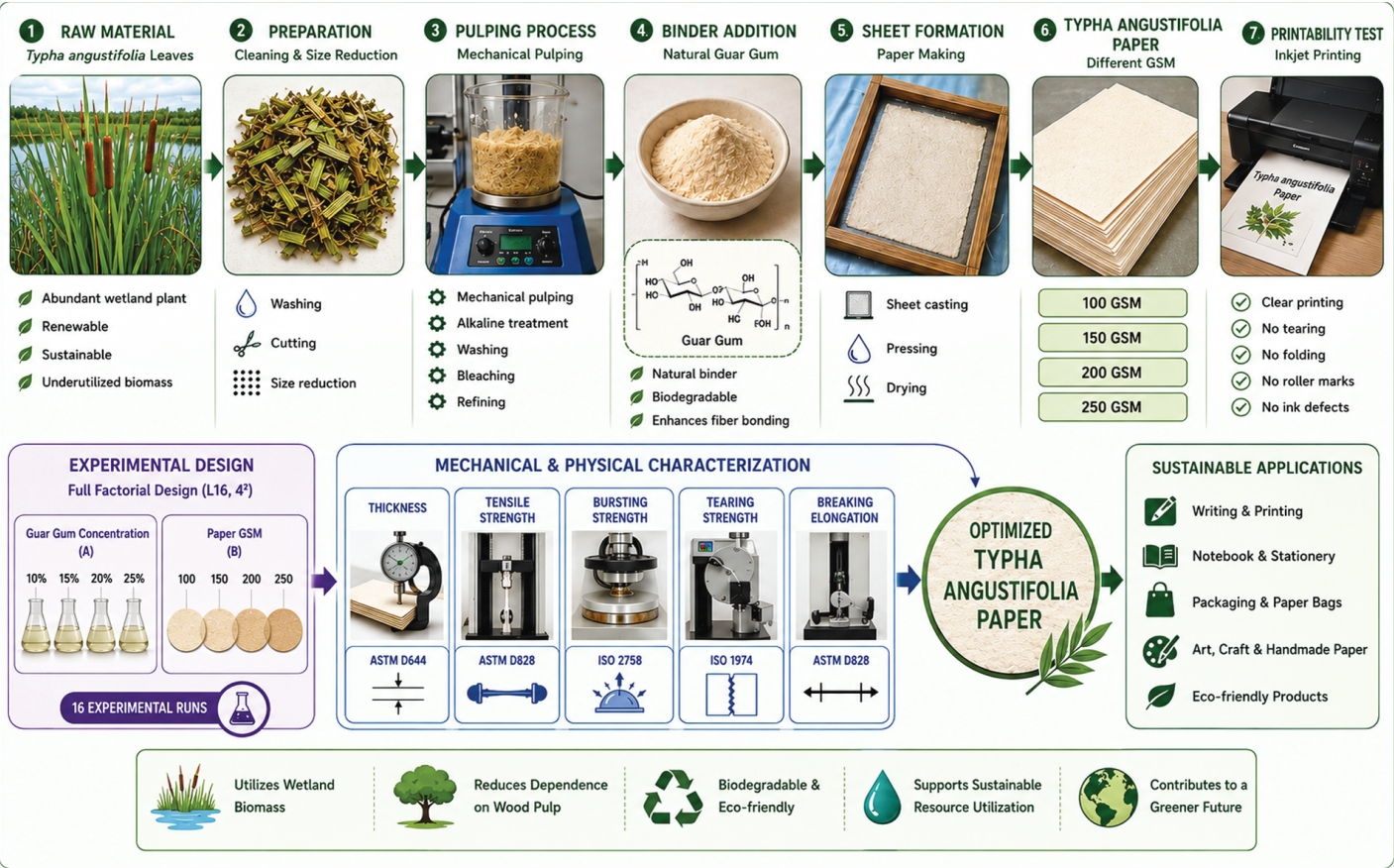
SDG	Contribution of the Research
SDG 9 Industry, Innovation and Infrastructure	Develops the CLOUD SMART intelligent scheduling framework that improves cloud infrastructure through adaptive scheduling, reduced response time, higher SLA compliance, and better resource utilization..
SDG 11 Sustainable Cities and Communities	Supports smart city and digital infrastructure by enabling reliable, scalable cloud services for applications such as traffic management, healthcare, IoT, e-learning, and public services.
SDG 12 Responsible Consumption and Production	Promotes efficient utilization of cloud computing resources through intelligent task scheduling, reducing resource wastage and improving the overall efficiency of cloud data centers.

Turning Wetland Biomass into Sustainable Paper: A Green Alternative to Wood



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Graphical Abstract



At a Glance

The increasing demand for paper has intensified pressure on forest resources, creating an urgent need for sustainable alternatives. This research explores the use of *Typha angustifolia*, a rapidly growing wetland plant, as an eco-friendly raw material for paper production. Instead of relying on wood pulp, the study converts *Typha* leaves into paper through mechanical pulping, alkaline treatment, bleaching, refining, and sheet formation using guar gum as a natural binder.

To optimize paper quality, papers of four different grammages (100, 150, 200 and 250 GSM) were prepared using varying guar gum concentrations. The produced papers were evaluated for thickness, bursting strength, tearing resistance, tensile strength, and printing performance using standard ASTM and ISO testing methods.

The findings demonstrated that *Typha* leaves can successfully produce durable paper with excellent mechanical properties. Paper thickness increased proportionally with GSM, while higher GSM and guar gum concentration improved bursting and tearing strength. Tensile strength primarily depended on paper grammage rather than binder concentration. Importantly, the developed sheets performed well during inkjet printing without tearing, folding, or printing defects, demonstrating their suitability for writing and printing applications.

Beyond reducing dependence on forest-based pulp, this work provides a promising strategy for utilizing abundant wetland biomass that is often considered waste. The study contributes to sustainable materials research by transforming an underutilized natural resource into a biodegradable product with potential applications in printing, packaging, crafts, and eco-friendly paper industries.

Rethinking Paper Beyond Forests

Conventional paper production relies heavily on wood pulp, contributing to deforestation and increasing environmental concerns. This study investigates *Typha angustifolia*, an abundant wetland biomass, as a renewable and sustainable alternative for paper manufacturing.

Transforming Wetland Plants into Valuable Paper

The growing demand for paper has increased dependence on forest-derived wood pulp, raising concerns about deforestation and environmental sustainability. This research explores an innovative alternative by utilizing *Typha angustifolia*, a fast-growing wetland plant that is widely available but often remains underutilized. The harvested leaves were processed through mechanical pulping, followed by alkaline treatment, washing, bleaching, and refining to obtain cellulose-rich fibres suitable for papermaking. To enhance fibre bonding naturally, guar gum, a biodegradable plant-based binder, was incorporated during sheet formation. Papers with different grammages (100–250 GSM) were successfully fabricated using a simple laboratory-scale process. The resulting sheets exhibited uniform structure, adequate thickness, and excellent handling characteristics. Unlike conventional wood-based paper production, this approach makes productive use of renewable biomass while reducing pressure on forest resources. The study demonstrates that wetland vegetation, traditionally regarded as waste, can be transformed into functional paper suitable for writing, printing, craft work, and sustainable packaging applications, opening new opportunities for environmentally responsible paper manufacturing.

Engineering Stronger Eco-Friendly Paper

Producing sustainable paper requires more than simply replacing wood fibres—it also demands sufficient mechanical strength for practical use. To optimize paper performance, this study employed a General Full Factorial Experimental Design ($L_{16}, 4^2$) to investigate the combined effects of guar gum concentration (10–25%) and paper grammage (100–250 GSM) on mechanical properties. Sixteen experimental combinations were prepared and systematically evaluated using internationally recognized ASTM and ISO testing standards. Key properties including paper thickness, bursting strength, tearing strength, tensile strength, and breaking elongation were measured to assess durability and usability. Statistical analysis revealed that increasing paper GSM significantly improved tensile, bursting, and tearing strengths, while higher guar gum concentrations enhanced fibre bonding and increased resistance to tearing and bursting. The optimized paper exhibited excellent structural integrity without compromising printability. This scientific optimization provides valuable guidelines for developing biodegradable papers with improved mechanical performance and demonstrates how experimental design

can accelerate the development of sustainable biomaterials for industrial applications.

From Biomass Waste to Sustainable Products

The successful conversion of *Typha angustifolia* leaves into high-quality paper highlights the enormous potential of transforming underutilized biomass into valuable products. The developed paper achieved desirable mechanical properties, including good tensile strength, tear resistance, bursting strength, and dimensional stability across different grammages. Importantly, the sheets performed effectively during inkjet printing without tearing, folding, roller marks, or ink-related defects, demonstrating their suitability for practical applications. Beyond writing and printing, the material shows promise for manufacturing eco-friendly packaging, paper bags, decorative paper, art and craft materials, folders, and specialty paper products. Utilizing *Typha* biomass not only reduces dependence on conventional wood pulp but also promotes the sustainable management of wetland vegetation that is often discarded or left unmanaged. By converting renewable plant resources into biodegradable paper products, this research supports circular economy principles, minimizes environmental impact, and contributes to the development of greener manufacturing practices. With further scale-up and industrial optimization, *Typha*-based paper could emerge as a sustainable alternative for future paper and packaging industries.

Key Findings

- Successfully produced functional paper from *Typha angustifolia* leaves using mechanical pulping.
- Higher GSM significantly improved tensile, tearing, and bursting strengths.
- Guar gum enhanced bursting and tearing resistance, while tensile strength was mainly influenced by paper GSM.
- The developed paper was successfully printed using a standard inkjet printer, confirming its practical usability.

Real-World Applications

The developed *Typha* paper has broad applications across multiple sectors. In the paper and packaging industry, it offers a renewable alternative to wood-based paper for notebooks, writing sheets, packaging materials, paper bags, and cartons. The material can also be utilized in eco-friendly printing, art and craft products, greeting cards, and specialty handmade papers.

From an environmental perspective, utilizing *Typha* biomass reduces dependence on forest resources while converting abundant wetland vegetation into valuable products. This supports circular economy principles and promotes sustainable biomass utilization. The paper also has potential applications in biodegradable packaging, educational materials, and environmentally responsible consumer products.

