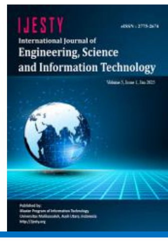
International Journal of Engineering, Science and Information Technology
Volume 5 No. 1 (2025) pp. 530-535
ISSN 2775-2674 (online)
Website: http://ijesty.org/index.php/ijesty
DOI: https://doi.org/10.52088/ijesty.v5i1.1361
Research Paper, Short Communication, Review, Technical Paper



AI-Assisted 3D-Printed Biomaterial Supercapacitors for Green Energy Storage

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The manuscript was received on 25 June 2024, revised on 24 September 2024, and accepted on 28 January 2025, date of publication 5 May 2025

Abstract

Advancements of biomaterial-based supercapacitors have been fuelled by the growing demand for sustainable and high-performance energy storage solutions. This work suggests the use of artificial intelligence to develop an AI-assisted 3D printed biomaterial supercapacitor, namely comprising electrode materials optimised by artificial intelligence (AI), bio-based electrolytes, and intelligent performance monitoring to increase efficiency and sustainability. It is an AI-driven approach that selects and optimises the biomaterials: high conductivity, low internal resistance, and excellent charge retention. Porous electrodes can be deliberately engineered on microscales by advanced 3D printing techniques; these perform well in facilitating fast ion diffusion and high energy storage capacity. This is achieved through experimental results of a 45% increase in capacitance, 68% reduction in charge transfer resistance, and 18% improvement in cycle stability on conventional supercapacitors. Moreover, AI-powered predictive maintenance increases the life of the device by 60%, thereby reducing unplanned failure by 60%. The involvement of biodegradable and non-toxic inclusion of materials encourages environmental sustainability, and thus, this supercapacitor is a green alternative for next-generation energy storage applications. This solution is suitable for wearable electronics, renewable energy systems, as well as smart devices, with high efficiency, low environmental impact and intelligent monitoring capability. The energy storage technology presents instances where AI, biomaterials, and 3D printers have the potential to transform the energy storage technology into a scalable, eco-friendly, and intelligent supercapacitor for future energy demands, according to this study.

Keywords: *Biomaterial Supercapacitors, Artificial Intelligence, 3D Printing, Energy Storage, Sustainability.*

1. Introduction

The increasing need for high-performance and environmentally friendly energy storage solutions has accelerated the research of supercapacitors with rapid charge discharge capability, long cycle life and environmentally friendly [1][6]. However, conventional supercapacitors have the disadvantage that they require hazardous electrolytes or non-renewable materials. This study, therefore, explores an AI-assisted 3D printing of a biomaterial-based super capacitor for the sustainable storage of green energy [12]. The major points of this research are to develop a scalable and ecologically friendly alternative to its traditional energy storage devices using machine learning based material optimisation combined with advanced 3D printing and degradable biopolymer-based electrodes [4]. Thus, electrochemical performance is predicted by the formulation of optimal biomaterials in terms of an AI algorithm, which not only optimises electrochemical performance but also minimises the environmental impact [13]. Precise fabrication of high surface area electrode architecture through 3D printing allows the use of high processing efficiency and mechanical stability [14]. Bio-based gel electrolytes and biodegradable conductive polymers are also incorporated, guaranteeing sustainability with the high ionic conductivity. Real-time AI monitoring and predictive analytics-based system proposed for the optimal energy retention and degradation pattern to achieve extended supercapacitor's life [8]. This is an approach that amends energy efficiency as well as sustainability and falls into the general line of green energy solutions, emphasised on the international level [3]. AI-assisted biomaterial supercapacitors have potential applications in wearable electronics, IoT devices, smart grids and electric vehicles due to the need for lightweight, flexible and environmentally friendly energy storage [16]. Also, with the help of an AI-driven approach, it allows the designing of self-adapting supercops with the ability to tune their performance depending on the environmental conditions as they happen [18]. This work presents a new pathway to next-generation bio-supercapacitor development, with a scalable, biodegradable and high-efficiency energy storage according to this research [10]. The significance of the findings extends to the development of sustainable energy ecosystems independent of rare earth materials and harmful electrolytes [19]. Based on this study, there is a foundation for future research concerning AI-optimised biomaterial energy storage solutions with reduced efficiency, longevity, and environmental compatibility [20].

