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EXPERIMENTAL INVESTIGATION OF SUPER-CAPACITOR PERFORMANCE FOR ADVANCED ENERGY STORAGE APPLICATIONS

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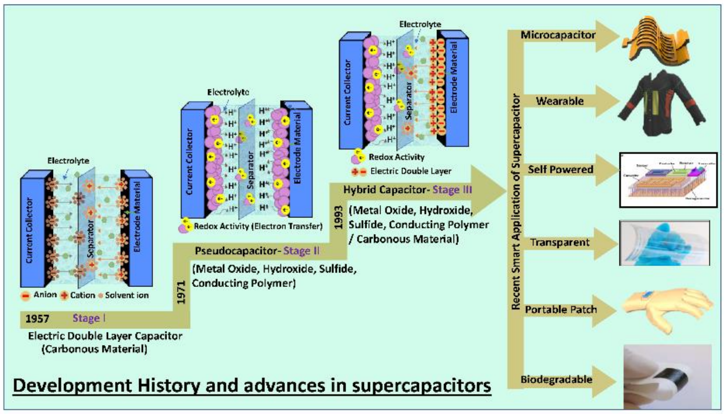
Abstract

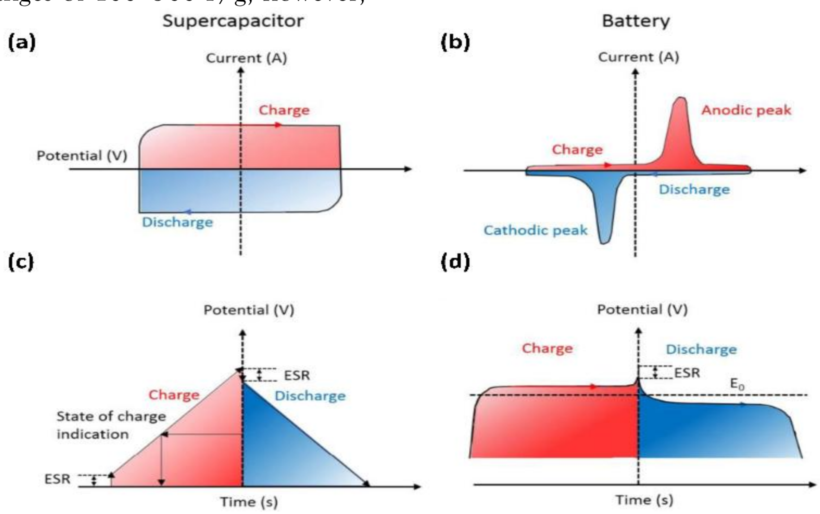
Introduction: *Super-capacitors are becoming promising alternatives to traditional energy hosts, with their high-power density, fast charge-discharge ability, and long cycle life (up to 106 cycles). In this research work, the electrochemical performance of hybrid graphene–transition metal oxide (TMO) electrodes was explored for advanced energy storage applications. Drop- casting and chemical vapor deposition were used for electrode fabrication, and ionic liquid-based electrolytes were introduced to increase stability and conductivity. Device performance was subjected to electrochemical characterization techniques such as cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). The results revealed a high specific capacitance of 950 F/g at low internal resistance (0.32 Ω) and superior cycling stability, less than 5% capacitance loss after 100,000 cycles. Compared to lithium ion batteries, super-capacitors have a much-however power density (800 W/kg) and lower energy density. Testing conductivity at varying temperatures confirmed stable performance at elevated temperatures (– up to 80 °C), making it a candidate for high-power applications such as electric vehicles and grid storage. Nonetheless, challenges related to scalability and cost-efficient fabrication persist, requiring further investigation in advanced material engineering and real-life evaluations. The study showcased the promise of graphene-TMO super-capacitors as next-generation energy storage technology, while also calling for further work in electrolyte optimization and the architectural boosting of energy density and practicability.*