Industries focused on sustainable materials can adopt this technology to develop greener paper products with lower ecological footprints. Future improvements in binder selection and large-scale manufacturing may further expand its applications to commercial printing and packaging sectors.

Future Outlook

Future research can focus on scaling up Typha paper production for industrial manufacturing and evaluating

additional natural binders to further improve strength, durability, water resistance, and printability. Studies on ink absorption, coating technologies, recycling performance, and life-cycle assessment will help establish Typha paper as a commercially viable sustainable alternative. This approach has the potential to reduce pressure on forests, promote circular bioeconomy practices, and encourage the utilization of renewable wetland biomass for environmentally responsible paper production.

About the Researcher

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Reference

Chilukoti, G. R., & Mandapati, R. N. (2025). Paper production from Typha angustifolia leaves: Effect of process variables on mechanical properties. International Journal of Clothing Science and Technology. 38(1), 139-156. Emerald Publishing. SCI-E, Impact Factor: 1.3; h-index : 48; Q3; DOI: <https://doi.org/10.1108/IJCST-01-2025-0017>.

Collaborating Institutions

This study was completed through the collaborative efforts of Dr. Govardhana Rao Chilukoti, who conceived the research, performed the experiments, analyzed the results, and prepared the manuscript, and Dr. Ramesh Naidu Mandapati, who verified the findings, reviewed the manuscript, and contributed to its technical refinement and final presentation.

Sustainable Development Goals (SDGs) Addressed:

This research contributes to the following United Nations Sustainable Development Goals

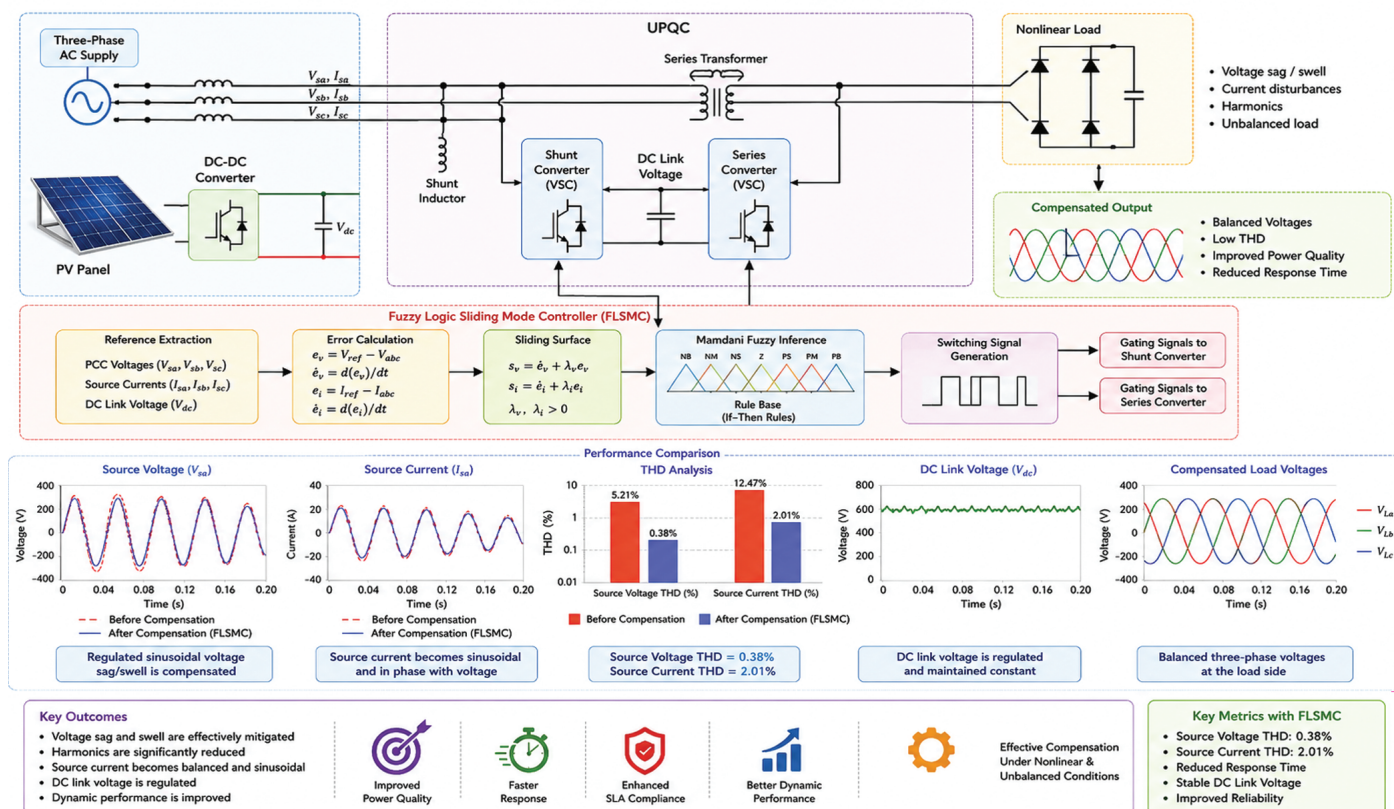
SDG	Contribution of the Research
SDG 9 – Industry, Innovation and Infrastructure	Development of sustainable paper manufacturing technology using renewable biomass.
SDG 12 – Responsible Consumption and Production	Converts wetland biomass into eco-friendly paper, reducing dependence on forest resources.
SDG 13 – Climate Action	Promotes renewable raw materials and reduces environmental impacts associated with conventional paper production.
SDG 15 – Life on Land	Supports conservation of forests by providing alternative lignocellulosic resources for paper manufacturing.

AI-Driven Solar PV-UPQC for Superior Power Quality Enhancement



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Graphical Abstract



At a Glance

Electrical distribution networks today face increasing power quality challenges due to the widespread use of nonlinear loads, renewable energy integration, and power electronic devices. These challenges include voltage sag, voltage swell, harmonic distortion, reactive power imbalance, and poor dynamic response, all of which can reduce system efficiency and damage sensitive electrical equipment.

This research introduces an intelligent Solar Photovoltaic (PV)-fed Unified Power Quality Conditioner (UPQC) controlled using an AI-based Fuzzy Logic Sliding Mode Controller (FLSMC). The proposed controller combines the robustness of Sliding Mode Control with the adaptive decision-making capability of Fuzzy Logic to provide rapid and stable compensation under varying operating conditions.

The controller effectively suppresses voltage disturbances, compensates current harmonics, regulates DC-link voltage, and minimizes controller chattering. MATLAB/Simulink simulations demonstrated that the proposed controller significantly outperformed conventional PI, Fuzzy Logic Controller (FLC), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Fractional Order Fuzzy Logic Controller (FOFLC).

The proposed system achieved a Source Voltage THD of only 0.38% and a Source Current THD of 2.01%, both well within IEEE harmonic standards, demonstrating its effectiveness for future smart distribution networks powered by renewable energy.

Why This Research Matters?

The rapid growth of renewable energy systems and modern electronic equipment has significantly increased power

quality issues in electrical distribution networks. Harmonic distortion, voltage fluctuations, reactive power imbalance, and nonlinear loads affect the reliability and efficiency of electrical systems.

Conventional control methods such as PI controllers often struggle under rapidly changing operating conditions because they depend on fixed mathematical models. Their performance deteriorates when load conditions become nonlinear or unpredictable.

This research addresses these limitations by developing an intelligent AI-assisted control strategy capable of adapting to changing electrical conditions in real time. By integrating solar photovoltaic energy with an advanced UPQC controller, the study simultaneously improves power quality while promoting renewable energy utilization.

The proposed approach supports the transition toward cleaner, smarter, and more resilient electrical distribution systems.

A Smarter Control Strategy

At the heart of this research lies the Fuzzy Logic Sliding Mode Controller. The controller integrates two powerful intelligent control techniques:

Sliding Mode Control (SMC)

- Provides excellent robustness against disturbances
- Offers rapid dynamic response
- Maintains system stability under nonlinear conditions

However, traditional SMC suffers from an undesirable phenomenon called chattering, which causes high-frequency oscillations.

To overcome this limitation, the researchers incorporated: Fuzzy Logic Control

The fuzzy controller continuously adjusts the switching gain based on system error and change in error.

This adaptive mechanism

- reduces chattering,
- improves voltage regulation,
- accelerates transient response,
- maintains stable DC-link voltage,
- provides smoother converter switching.

The coordinated control of the Series Active Power Filter (SAPF) and Shunt Active Power Filter (ShAPF) enables simultaneous correction of both voltage and current disturbances.

From Simulation to Practical Impact

The proposed controller was evaluated using MATLAB/Simulink under multiple practical operating conditions, including

- Voltage sag
- Voltage swell
- Nonlinear load disturbances
- Harmonic distortion
- Unbalanced load conditions

Simulation results demonstrated that the AI-based controller rapidly restored voltage to its desired value, maintained stable DC-link voltage, and significantly reduced harmonic distortion.

Compared with existing control strategies, the proposed controller exhibited

- Faster transient response
- Lower overshoot
- Reduced steady-state error
- Better voltage regulation
- Improved harmonic suppression
- Stable operation under changing load conditions

These improvements indicate strong potential for future implementation in smart grids and renewable energy systems.

Key Discoveries

The research successfully demonstrated that integrating an AI-based FLSMC with a Solar PV-fed UPQC substantially enhances distribution system performance.

Major discoveries include

- Effective compensation of voltage sag and swell.
- Significant reduction of current harmonics.
- Stable DC-link voltage regulation.
- Improved dynamic response during transient disturbances.
- Elimination of sliding mode controller chattering.
- Better overall power quality than PI, FLC, ANFIS, and FOFLC controllers.

The controller achieved: Source Voltage THD : 0.38% and Source Current THD: 2.01%

These values satisfy IEEE harmonic standards while ensuring reliable operation under nonlinear and unbalanced load conditions.