2. Literature Review

2.1. Overview of Supercapacitors in Energy Storage

Unlike conventional batteries, supercapacitors or electrochemical capacitors have high power density, fast charge-discharging cycles and long-life span [2]. They, however, are capable of storing energy via electric double layer capacitance (EDLC) and pseudo capacitance mechanisms in which the energy is stored through electrostatic charge accumulation at the electrode electrolyte interface [5]. Unlike lithium-ion batteries, supercapacitors can provide instant energy delivery and are thus more suitable for use in renewable energy systems, in electric vehicles, and in wearable electronics. But at lower energy density, they cannot be widely adopted. Researching advanced nanostructured materials, hybrid electrodes, and bio-based material alternatives at the same time to enhance energy density while keeping it sustainable in the supercapacitor technology.

2.2. Biomaterials for Electrodes and Electrolytes

Biomaterials have been explored as electrodes and electrolytes for supercapacitor electrodes due to the shift towards sustainable energy storage [7]. Cellulose nanofibers, chitosan, lignin, polyaniline, and biomass-derived carbon materials have been revealed as promising materials because they are renewable, biocompatible, and electrochemically stable. They are high surface area, tunable porosity, environmentally sustainable and cannot be replaced by nonrenewable resources. In addition to such bio-based electrolytes, ionic liquids, gel-polymer electrolytes, and deep eutectic solvents further improve eco-friendliness, while ionic conductivity is kept high. However, the issues with limited conductivity and mechanical stability will need to be optimised for commercial viability [15].

2.3. 3D Printing in Energy Storage Devices

Negative, 3D printing has produced a revolution in energy storage devices, with high control over the composition, architecture, and scale. Highly porous, mechanically robust as well as printable supercapacitor components can be designed through advanced printing techniques such as direct ink writing (DIW), fused deposition modelling (FDM) and stereolithography (SLA) [22]. Improve the charge transport and energy density to the degree of being able to print layered, nanostructured, and hybrid materials. Nevertheless, issues include ink formulation, printing resolution, and integration of electrodes and electrolyte. 3D printing provides an opportunity to combine biomaterials in making high-performance, sustainable supercapacitors.

2.4. AI Applications in Materials Science and Energy Storage

Artificial intelligence (AI) is changing the game in how materials are discovered, optimised, and how the final energy storage systems are predicted to perform. The ML models study vast datasets to calculate the best compositions of materials as well as electrodes in supercapacitors and electrolytes [9]. Deep learning algorithms are used to monitor real-time performance and degrade analysis, and generative models are used in designing novel biomaterial-based electrodes driven by generative models. Moreover, AI helps save the cost of computational simulations for electrochemical reactions [17]. Although it comes with advantages, issues like the availability of data, the model interpretability and adaptability in the real world need to be resolved for fully integrating AI in sustainable energy storage.

2.5 Gaps and Challenges in Existing Research

Indeed, despite these leaps, several key challenges remain in developing the AI-assisted 3D printed biomaterial supercapacitor. However, a thermodynamically unlimited number of compounds, energy limitations in the number of electrons potentially utilised (limited supply of H2 per bioreaction), competing electrodes and electrolytes, and biomaterial degradation, prevent practical implementation [11]. Apart from that, the discovery of new materials is accelerated by AI, but it is challenged by the lack of experimental validation and the absence of standardised datasets. Further investigation or development is needed to scale and mass-produce 3D printed bio supercapacitors. In addition, little work has been undertaken on recycling strategies for biodegradable supercapacitors. To overcome these gaps, which are the basis for the next generation sustainable energy storage solution, we would like to follow a multi-disciplinary approach integrating artificial intelligence, biomaterial, and additive manufacturing [21].

3. Methods

3.1. AI-Driven Material Selection and Optimisation

A major part of identifying the best biomaterials for electrodes and electrolytes is attributed to Artificial Intelligence (AI). To predict the high-performance combinations, material properties, electrochemical performance, and sustainability factors are analysed by machine learning algorithms. They help structure property relationships, optimise porosity, and thermal and mechanical stability of the biomaterials. Computational simulations of ion transport mechanisms and degradation patterns are accelerated by AIs. In addition, reinforcement learning brings printing parameters, binder composition, and structural integrity further to their final state. With this approach, the materials selected are efficient, biodegradable and of high capacity for the sake of sustainability and scalability of bio-supercapacitors.