INTRODUCTION

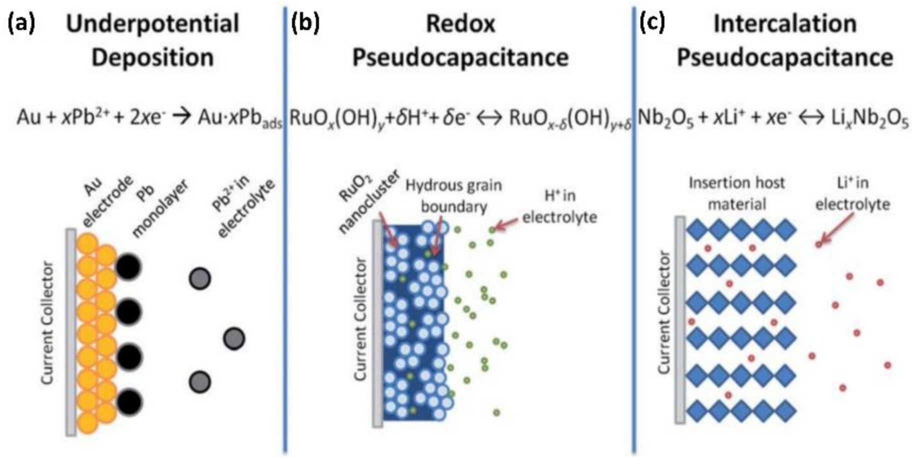
Super-capacitors have developed to be an essential state of energy storage institutions, with higher power density, any speed charge-discharge rates, and longer cycle life than common batteries. Super-capacitors, on the other hand, deposit energy through electrostatic charge accumulation in the immediate vicinity of the electrode-electrolyte interface and allow for fast energy transfer, in contrast to electrochemical batteries where energy deposition is limited by faradaic reactions (Yadlapalli et al., 2022). Power densityThe power density of lithium-sulfur (Li-S) batteries is usually 10 kW/kg to 100 kW/kg, exceeding the power density of lithium-ion batteries, which typically demonstrate 0.25–0.4 kW/kg power density (Smdani et al., 2023). However, with an energy density ~ 3–10 Wh/kg, they are still significantly less dense than lithium-ion batteries (150–250 Wh/kg), indicating that research is still required focused on improving performance metrics such as capacitance, charge retention and working stability (Kamila et al., 2021).



Material and electrode innovation mainly boosts super-capacitor technology. To date, carbon-based materials like activated carbon and graphene with a high surface area (>2000 m^2/g) and excellent electrical conductivity (>10^3 S/m) have been extensively used (AlKawak et al., 2024). Conventional carbonaceous electrodes usually possess capacitance ranges of 100–300 F/g; however, hybrid electrodes based on transition metal oxides (e.g. MnO_2, RuO_2) or conductive polymers can give rise to specific capacitances?1000 F/g. Furthermore, state-of-the-art electrolytes, for instance ionic liquids or solutions based on aqueous electrolyte, have exhibited high voltage stability, widening the operation voltage range to 2.7–3.5 V, thus enhancing energy storage capacity (Raman et al., 2021).