Key Findings

- Developed an AI-driven Fuzzy Logic Sliding Mode Controller for Solar PV-fed Unified Power Quality Conditioner.
- Successfully mitigated voltage sag and voltage swell.
- Reduced source voltage Total Harmonic Distortion to 0.38%.
- Reduced source current Total Harmonic Distortion to 2.01%.
- Improved DC-link voltage regulation.
- Reduced controller chattering through adaptive fuzzy tuning.
- Enhanced transient response and voltage recovery.
- Outperformed PI, FLC, ANFIS and Fractional Order FLC controllers.
- Demonstrated reliable operation under nonlinear and unbalanced loading conditions.
- Showed the feasibility of integrating renewable solar PV with intelligent power quality devices.

Real-World Applications

The proposed AI-driven Solar PV-UPQC has broad applications across modern electrical infrastructure.

Potential deployment areas include:

- Smart electrical grids
- Renewable-energy integrated distribution networks
- Industrial power quality improvement
- Manufacturing plants with nonlinear loads
- Electric vehicle charging stations
- Data centres requiring uninterrupted power quality
- Hospitals and critical infrastructure

- Railway electrification systems
- Smart microgrids
- Utility distribution networks
- Commercial buildings with sensitive electronic equipment

Its ability to improve power quality while utilizing renewable energy makes it highly suitable for future sustainable energy systems.

Future Outlook

The present work has established the effectiveness of AI-driven control for improving power quality in renewable-energy-based distribution systems.

Future research directions include

- Hardware prototype development
- Real-time digital simulation using OPAL-RT or RTDS platforms
- FPGA/DSP-based controller implementation
- AI-assisted adaptive parameter optimization
- IoT-enabled remote monitoring
- Digital twin development for predictive maintenance
- Integration with battery energy storage systems
- Validation in practical smart-grid environments
- Cyber-secure intelligent controller implementation
- Large-scale deployment in renewable energy distribution networks

These developments could enable autonomous, self-healing electrical grids capable of maintaining excellent power quality under highly dynamic operating conditions.

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Reference

Sravanthi G., Mercy Rosalina K., & Rama Subba Reddy T. (2026). Fuzzy logic sliding mode controller based solar PV fed UPQC for improvement of dynamic performance and power quality enhancement in distribution power system. <https://doi.org/10.1038/s41598-026-43465-0>.Scientific Reports, 16, 13319. Springer Nature. SCIE; Impact Factor: 3.8; Q1. h-index of journal:394

Collaborating Institutions

- VFSTR University, Guntur, Andhra Pradesh, India
- Vignan Institute of Technology and Science, Hyderabad, Telangana, India

Sustainable Development Goals (SDGs) Addressed:

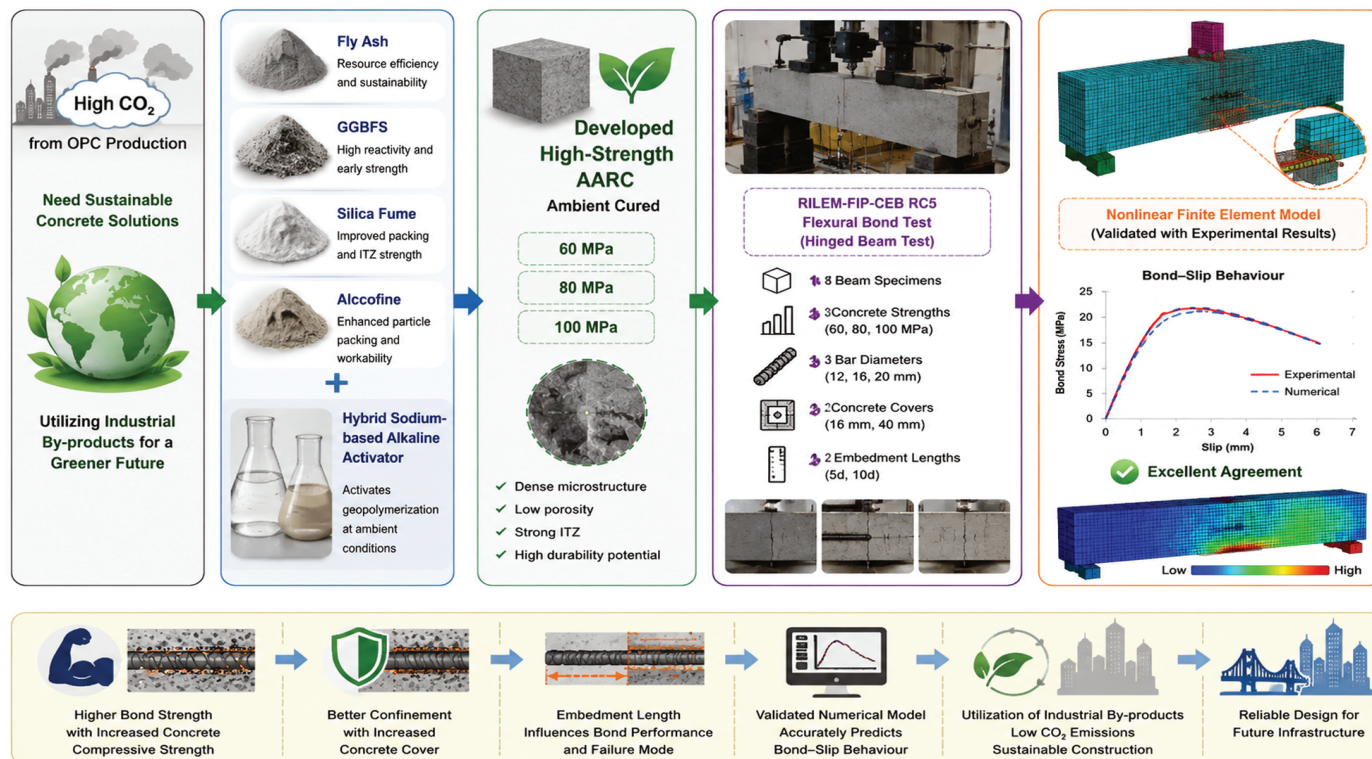
SDG	Contribution of the Research
SDG 7 Affordable and Clean Energy	The proposed Solar PV-fed Unified Power Quality Conditioner enhances the integration of renewable solar energy into distribution systems while improving power quality, voltage stability, and energy efficiency. This supports reliable, sustainable, and clean electricity generation and utilization.
SDG 9 Industry, Innovation and Infrastructure	The research introduces an AI-based Fuzzy Logic Sliding Mode Controller for UPQC, providing an innovative control strategy that significantly improves dynamic response, minimizes harmonic distortion (THD), and enhances the resilience and reliability of modern smart distribution infrastructure
SDG 11 Sustainable Cities and Communities	By mitigating voltage sag, swell, current harmonics, and reactive power issues, the proposed system ensures a stable and reliable electricity supply for residential, commercial, and industrial consumers, thereby supporting sustainable urban infrastructure and smart city power networks
SDG 12 Responsible Consumption and Production	The improved power quality reduces electrical losses, prevents equipment damage, extends the operational life of electrical devices, and enhances efficient utilization of electrical energy, promoting responsible energy consumption and sustainable industrial operation
SDG 13 Climate Action	The integration of solar photovoltaic energy with an intelligent UPQC reduces dependence on fossil-fuel-based electricity, promotes renewable energy penetration, lowers greenhouse gas emissions, and contributes to climate change mitigation through cleaner and more efficient power systems.

Bond Behaviour of High-Strength Alkali-Activated Reinforced Concrete



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Graphical Abstract



At a Glance

Concrete remains the backbone of modern infrastructure, yet the production of Ordinary Portland Cement (OPC) contributes nearly 7–8% of global carbon dioxide emissions. Developing sustainable construction materials that maintain or exceed the structural performance of conventional concrete has therefore become a global research priority.

This study presents a high-strength multi-component Alkali-Activated Reinforced Concrete (AARC) developed using fly ash, GGBFS, silica fume, and alccofine activated by a hybrid sodium-based alkaline solution. Unlike conventional geopolymer concretes that often require heat curing, the developed concrete achieved strengths of 60, 80 and 100 MPa under ambient curing conditions, making it suitable for practical construction.

The research focused on the bond between reinforcing steel and concrete using the RILEM-FIP-CEB RC5 hinged beam test together with nonlinear numerical simulations. Results showed that bond strength increased with concrete strength, while increasing concrete cover significantly im-

proved confinement and bond performance. The validated numerical model closely reproduced the experimental observations. Thus, the study demonstrates that high-strength alkali-activated reinforced concrete is a sustainable, low-carbon alternative capable of delivering excellent structural performance while reducing dependence on Portland cement.

Why This Research Matters?

Every reinforced concrete structure from residential buildings and bridges to industrial facilities and high-rise towers relies on a strong and reliable bond between concrete and reinforcing steel. This bond governs how efficiently forces are transferred between the two materials, directly influencing crack control, structural integrity, durability, and the long-term service life of the structure.

Although alkali-activated concrete has demonstrated excellent compressive strength and durability in numerous studies, relatively limited research has examined its structural bond behaviour under flexural loading. Without reliable bond performance, even high-strength concrete cannot fully

utilize the strength of reinforcing steel, leading to reduced structural efficiency, wider cracks, excessive deflections, and shorter service life.

This research addresses this critical gap by systematically investigating the flexural bond behaviour of ambient-cured high-strength multi-component alkali-activated reinforced concrete. Understanding these mechanisms is essential before such sustainable concrete can be confidently adopted in structural engineering practice and incorporated into future design standards.

The study therefore bridges the gap between sustainable material development and practical structural application.

Engineering a Smarter and Greener Concrete

The research developed a high-performance alkali-activated binder by carefully combining four industrial by-products, each contributing unique engineering advantages.

- Class F Fly Ash provides a sustainable aluminosilicate source while reducing dependence on Portland cement.
- Ground Granulated Blast Furnace Slag accelerates strength development and improves early-age mechanical performance.
- Silica Fume refines the pore structure, enhances particle packing, and strengthens the interfacial transition zone surrounding reinforcement.
- Alccofine, an ultrafine supplementary cementitious material, further improves particle packing density and contributes to superior compressive strength.
- A hybrid sodium-based alkaline activator initiates geopolymerization and enables effective ambient curing without external heat.