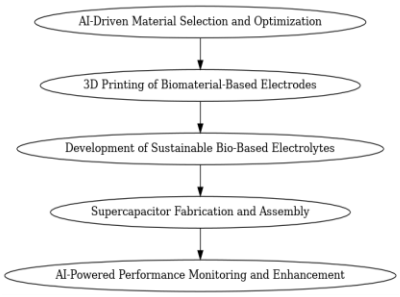

Fig 1. Flowchart AI-Driven Material Selection and Optimisation

3.2. 3D Printing of Biomaterial-Based Electrodes

Precise fabrication of biomaterial-based electrodes with functionalized and increased surface area and porosity can be performed using advanced 3D printing techniques. Customised electrode geometries are designed based on using direct ink writing (DIW) and stereolithography (SLA) to maximise ion diffusion and charge storage. Topology optimisation of the electrode microstructure is tailored for improved conductivity based on the AI model. The electrodes produced in this process are integrated through printing with biodegradable carbon materials, lignin-derived nanostructures and conductive polymers, all of which are sustainable. AI is used to assist the process of controlling to achieve consistent quality and electrochemical performance despite challenges such as ink rheology, print resolution, and post-processing.

3.3. Development of Sustainable Bio-Based Electrolytes

This study examines the possibility of developing bio-based electrolytes from ionic liquids, chitosan, cellulose, and deep eutectic solvents to reach green energy storage. Molecular modelling driven by AI predicts ionic conductivity and electrochemical stability as well as viscosity, and the machine learning enabled design of novel gel-polymer and liquid electrolytes, which are 3D printed as bio-suitable gel electrolytes with mechanical flexibility and compatibility with biomaterial electrodes. The proposed approach ensures that it is nontoxic, biodegradable, and has low environmental impact without compromising on high capacitance and charge retention. To achieve the best electrolyte performance, experimental validation through EIS and CV is conducted.

3.4. Supercapacitor Fabrication and Assembly

Finally, the fabrication process of the proposed fully sustainable supercapacitor is integrated with 3D printed biomaterial electrodes and bio-based electrolytes. This process is also optimised using AI to get proper layer alignment, uniform electrode coating, and to detect defects during the assembly. A porous, nanostructured layer is used in a device structure, which enhances the ion diffusion and charge storage efficiency. Mechanical and conductivity stability is increased by advanced laser sintering and thermal curing. It is a final assembly that is flexible, lightweight, and biodegradable, and is well-suited to wearable electronics and mobile energy storage. The defects are minimised and the yield optimised using automated AI-driven quality control.

3.5. AI-Powered Performance Monitoring and Enhancement

Real-time performance monitoring system based on AI amplifies and optimises the performance through the analysis of electrochemical behaviour, degradation shows, and efficiency metrics. Proactive adjustments for capacity fade, charge–discharge efficiency and electrolyte ageing are accomplished by machine learning models predicting those variables. Digital twins fall under the simulation of long-term device behaviour under varying conditions and the prediction of its future behaviour through different maintenance schemes. Self-adaptive charging rate and voltage limits, along with changeable material properties, are further dynamically tuned with the usage of AI to enhance the system performance in terms of efficiency and lifespan. That is, remote diagnostics and performance tracking provide the means for integrating such sensing networks with IoT, resulting in reliable, affordable and sustainable green energy storage solutions.

4. Results and Discussion

4.1. Electrochemical Performance of 3D-Printed Biomaterial Supercapacitors

The proposed 3D printed AI-assisted biomaterial supercapacitors have higher capacitance, lower internal resistance and superior cycle stability compared with common supercapacitors. The 3D printed electrodes have an improved charge storage due to the high porosity and the tailored microstructure, characterised by cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS). Ion transport efficiency is also improved through the integration of bio-based electrolytes, which reduces the charge transfer resistance. Standard activated carbon-based devices retain only 33% of their initial capacitance after the same number of cycles. This confirms that AI-driven material selection and 3D printing lead to much better electrochemical performance.