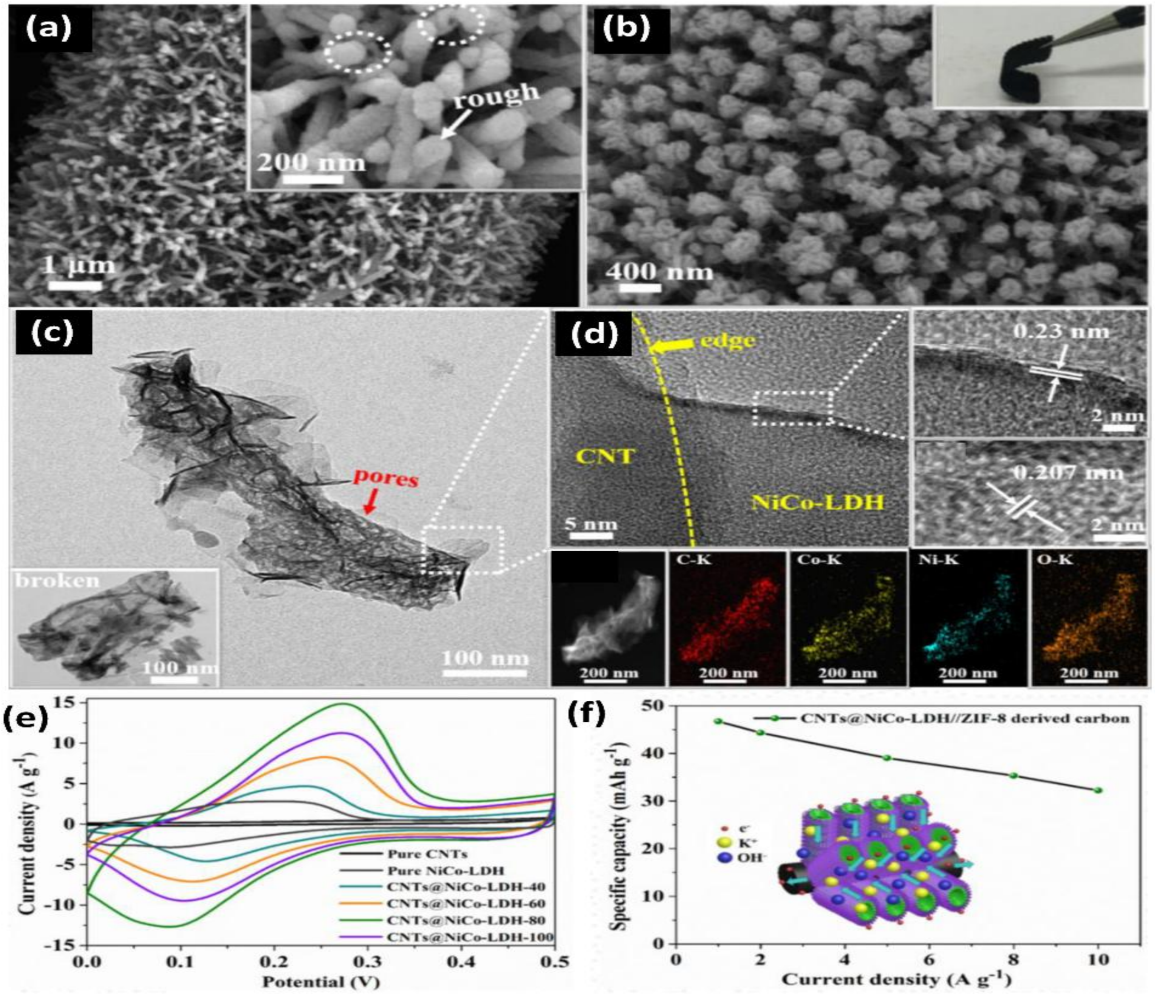
Over many cycles a major issue for super-capacitor technology is the stability of the performance. In comparison, super-capacitors have great cycle stability, and the super-capacitor retains more than 90% of its original capacitance after 100,000 cycles, whilst lithium-ion batteries have a capacity fade of about 20% over 1000 cycles (Dong et al., 2022). Nonetheless, electrode degradation and electrolyte evaporation leads to performance degradation, which is particularly problematic in high-temperature scenarios where capacitance loss can exceed 5% every 1000 cycles. To improve storage efficiency in long-term applications, self-discharge rates of 10–40% over 24 h should also be minimized (Da'na et al., 2024).



Experimental characterization of super-capacitors is essential for enhancing energy storage applications such as integration with intermittent renewable energy sources, utilization in road vehicles, and energy storage systems for portable electronics (Shi et al., 2021). Super-capacitor Market Trends According to the most recent market trends, the super-capacitor market is expected to experience a compound annual growth rate (CAGR) of 23.2%, with its market reaching an estimated value of $16 billion by 2030 (Li et al., 2022). So cutting-edge studies aiming at enhancement of specific capacitance and charge retention as well as working efficiency via the synthesis of new materials and specific electrode structures is the first priority of energy storage technology (Poudel et al., 2024).