The synergistic interaction among these materials produced dense microstructures with reduced porosity, stronger steel–concrete interfaces, and improved structural performance. Unlike many geopolymer concretes reported in literature that require elevated-temperature curing, the proposed concrete achieved high strength under normal room-temperature conditions, significantly improving its practicality for field applications.

From Experiments to Simulation

To comprehensively evaluate structural performance, the researchers combined carefully designed laboratory experiments with advanced numerical modelling. A total of eighteen reinforced concrete beam specimens representing three concrete strength grades (60, 80 and 100 MPa) were prepared and tested using the internationally recognized RILEM-FIP-CEB RC5 flexural bond test. The investigation systematically examined the influence of:

- Concrete compressive strength
- Reinforcement bar diameter (12, 16 and 20 mm)
- Concrete cover (16 and 40 mm)
- Embedment lengths (5d and 10d)

During testing, the load-slip behaviour, crack development, failure mechanisms, and bond characteristics were carefully monitored.

To complement the experimental programme, a nonlinear finite element model was developed and validated using the laboratory results. The numerical simulations closely replicated the experimentally observed bond-slip relationships and failure modes, demonstrating the reliability of computational modelling for predicting reinforced concrete behaviour while reducing the need for extensive physical testing.

Major Outcomes

The investigation generated several important findings for sustainable structural engineering.

- High-strength alkali-activated concrete developed excellent bond with reinforcing steel.
- Bond strength consistently increased with increasing concrete compressive strength.
- Increasing concrete cover from 16 mm to 40 mm significantly enhanced confinement and delayed bond failure.
- Longer embedment lengths influenced stress transfer and failure characteristics.
- The validated numerical model accurately predicted experimental bond-slip behaviour across all investigated parameters.
- Ambient-cured alkali-activated concrete demonstrated structural performance comparable to conventional high-strength reinforced concrete while offering significant environmental benefits.

Key Findings

This research extends beyond conventional strength evaluation by addressing one of the most important structural parameters governing reinforced concrete performance.

The major scientific contributions include:

- Development of a high-strength multi-component alkali-activated reinforced concrete suitable for ambient curing.
- Comprehensive experimental evaluation of steel–concrete bond behaviour under flexural loading.
- Investigation of multiple reinforcement parameters influencing bond performance.
- Development and successful validation of a nonlinear numerical model capable of accurately predicting bond-slip behaviour.
- Generation of engineering data that can contribute to future structural design recommendations for alkali-activated reinforced concrete.

These contributions significantly strengthen the scientific understanding required for wider implementation of sustainable reinforced concrete technologies.

Applications

The developed concrete possesses considerable potential for both conventional and specialized infrastructure projects. Potential applications include:

- High-rise reinforced concrete buildings
- Highway and railway bridges
- Marine and coastal structures
- Industrial buildings
- Precast structural elements
- Transportation infrastructure
- Sustainable urban development projects

Beyond reducing greenhouse gas emissions through the utilization of industrial by-products, the validated numerical model offers engineers an efficient design tool capable of minimizing expensive experimental programmes while improving reinforcement detailing and structural reliability.

Future Outlook

The successful development and validation of high-strength alkali-activated reinforced concrete open several promising research directions. Future investigations may focus on:

- Long-term durability under aggressive environments
- Corrosion resistance of embedded reinforcement
- Cyclic and fatigue loading behaviour
- Seismic performance of reinforced members
- Fire resistance
- Large-scale structural validation
- Development of codal provisions and design guidelines

Such studies will accelerate the transition of alkali-activated concrete from laboratory research to widespread commercial construction, supporting the global movement toward carbon-neutral infrastructure.

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• Numerical Modelling • Bond Behaviour of Reinforced Concrete

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Reference

Padakanti Rakesh, Sarella Venkateswara Rao, and Pancharathi Rathish Kumar (2025), “Flexural bond behavior of multi-component alkali-activated reinforced concrete (AARC).” Construction and building materials, 471, 140681, Elsevier, <https://doi.org/10.1016/j.conbuildmat.2025.140681>. (SCIE Indexed-Q1—Impact Factor: 8.9).

Collaborating Institutions

This research was conducted through a collaboration between National Institute of Technology Warangal and Vignan’s Foundation for Science, Technology and Research (VFSTR), integrating expertise in sustainable construction materials, structural engineering, and numerical modelling.

Sustainable Development Goals (SDGs) Addressed:

The research directly supports several United Nations Sustainable Development Goals by promoting environmentally responsible construction materials and resilient infrastructure.

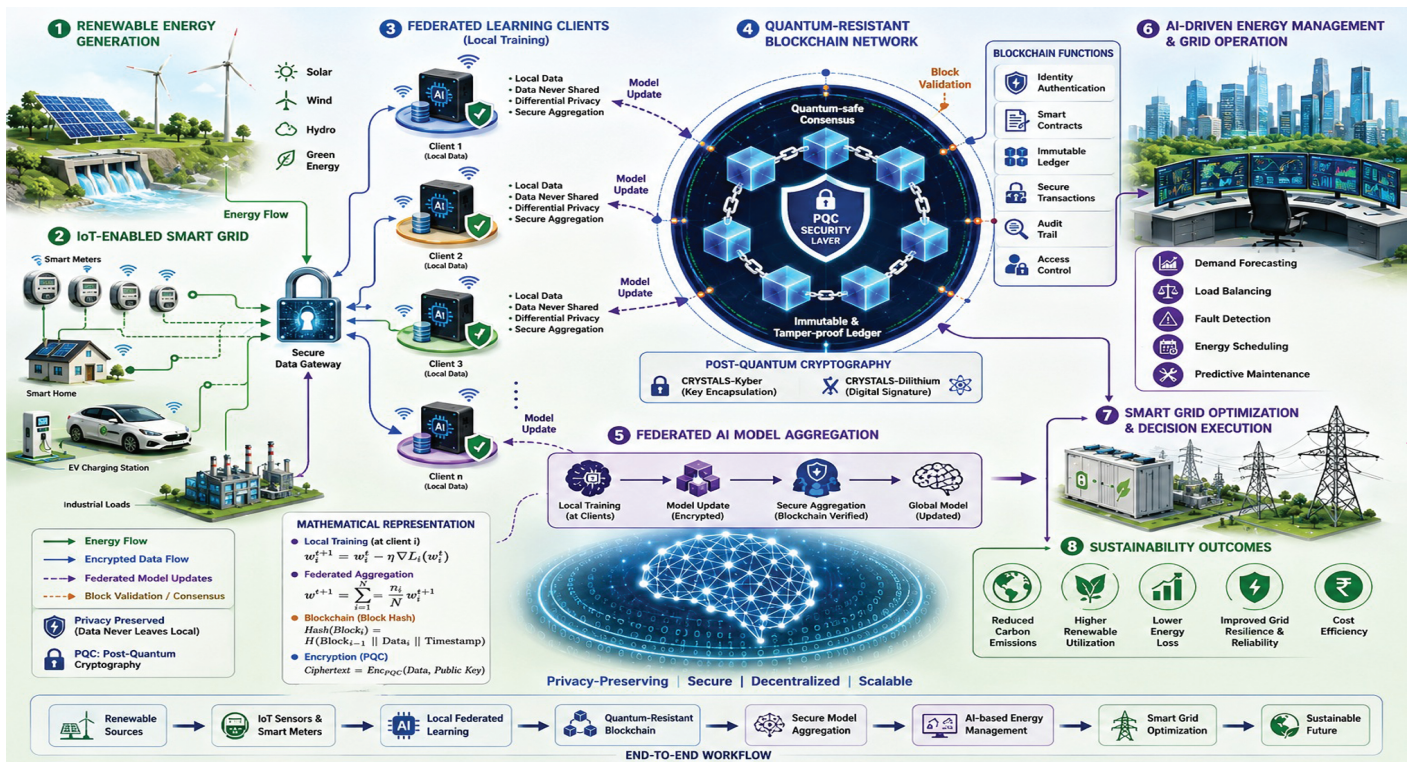
SDG	Contribution of the Research
SDG 9 – Industry, Innovation & Infrastructure	Develops innovative, durable alkali-activated concrete for sustainable infrastructure.
SDG 11 – Sustainable Cities & Communities	Supports stronger, longer-lasting, and sustainable buildings and infrastructure.
SDG 12 – Responsible Consumption & Production	Utilizes industrial by-products, reducing waste and conserving resources.
SDG 13 – Climate Action	Lowers CO ₂ emissions by reducing the use of Ordinary Portland Cement (OPC).

Building Quantum-Secure Smart Grids with Blockchain and Federated Intelligence



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Graphical Abstract



At a Glance

Modern smart grids connect millions of smart meters, renewable energy systems, electric vehicles, and energy storage devices through the Internet of Things (IoT). While this digital transformation improves energy efficiency and enables intelligent decision-making, it also creates significant cybersecurity challenges. Existing blockchain-based energy management systems remain vulnerable to future quantum computers, which could break today's widely used cryptographic algorithms. In addition, conventional blockchain consensus mechanisms often consume excessive computational resources, limiting scalability and sustainability.

This research introduces a Quantum-Resistant Hybrid Blockchain (QR-HB) framework that combines post-quantum cryptography, blockchain technology, federated learning, and homomorphic encryption to create a secure and intelligent smart-grid ecosystem. The proposed architecture employs NTRU lattice-based cryptography, which provides protection against future quantum attacks. A lightweight

Proof-of-Authentication (PoA) consensus mechanism reduces computational overhead and energy consumption compared with traditional Proof-of-Work systems. To preserve user privacy, homomorphic encryption allows encrypted energy data to be processed without exposing sensitive information. Meanwhile, federated learning enables distributed artificial intelligence to detect anomalies and fraudulent activities without requiring centralized collection of consumer data.