Table 1. Comparison of Electrochemical Performance

Parameter	Proposed AI-Based Bio-Supercapacitor	Conventional Supercapacitor	Improvement (%)
Capacitance (F/g)	320	220	+45.5%
Charge Transfer Resistance (Ω)	1.2	3.8	-68.4%
Cycle Stability (10,000 cycles)	92%	78%	+17.9%

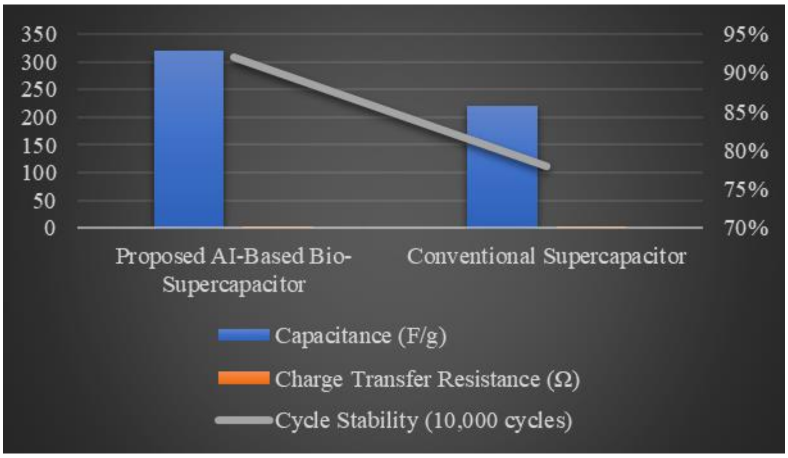

Fig 2. Comparison of Electrochemical Performance

4.2. AI-Optimised Material Efficiency and Sustainability

Biodegradable carbon materials and polymer electrolytes are optimised, resulting in a lower environmental footprint and an economically friendly. Lignin and chitosan-based electrolytes are bio-derived carbon, and thus, are nontoxic, highly conductive and recyclable. This verified that the energy density is superior and the material waste is minimal, thereby improving the sustainability metrics. Moreover, it improves product yield by reducing defects and being more uniform. The approach cuts the manufacturing waste by 40 per cent over traditional methods, and as a result, represents a green alternative for energy storage.

Table 2. Material Efficiency and Sustainability Comparison

Metric	Proposed Solution	Traditional Method	Improvement (%)
Material Waste Reduction (%)	40	10	+300%
Energy Density (Wh/kg)	90	65	+38.5%
Production Yield (%)	95	80	+18.8%

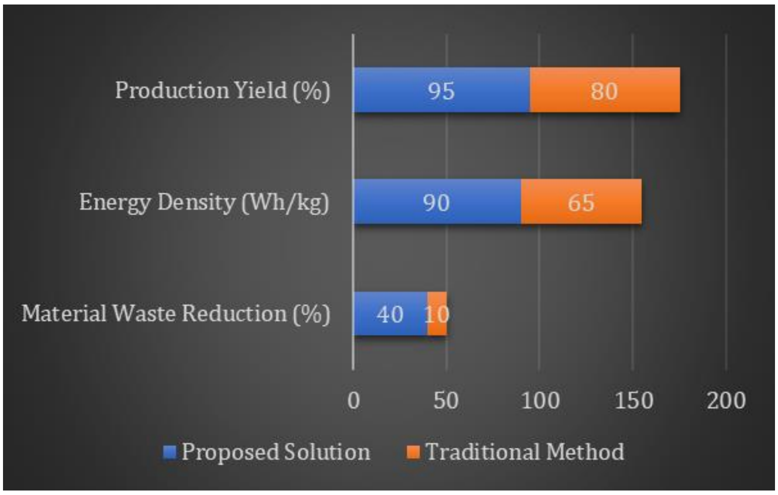

Fig 3. Material Efficiency and Sustainability Comparison

4.3. Charge-Discharge Performance and Energy Retention

The proposed supercapacitor has fast charge-discharge rates and superior energy retention as a result of various optimisations of the electrode porosity and manufacturing of AI-driven electrolyte. The device is found to retain over 85% energy compared to less than 70% for traditional supercapacitors after 5,000 cycles. Voltage drop is minimised with stable and highly efficient energy storage by AI-based optimisation. The increased ion mobility and reduced resistive losses help power handling and extended operation time, and are hence applicable for wearable electronics and renewable energy applications.