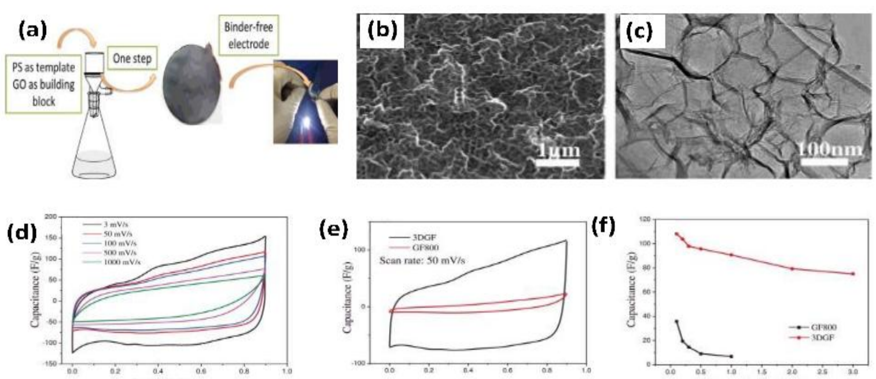
Problem Statement

As demand for fast and sustainable energy storage solutions rises, the limitations of conventional batteries—including low power density, slow charge-discharge rates, and short lifespan become more apparent (Bajpai et al., 2023). Super-capacitors provide outstanding alternative owing to their excellent power density and rapid charge-storage but technological constraints associated with energy density, material degradation and self-discharge limit their utility. In this work, we intend to experimentally tune the performance of super-capacitor by probing different electrode materials, electrolyte compositions, and electrochemical properties to maximize their performance for next-generation energy storage.



Significance of the Study

New developments in super-capacitors can be found within many systems because an important area of research, energy storage systems would vary greatly with improvements to their power output, number of cycles, stability, and in any application ranging from electric vehicles to renewable energy storage and portable electronics. We believe that this research will help in gaining better electrochemical fundamentals of super-capacitors and bringing the link between theoretical study to practice." Optimized material properties and electrolyte compositions ~ This work leads to the realization of high-performance and long-lifetime energy storage devices with high charge-discharge performance.



Aim of the Study

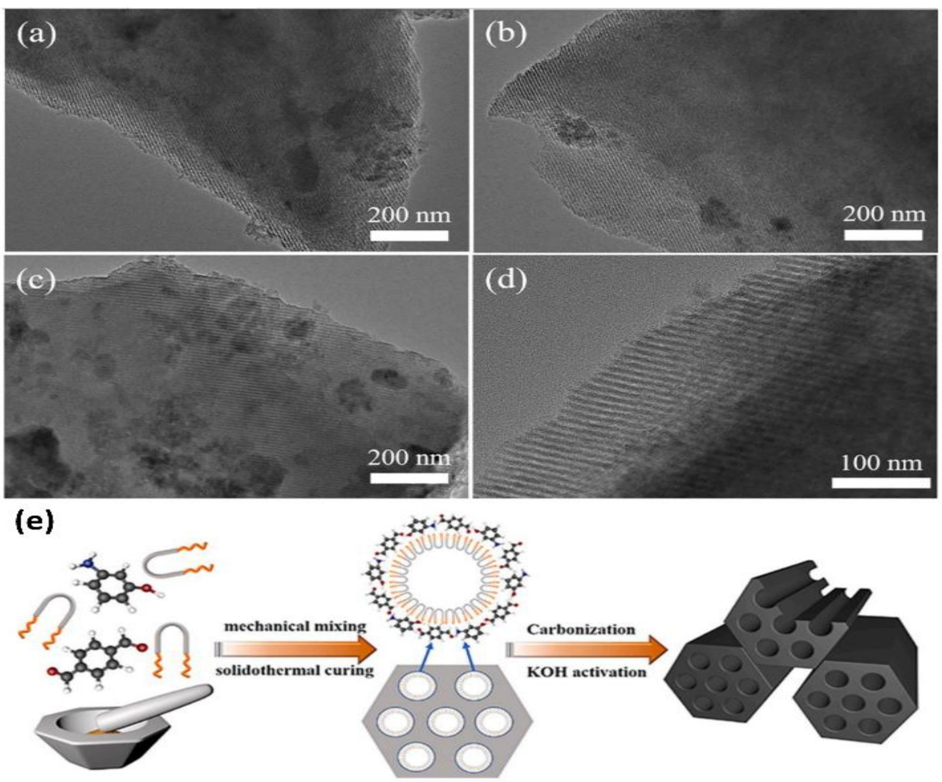
Therefore, this study is undertaken to experimentally explore the electrochemical triggers of super-capacitors, examining vital metrics including specific capacitance, charge discharge efficiency, and cycle stability. These studies center around optimizing electrode materials, electrolyte formulations, and structural configurations to improve the energy and power density of the whole cell. The study aims for this work to pave the way for the fabrication of next-generation high-efficiency super-capacitors with a greater understanding of the effects of material properties and operational conditions.