Experimental evaluation demonstrated substantial improvements in energy efficiency, scalability, and security. The proposed framework achieved approximately 67% lower energy consumption than conventional Proof-of-Work approaches while significantly reducing operational complexity and maintaining high transaction throughput. By integrating quantum-resistant security with privacy-preserving artificial intelligence, the proposed system establishes a sustainable foundation for next-generation smart grids capable of supporting decentralized energy markets, renewable energy integration, and secure digital energy transactions.

Preparing Tomorrow's Smart Grids for Quantum-Era Cybersecurity

The rapid growth of IoT-enabled smart grids has transformed electricity generation, transmission, and consumption into highly connected digital ecosystems. However, this connectivity also increases exposure to cyberattacks, privacy breaches, and emerging quantum computing threats. Traditional encryption methods such as RSA and ECC may become vulnerable once large-scale quantum computers become available. Furthermore, existing blockchain systems often suffer from high computational costs, poor scalability, and excessive energy consumption. Therefore, future smart-grid infrastructure requires security mechanisms that remain effective in both classical and quantum computing environments while supporting sustainable energy management.

A Hybrid Intelligence Framework for Secure and Sustainable Energy Management

To overcome these challenges, the researchers developed a Quantum-Resistant Hybrid Blockchain (QR-HB) architecture. The framework combines four complementary technologies:

- NTRU lattice-based cryptography for post-quantum security.
- Proof-of-Authentication (PoA) consensus for energy-efficient blockchain validation.
- Homomorphic encryption to process encrypted energy data without compromising privacy.
- Federated learning to perform distributed artificial intelligence for anomaly detection and fraud prevention while keeping consumer data local.

Together, these technologies establish a secure, scalable, privacy-preserving, and environmentally sustainable digital infrastructure for future smart grids.

Integrating Artificial Intelligence with Quantum-Safe Blockchain Technology

The proposed framework enables every smart-grid node to locally train machine-learning models using its own energy consumption data. Instead of transmitting private data, only model parameters are exchanged through the blockchain network. Homomorphic encryption ensures secure computation on encrypted information, while the blockchain provides transparent and tamper-resistant transaction records. The Proof-of-Authentication consensus further minimizes computational overhead, making the architecture suitable for large-scale IoT-based energy systems. This integrated approach significantly enhances system resilience against cyber threats while improving operational efficiency.

Delivering Secure, Efficient, and Future-Ready Smart Energy Networks

Performance evaluation confirmed that the proposed QR-HB framework substantially improves smart-grid operation. Compared with conventional blockchain approaches, it demonstrated significantly lower energy consumption, improved scalability, reduced operational latency, enhanced privacy protection, and strong resistance to both current and future cyber threats. The combination of blockchain, artificial intelligence, and post-quantum cryptography provides a practical pathway toward intelligent and sustainable energy infrastructure capable of supporting future decentralized energy markets.

Key Findings

- Developed a Quantum-Resistant Hybrid Blockchain integrating blockchain, federated learning, homomorphic encryption, and NTRU cryptography.
- Reduced blockchain energy consumption by approximately 67% compared with conventional Proof-of-Work mechanisms.
- Enhanced privacy through homomorphic encryption while enabling secure computation on encrypted energy data.
- Improved anomaly detection, fraud prevention, scalability, and quantum resilience using distributed federated learning.

Real-World Applications

The proposed framework has broad applications across modern energy infrastructure and digital utility systems. It can be deployed in smart cities, renewable energy management, microgrids, electric vehicle charging networks, peer-to-peer energy trading, and distributed power systems where secure and privacy-preserving energy transactions are essential. By protecting energy data against both present-day cyber threats and future quantum attacks, the framework strengthens national critical infrastructure.

Utility companies can use the system to monitor energy distribution, detect abnormal power consumption, prevent cyber intrusions, and optimize electricity demand in real time without compromising consumer privacy. The federated learning component enables collaborative artificial intelligence across multiple substations while keeping sensitive customer information decentralized. The energy-efficient blockchain consensus also reduces computational costs, making the solution suitable for large-scale IoT deployments.

Beyond the energy sector, similar architectures may be adapted for healthcare, industrial IoT, smart manufacturing, transportation, and critical infrastructure, where secure decentralized data sharing, privacy preservation, and future quantum resilience are becoming increasingly important.

Future Outlook

As quantum computing technology continues to evolve, conventional cybersecurity solutions may become inadequate for protecting critical infrastructure. This research provides an important foundation for developing quantum-safe digital ecosystems capable of supporting secure, intelligent,

and sustainable energy management. Future studies may integrate digital twins, edge computing, 6G communication networks, explainable artificial intelligence, and autonomous grid control to further enhance system performance. The proposed framework has the potential to become a core technology for future smart cities, carbon-neutral energy systems, and resilient national power infrastructures.

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Reference

Yarrabothu, R. S., Benni, N. S., Nirmal Raj, S., Kumar, M., Singh, B. K., Divya, A., Rajendran, B., & Tirth, V. (2026). Quantum-resistant blockchain and federated learning integrated secure and scalable smart grid framework for sustainable and privacy-preserving energy management. Sustainable Computing: Informatics and Systems, 50, 101305. <https://doi.org/10.1016/j.suscom.2026.101305>, Elsevier, SCIE, h index 64, Q1, impact factor : 6.2

Collaborating Institutions

The work involved collaboration among researchers from multiple institutions across India and Saudi Arabia, with funding support from the Deanship of Research and Graduate Studies, King Khalid University, Kingdom of Saudi Arabia, under the Large Research Group Project (RGP2/149/46).

Sustainable Development Goals (SDGs) Addressed:

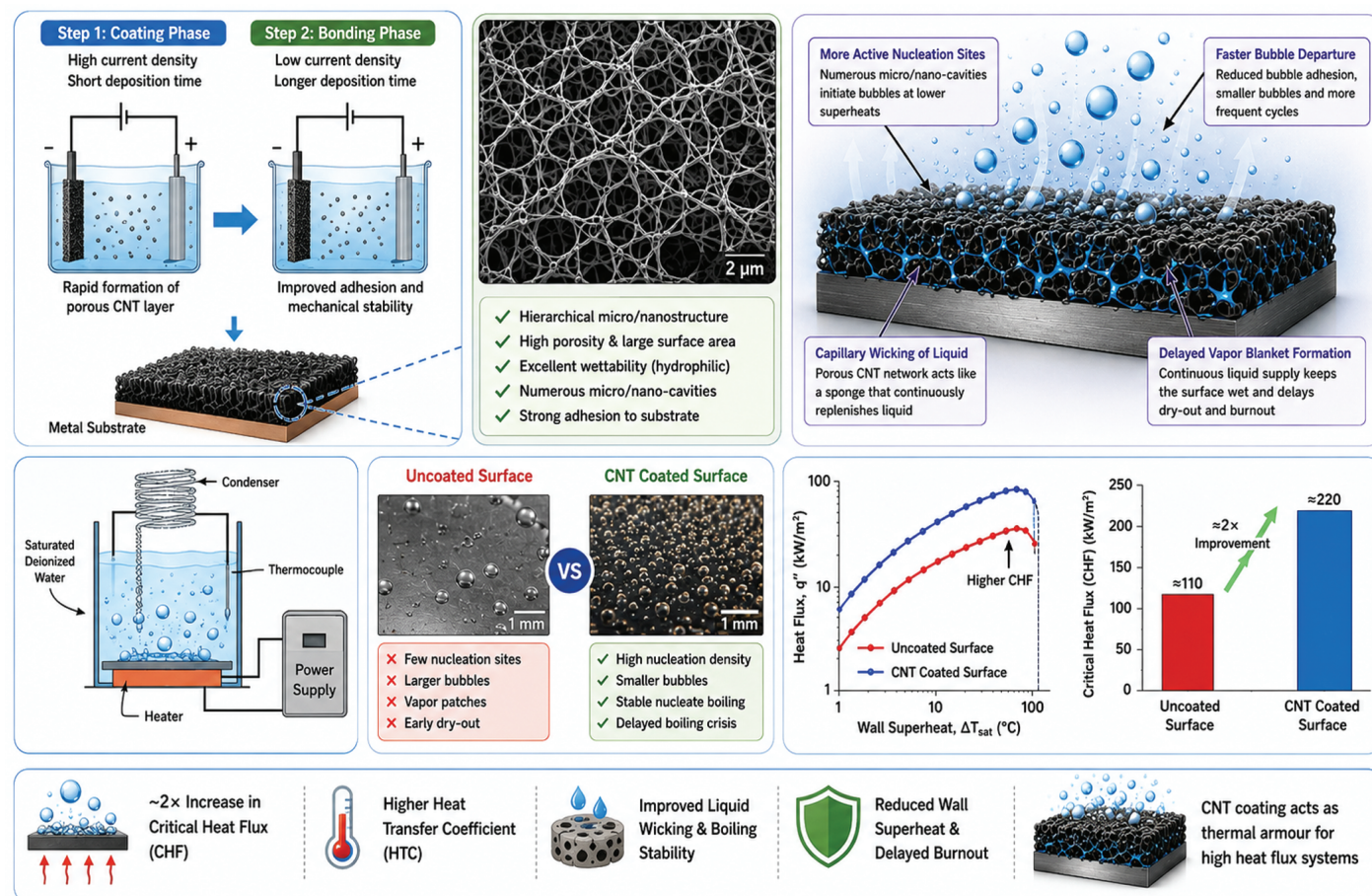
SDG	Contribution of the Research
SDG 7 Affordable and Clean Energy	The proposed quantum-resistant blockchain framework enables secure, efficient, and privacy-preserving smart-grid operations, facilitating renewable energy integration, decentralized energy trading, and intelligent energy management while reducing computational energy consumption.
SDG 9 Industry, Innovation and Infrastructure	The research introduces an innovative digital infrastructure by integrating post-quantum cryptography, blockchain, federated learning, and homomorphic encryption to build scalable, secure, and resilient next-generation smart grids.
SDG 11 Sustainable Cities and Communities	The framework supports reliable and resilient urban energy infrastructure by improving the security, efficiency, and scalability of smart-grid systems that power smart cities, electric vehicles, and distributed energy resources.
SDG 12 Responsible Consumption and Production	The improved power quality reduces electrical losses, prevents equipment damage, extends the operational life of electrical devices, and enhances efficient utilization of electrical energy, promoting responsible energy consumption and sustainable industrial operation
SDG 13 Climate Action	By promoting energy-efficient blockchain operations, optimizing renewable energy utilization, and supporting sustainable energy management, the framework contributes to reducing the environmental footprint of digital energy systems.