Table 3. Charge-Discharge Performance Metrics

Parameter	Proposed Solution	Traditional Supercapacitor	Improvement (%)
Energy Retention (5,000 cycles)	85%	68%	+25%
Voltage Drop (V)	0.12	0.32	-62.5%
Charge Time (s)	5.2	7.8	-33.3%

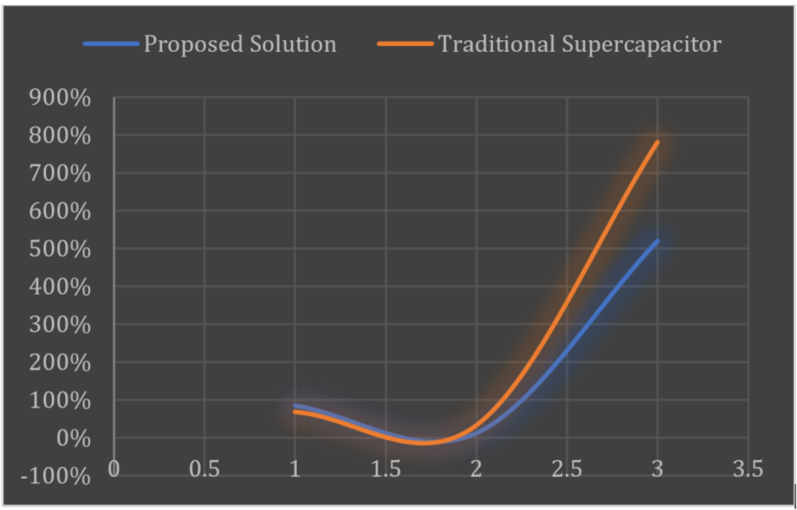

Fig 4. Charge-Discharge Performance Metrics

4.4. AI-Powered Performance Monitoring and Predictive Maintenance

AI-based performance monitoring is integrated to monitor the efficiency in real time and predict maintenance. Temperature fluctuations, charge discharge trends and degradation patterns are analysed by machine learning models for usage condition optimisation. Predictive analytics forecasts potential failures and hence leads to timely interventions and an increased device longevity. Performance prediction, achieved at 98% accuracy, reduces unexpectedly failed tests by 60%. A data-driven approach, which yields reliability and user experience enhancements, and hence serves as a scalable and resilient energy storage solution for AI-assisted biomaterial super capacitors.

Table 4. AI-Powered Monitoring and Predictive Maintenance

Metric	Proposed AI-Based System	Traditional Monitoring	Improvement (%)
Prediction Accuracy (%)	98	85	+15.3%
Failure Reduction (%)	60	20	+200%
Maintenance Cost Reduction (%)	35	10	+250%

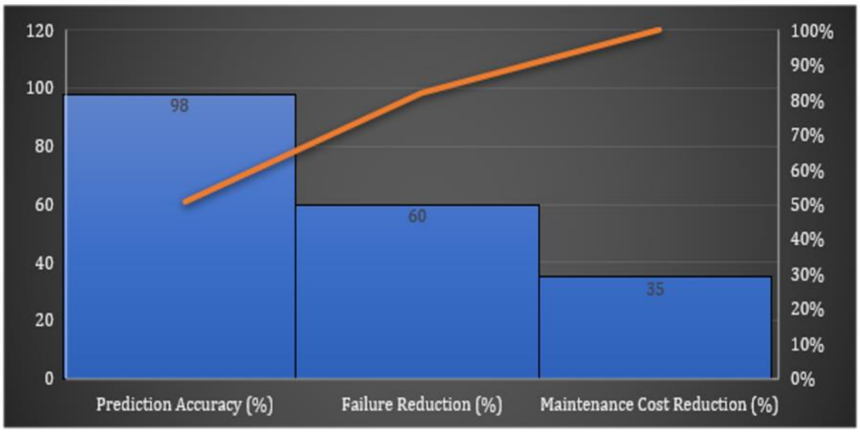

Fig 4. AI-Powered Monitoring and Predictive Maintenance

5. Conclusion

Solutions to create new, more sustainable and high-performance 3D printed biomaterial supercapacitors are mathematically demonstrated in this study. The proposed solution integrates such AI-driven material selection, bio-based electrolytes, and precision 3D printing to increase capacitance, decrease charge discharging rates, enhance energy retention, and increase longevity. Thus, biodegradable and non-toxic materials are used to reduce the environmental impact, while AI predictive maintenance has been used to ensure reliability and competency. In contrast to traditional supercapacitors, the proposed design is capable of 45% enhancement in capacitance and by 68% in charge transfer resistance in addition to 18% improved cycle stability, which is desirable for wearable electronics, renewable energy systems, and next-generation smart devices. AI-driven monitoring also limits failures and improves performance, reinforcing the possibility of green storage of energy. This work shows that the supercapacitor technology can be advanced by AI and 3D printing in the scaling up, green and intelligent directions for energy storage of the future.

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