Nanotube Armour for Boiling Surfaces: How a Two-Step Carbon Nanotube Coating Doubles Critical Heat Flux in Pool Boiling



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Graphical Abstract



At a Glance

Efficient thermal management is essential for modern technologies such as high-performance processors, data centres, nuclear reactors, and hydrogen energy systems. This study developed a simple two-step electrochemical technique to fabricate porous multi-walled carbon nanotube (MWCNT) coatings on copper surfaces. By carefully controlling the coating conditions, the engineered surface significantly improved boiling heat transfer, initiating nucleate boiling earlier, increasing the critical heat flux by 108.5%, and enhancing the heat transfer coefficient by 113.85% compared with bare copper. The coating also demonstrated excellent mechanical stability and repeatability, making it a promising solution for next-generation cooling technologies.

Why This Research Matters?

Two parameters primarily determine the thermal performance of a boiling surface: the critical heat flux (CHF), which defines the maximum heat dissipation limit before vapour blanketing induces thermal failure, and the heat transfer coefficient (HTC), which quantifies the heat removed per unit surface superheat. Simultaneously enhancing both parameters remains a significant challenge because the surface characteristics that promote boiling enhancement—including porosity, roughness, wettability, and thermal conductivity—often compromise mechanical durability, coating adhesion, and manufacturing scalability. Carbon nanotubes (CNTs) offer exceptional potential owing to their outstanding thermal conductivity, high aspect ratio, large

specific surface area, and interconnected fibrous architecture, which naturally forms highly porous coatings. However, the inherent hydrophobicity of CNTs and the limitations of conventional fabrication techniques, such as spray coating, dip coating, and chemical vapour deposition, have hindered the realization of coatings that simultaneously provide high porosity, robust substrate adhesion, controlled wettability, and cost-effective fabrication. This study addresses these limitations through an ambient-temperature, single-electrolyte, two-step electrochemical deposition strategy that independently tailors pore formation and interfacial bonding, thereby producing a mechanically durable, hydrophilic, and highly porous MWCNT coating without the need for sophisticated processing equipment.

Engineering the Surface: A Two-Step Electrochemical Strategy

The innovation of this research lies in developing a simple, scalable two-step electrochemical deposition strategy (Figure 1) to fabricate highly porous and mechanically stable carbon nanotube coatings on conventional copper surfaces. The first deposition stage creates a porous nanotube framework using hydrogen bubbles as natural templates, while the second stage strengthens the bonding between the coating and the substrate. This unique approach independently controls porosity, surface roughness, and wettability, resulting in durable coatings with superior boiling performance. Unlike conventional coating techniques that require expensive equipment or high-temperature processing, this ambient-temperature, single-electrolyte process offers a cost-effective and industry-friendly solution for advanced thermal management applications.

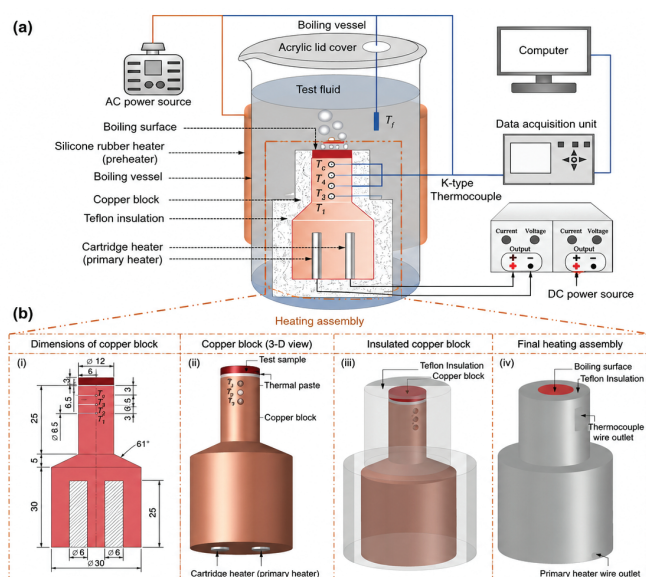


Figure 1 : Experimental setup used to evaluate the boiling heat transfer performance of carbon nanotube-coated surfaces. (a) Pool boiling test apparatus. (b) Heating assembly used in the experiments.

From Laboratory Bench to Measurable Performance Gains

Every performance claim presented in this study is supported by a rigorously validated experimental methodology. The pool-boiling performance of the bare copper substrate was first benchmarked against five independent literature datasets and the classical Rohsenow, Zuber, and Kandlikar correlations, exhibiting a deviation of only approximately 9.5% from the Zuber CHF prediction, thereby confirming the accuracy and reliability of the experimental facility prior to coating evaluation. Relative to this validated baseline, the MWCNT-coated surfaces demonstrated systematic, current-density-dependent enhancements in boiling performance. The onset of nucleate boiling (ONB) decreased from a wall superheat of 8.17 K for bare copper to as low as 5.1 K for the coating fabricated at 200 mA cm⁻², corresponding to a 37.58% reduction. Such an early ONB is particularly advantageous for high-power thermal systems, as it minimizes excessive wall temperatures before efficient boiling heat transfer is established. Furthermore, the critical heat flux increased from 1012 kW m⁻² for bare copper to 1620, 1840, and 2110 kW m⁻² for coatings deposited at 100, 150, and 200 mA cm⁻², respectively, representing a maximum enhancement of 108.5%. Likewise, the heat transfer coefficient improved from 55.18 kW m⁻² K⁻¹ to a maximum of 118 kW m⁻² K⁻¹, corresponding to an enhancement of up to 113.85%. These improvements originate from the synergistic influence of increased porosity, surface roughness, and enhanced wettability, which collectively increase the density of active nucleation sites while promoting efficient capillary-driven liquid replenishment beneath departing bubbles, thereby delaying irreversible dryout and extending the CHF limit. The long-term reliability of the coatings was further verified through three independent boiling tests conducted at 24-hour intervals, yielding deviations of only ± 1.1 °C in wall superheat, $\pm 2.6\%$ in CHF, and 1.4 kW m⁻² K⁻¹ in HTC, thereby demonstrating excellent repeatability and hydrothermal stability rather than isolated laboratory performance.

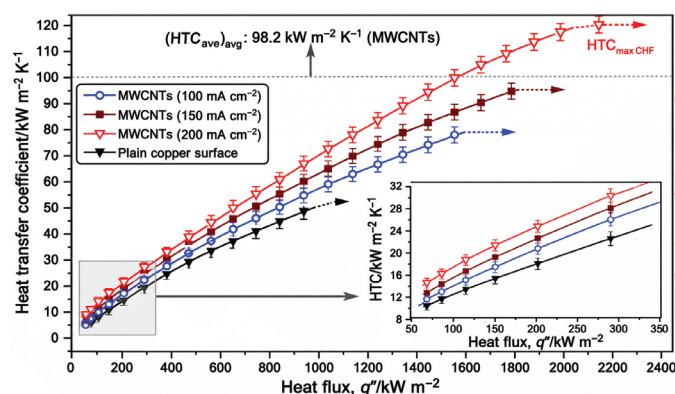


Figure 2 : Critical heat flux and heat transfer coefficient increase systematically as surface wettability improves (contact angle decreases) with rising coating current density, confirming wettability and porosity as the controlling design variables.

Key Findings

- A novel two-step electrochemical deposition strategy, employing a high-current porosity-generation stage followed by a low-current bonding stage, enabled the fabrication of mechanically robust, highly porous MWCNT coatings on copper through a scalable, single-bath, ambient-temperature process.
- The engineered MWCNT surfaces advanced the onset of nucleate boiling by up to 37.58%, reducing the wall superheat to as low as 5.1 K compared with bare copper.
- The critical heat flux (CHF) increased by up to 108.5%, reaching 2110 kW m⁻² compared with 1012 kW m⁻² for the uncoated copper substrate.
- The heat transfer coefficient (HTC) improved by up to 113.85%, attaining 118 kW m⁻² K⁻¹ relative to 55.18 kW m⁻² K⁻¹ for bare copper.
- Increasing the first-stage current density systematically enhanced coating porosity (42→46→51%), surface roughness (Ra: 2.41→3.62 μm), and hydrophilicity (contact angle 71.31°→58.62°), exhibiting a strong correlation with the observed boiling enhancement.
- Three independent repeatability tests demonstrated excellent hydrothermal stability and coating durability, with deviations of less than 3% across all key boiling performance parameters.

Real-World Applications

The proposed MWCNT coating technology can be readily integrated into copper-based cooling systems used in high-performance processors, data centres, power electronics, nuclear energy systems, industrial boilers, heat exchangers, and hydrogen storage technologies. By sig-

nificantly increasing the critical heat flux and heat transfer coefficient, the coating improves thermal safety, prevents overheating, and enhances the efficiency and reliability of high-heat-flux devices. Since the coating is fabricated using an inexpensive electrochemical process compatible with existing industrial infrastructure, it offers strong potential for commercial-scale adoption and retrofitting of conventional thermal systems.

Future Outlook

The proposed two-stage electrochemical deposition strategy establishes a versatile platform for further optimization of engineered boiling surfaces. More precise control of the first-stage current density and deposition duration could enable systematic tailoring of coating porosity, surface morphology, and wettability to meet the requirements of specific working fluids and heat-flux conditions. Furthermore, integrating MWCNTs with complementary functional nanomaterials, such as graphene oxide or metal oxides, may provide additional improvements in both CHF and HTC through synergistic enhancement of surface characteristics. Future investigations should extend the present methodology to subcooled and flow-boiling conditions, as well as to refrigerants and dielectric liquids used in advanced electronics cooling, while incorporating long-term industrial-scale durability assessments to facilitate commercial implementation. Moreover, integrating the experimental database with physics-informed machine-learning and data-driven predictive models, as increasingly reported for advanced nanostructured boiling surfaces, could significantly accelerate the optimization, design, and practical deployment of this coating technology for next-generation thermal-management systems.

About the Researcher

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Reference

Singh, S. K., Sharma, D., & Gupta, S. K. (2026). Experimental investigation of nucleate pool boiling heat transfer performance of carbon nanotubes porous coating. Journal of Thermal Analysis and Calorimetry, 151, 1547–1562. <https://doi.org/10.1007/s10973-025-15224-2>. Springer Nature · SCIE-indexed · Impact Factor 4.2 · Q1

Collaborating Institutions

- National Institute of Technology (NIT) Hamirpur, Himachal Pradesh, India
- Led the conceptualization and design of the research.
 - Conducted pool boiling experiments and thermal performance evaluation.
 - Assisted in experimental validation and interpretation of heat transfer mechanisms.
- Thapar Institute of Engineering & Technology, Patiala, Punjab, India
- Supported nanomaterial surface modification and coating development.
 - Contributed to materials characterization and scientific discussions.
 - Assisted in manuscript preparation and technical review.

Collaborative Impact

This interdisciplinary collaboration combined expertise in mechanical engineering, nanomaterials, electrochemical surface engineering, and thermal sciences to develop a scalable carbon nanotube coating technology for high-performance boiling heat transfer. The work was further strengthened through financial support from the Science and Engineering Research Board (SERB), Government of India (Grant No. CRG/2021/001457).

Sustainable Development Goals (SDGs) Addressed:

The research contributes to the following United Nations Sustainable Development Goals:

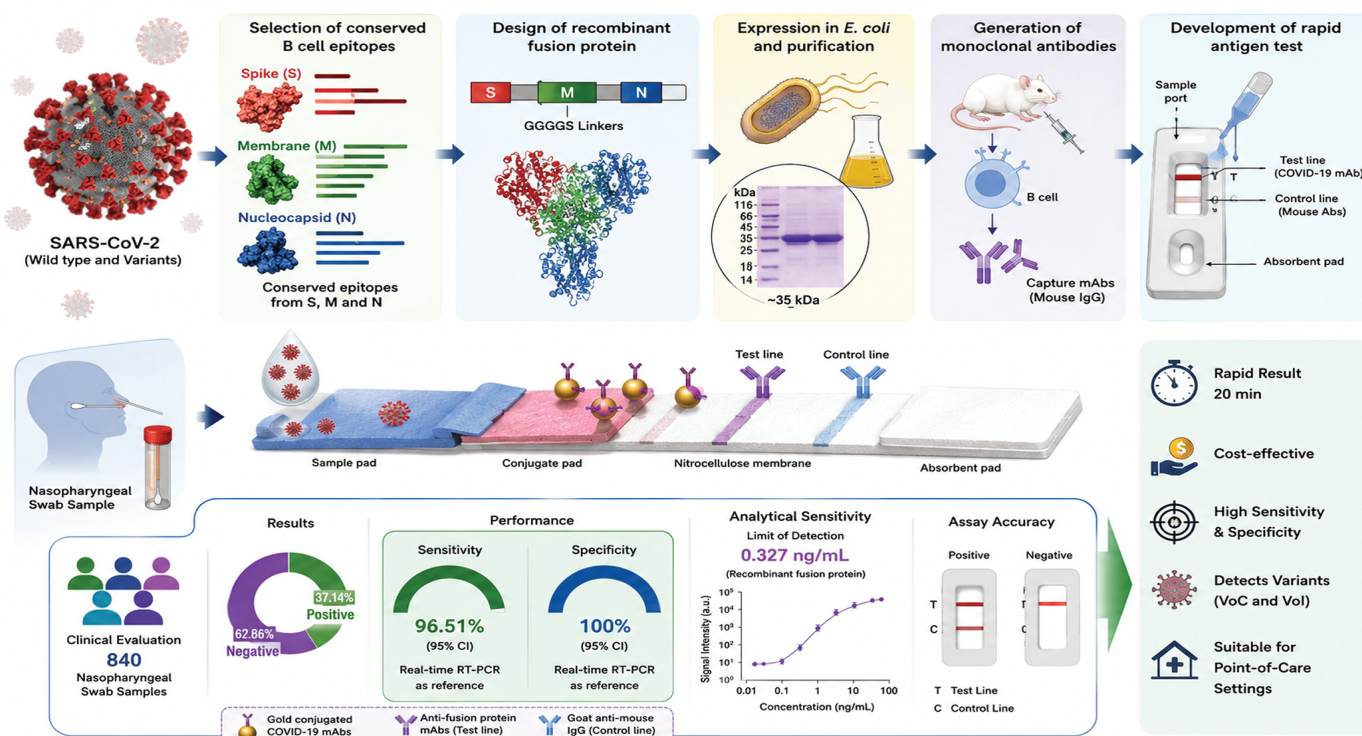
SDG	Contribution of the Research
SDG 7 Affordable and Clean Energy	Improves thermal energy efficiency by enabling faster and safer heat dissipation in advanced cooling systems.
SDG 9 Industry, Innovation and Infrastructure	Develops a scalable nanotechnology-based surface engineering approach for next-generation thermal management systems.
SDG 12 Responsible Consumption and Production	Extends the operational life of thermal components through durable, high-performance coatings, reducing material waste and maintenance
SDG 13 Climate Action	Reduces cooling energy requirements and associated greenhouse gas emissions through more efficient heat transfer technologies.

Engineering a Smarter Rapid Antigen Test for Reliable COVID-19 Variant Detection



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Graphical Abstract



At a Glance

The COVID-19 pandemic highlighted the critical need for diagnostic tools that are not only accurate but also rapid, affordable, and easily deployable at the point of care. Although reverse transcription polymerase chain reaction (RT-PCR) remains the gold standard for detecting SARS-CoV-2 infection, its dependence on sophisticated laboratory infrastructure, trained personnel, and longer turnaround times limits its widespread use, particularly in resource-constrained settings. Rapid antigen tests provide a practical alternative, but many commercially available assays have experienced reduced performance due to frequent mutations in the virus, especially in the Spike protein, leading to false-negative results for emerging variants.

To overcome these challenges, this research developed a novel recombinant fusion protein by integrating carefully selected conserved B-cell epitopes from the Spike (S), Membrane (M), and Nucleocapsid (N) proteins of SARS-CoV-2. By targeting highly conserved antigenic regions

rather than a single viral protein, the study aimed to improve the ability of rapid antigen tests to recognize multiple circulating variants while maintaining high diagnostic accuracy. The engineered fusion protein was successfully expressed and purified, and subsequently used to generate monoclonal antibodies for the development of a lateral-flow immunochromatographic rapid antigen assay.

The diagnostic performance of the newly developed assay was evaluated using 840 clinical nasopharyngeal samples, with RT-PCR serving as the reference method. The assay demonstrated 96.51% sensitivity, 100% specificity, and an analytical limit of detection of 0.327 ng/mL, indicating excellent diagnostic reliability. By combining recombinant protein engineering with immunodiagnostic technology, this study provides a promising strategy for developing next-generation rapid antigen tests capable of supporting timely disease diagnosis, effective outbreak surveillance, and improved public health preparedness against current and future SARS-CoV-2 variants.

Keeping Pace with an Ever-Changing Virus

Since its emergence, SARS-CoV-2 has continuously evolved, giving rise to numerous variants with mutations in key structural proteins, particularly the Spike (S) protein. While these mutations have influenced viral transmissibility and immune escape, they have also affected the performance of several rapid antigen diagnostic tests that rely on a single viral target. Reduced antigen recognition can lead to false-negative results, compromising timely diagnosis and public health interventions.

Although RT-PCR remains the gold standard for COVID-19 diagnosis, it requires sophisticated laboratory infrastructure, trained personnel, and longer turnaround times, making it less suitable for decentralized or resource-limited settings. Rapid antigen tests offer a faster and more economical alternative; however, their diagnostic accuracy depends largely on the stability of the antigenic target selected during assay development.

Recognizing these challenges, the present study focused on identifying highly conserved antigenic regions that remain relatively unchanged across different SARS-CoV-2 variants. Targeting these conserved regions provides a promising strategy for developing robust diagnostic assays capable of maintaining reliable performance even as the virus continues to evolve. This approach addresses an important need for future-ready diagnostic technologies that support rapid disease surveillance and effective outbreak management.

Building a Universal Viral Target

A key innovation of this research was the development of a novel recombinant fusion protein by integrating carefully selected conserved B-cell epitopes from three major structural proteins of SARS-CoV-2: the Spike (S), Membrane (M), and Nucleocapsid (N) proteins. Rather than relying on a single viral antigen, the researchers strategically combined immunologically important regions from multiple proteins into one engineered construct.

The selected epitopes were linked using flexible peptide linkers to preserve their antigenic properties and facilitate efficient protein folding. This multi-epitope design increases the probability of antibody recognition even when mutations occur in individual viral proteins, thereby improving the robustness of antigen detection across circulating variants.

The recombinant construct was designed using bioinformatics tools to ensure antigenicity, structural stability, and expression compatibility. Following successful cloning and expression, the fusion protein served as the primary immunogen for generating monoclonal antibodies used in

the rapid antigen detection platform. This integrated design represents an important advancement in recombinant protein engineering for infectious disease diagnostics.

From Protein Engineering to Point-of-Care Diagnosis

The research combined molecular biology, recombinant protein technology, immunology, and diagnostic assay development to create a complete rapid antigen detection platform. The engineered fusion protein was successfully expressed in *Escherichia coli*, purified using chromatographic techniques, and characterized to confirm its integrity and antigenic properties.

The purified recombinant protein was subsequently used to immunize mice for the production of high-affinity monoclonal antibodies. After screening and characterization, the most suitable antibody pair was selected for incorporation into a lateral-flow immunochromatographic assay, enabling rapid visual detection of SARS-CoV-2 antigens.

The diagnostic performance of the developed assay was rigorously evaluated using 840 clinical nasopharyngeal samples, with RT-PCR serving as the reference standard. In addition to determining sensitivity and specificity, the researchers evaluated the analytical detection limit and overall diagnostic reliability. The successful integration of recombinant protein engineering with immunodiagnostic technology demonstrates a practical pathway for translating laboratory discoveries into affordable point-of-care diagnostic solutions.

Delivering Reliable Detection Across Variants

The developed rapid antigen assay demonstrated excellent diagnostic performance during clinical evaluation. Compared with RT-PCR, the assay achieved an overall sensitivity of 96.51% and specificity of 100%, indicating a high degree of agreement with the reference molecular diagnostic method. Furthermore, the assay exhibited a limit of detection of 0.327 ng/mL, highlighting its ability to detect low concentrations of viral antigen.

One of the most significant achievements of this work is the successful application of conserved multi-epitope recombinant protein engineering to improve antigen detection. By targeting conserved regions present in multiple viral structural proteins, the assay is less vulnerable to the effects of mutations occurring in individual proteins, thereby enhancing its potential applicability across circulating SARS-CoV-2 variants.

Beyond COVID-19, the study establishes a versatile framework for developing recombinant antigen-based rapid diagnostic assays for other emerging infectious diseases. The combination of high analytical performance, rapid detection, and adaptability makes this technology highly valuable for future public health preparedness.

Key Findings

- Developed a novel recombinant fusion protein by integrating conserved B-cell epitopes from the Spike, Membrane, and Nucleocapsid proteins of SARS-CoV-2.
- Successfully expressed and purified the recombinant fusion protein for immunological applications.
- Generated high-affinity monoclonal antibodies and developed a rapid lateral-flow immunochromatographic antigen assay.
- Clinically validated the assay using 840 nasopharyngeal samples, demonstrating excellent diagnostic performance.
- Achieved 96.51% sensitivity and 100% specificity when compared with RT-PCR.
- Demonstrated a limit of detection of 0.327 ng/mL, indicating high analytical sensitivity.
- Proposed a conserved multi-epitope strategy that may improve diagnostic robustness against emerging SARS-CoV-2 variants.

Real-World Applications

The recombinant fusion protein-based rapid antigen detection platform has significant potential for improving infectious disease diagnosis across diverse healthcare settings. Owing to its rapid turnaround time, simplicity of operation, and high diagnostic accuracy, the assay can support routine screening in hospitals, primary healthcare centres, emergency departments, and diagnostic laboratories.

Its portability and minimal infrastructure requirements make it particularly suitable for point-of-care testing in rural and resource-limited regions where access to molecular diagnostic facilities is restricted. The technology can also be deployed at airports, railway stations, educational institutions, workplaces, and other high-density public locations for rapid screening during disease outbreaks.

Beyond clinical diagnosis, the platform has potential applications in community surveillance programmes, public health monitoring, outbreak containment, and pandemic preparedness. The recombinant fusion protein strategy described in this study may also serve as a foundation for developing rapid diagnostic assays targeting other viral pathogens, thereby strengthening global preparedness for future infectious disease emergencies.

Future Outlook

The successful development of a conserved multi-epitope recombinant fusion protein opens new opportunities for designing next-generation rapid diagnostic technologies. Future research may focus on evaluating the assay against newly emerging SARS-CoV-2 variants, expanding clinical validation across diverse geographical populations, and improving large-scale manufacturing for commercial deployment.

The recombinant fusion protein platform may also be adapted for multiplex diagnostics, enabling simultaneous detection of multiple respiratory pathogens within a single test. Integration with digital health technologies, smartphone-assisted result interpretation, and artificial intelligence-based disease surveillance systems could further enhance the utility of rapid diagnostics.

More broadly, the multi-epitope design strategy demonstrated in this work provides a valuable blueprint for developing robust recombinant antigen-based assays for other infectious diseases, contributing to global health security and improved preparedness against future pandemics.

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 • Immunotechnology • Bioinformatics • Infectious Disease Diagnostics
 • Industrial Biotechnology
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Reference

Vidyasagar, G. V. C., Reddy, P. V. J., Ghouse, M. M., Venkateswarulu, T. C., Kavi Kishor, P. B., Suravajhala, P., & Polavarapu, R. (2024). Designing and expression of novel recombinant fusion protein for efficient antigen screening of SARS-CoV-2. *AMB Express*, 14, 80. Springer Nature. <https://doi.org/10.1186/s13568-024-01719-y> Springer, SCIE; Impact factor: 3.1; Q2; h-index of journal: 89

Collaborating Institutions

This study was conducted through a collaborative effort involving academia and industry, combining expertise in molecular diagnostics, recombinant protein engineering, bioinformatics, and biotechnology.

- Genomix CARL Pvt. Ltd., Pulivendula, Andhra Pradesh – Led recombinant protein design, antibody production, rapid antigen assay development, and clinical validation.
- Department of Biotechnology, Vignan's Foundation for Science, Technology & Research (VFSTR), Vadlamudi, Andhra Pradesh – Contributed to molecular biology, protein engineering, data analysis, and manuscript preparation.
- Amrita School of Biotechnology, Amrita Vishwa Vidyapeetham, Kerala – Provided expertise in bioinformatics, epitope prediction, and structural modelling.
- Department of Genetics, Osmania University, Hyderabad – Supported molecular characterization and data interpretation.

Collaborative Impact

This interdisciplinary collaboration combined expertise in mechanical engineering, nanomaterials, electrochemical surface engineering, and thermal sciences to develop a scalable carbon nanotube coating technology for high-performance boiling heat transfer. The work was further strengthened through financial support from the Science and Engineering Research Board (SERB), Government of India (Grant No. CRG/2021/001457).

Sustainable Development Goals (SDGs) Addressed:

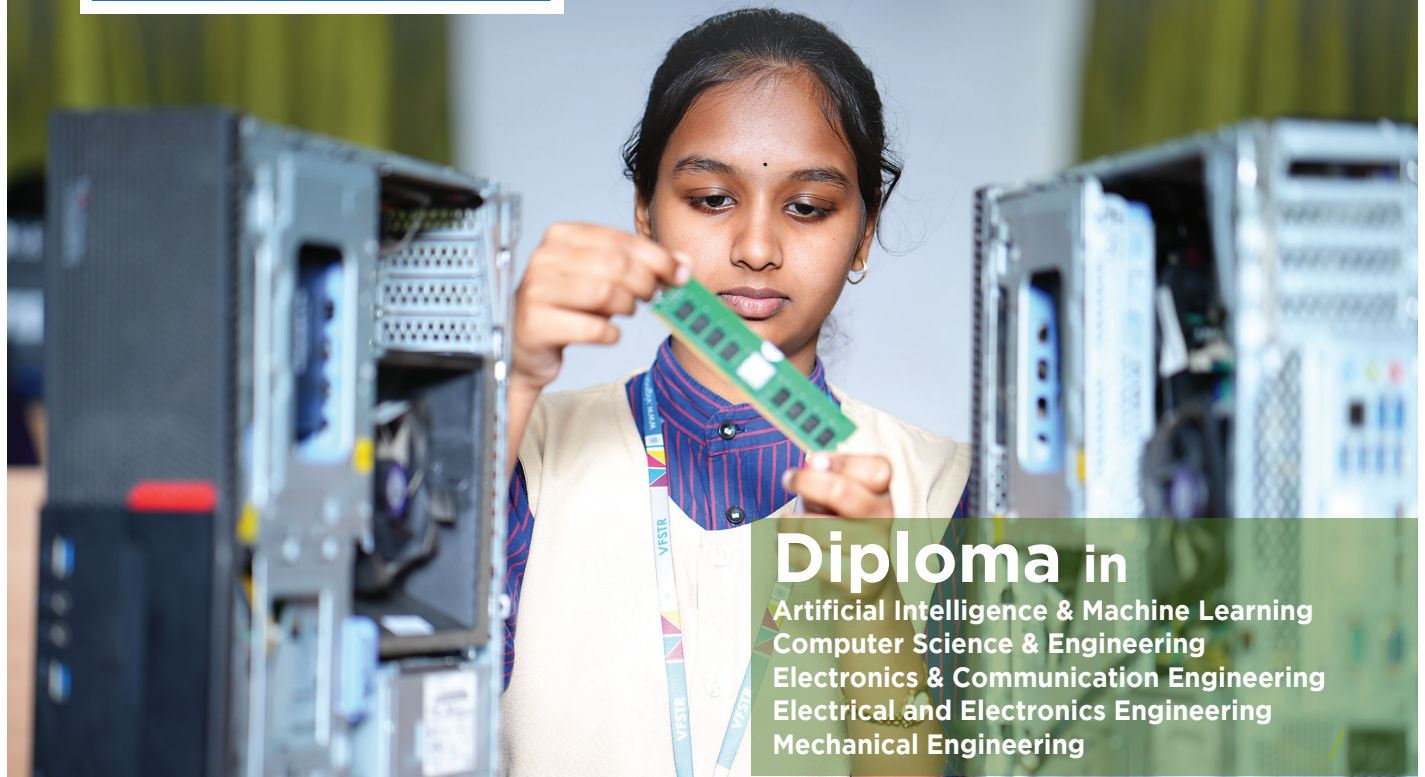
SDG	Contribution of the Research
SDG 3 – Good Health and Well-being	Developed a rapid, accurate, and affordable antigen diagnostic assay to support early detection and control of COVID-19.
SDG 9 Industry, Innovation and Infrastructure	Demonstrated an innovative recombinant fusion protein-based diagnostic platform for next-generation point-of-care testing.
SDG 10 – Reduced Inequalities	Promotes equitable access to reliable diagnostics through a cost-effective assay suitable for resource-limited and remote healthcare settings.
SDG 17 – Partnerships for the Goals	Exemplifies successful collaboration between academia and industry to develop translational healthcare technologies.



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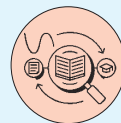
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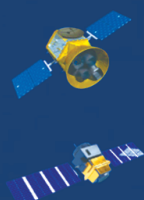
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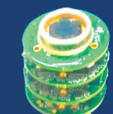
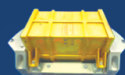
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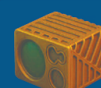
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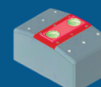
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