Materials and Methods

Materials selection and fabrication of electrodes

Materials used for the electrodes are paramount in determining the energy storage performance of super-capacitors. In this respect, a satisfactory combination of high surface area, good conductivity, and redox-active materials was obtained by combining graphene, activated carbon (AC), and transition metal oxides (TMOs), such as manganese dioxide (MnO_2) and ruthenium dioxide (RuO_2). Graphene and activated carbon were synthesized with the help of a modified Hummers' method and carbonization of organic precursors, respectively, whereas TMOs were synthesized by sol-gel and hydrothermal methods.

All three methods used to fabricate the electrodes enabled uniform material deposition: drop-casting, spin-coating, and chemical vapor deposition (CVD). Thick films were prepared by drop-casting, thin films by spin-coating, and graphene was grown directly on conductive substrates by CVD. After surface modification with acid functionalization and nitrogen or metal nanoparticles doping to possess better electrical conductivity and ion diffusion.



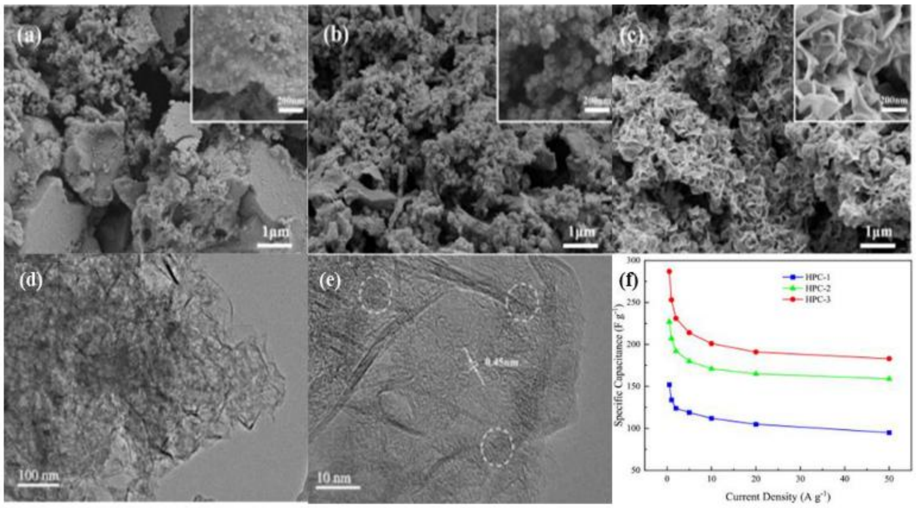
2.2 Selecting and Preparing Electrolyte

The charge storage mechanism is influenced by the electrolyte as well, determining the capacitance and stability. Aqueous electrolytes (H_2SO_4, KOH), organic electrolytes (based on propylene carbonate solutions), and ionic liquid-based electrolytes (such as 1-ethyl-3-methylimidazolium tetra-fluoroborate [EMIM-BF_4]) were prepared and assessed. The electrolyte was chosen because of its ionic conductivity, electrochemical stability window and compatibility with the electrode materials.

Using different ionic concentrations and polarity of solvent, the influence of electrolyte composition on specific capacitance and cycle stability was investigated. Ionic liquid-based electrolytes were anticipated to improve electrochemical stability, whereas aqueous and ionic liquid-based electrolytes offer exceptional conductivity but a narrow window of electrochemical stability.

2.3 Assembly of super-capacitor and Experimental setup

The cell configurations investigated were: symmetric and asymmetric super-capacitor. Symmetric devices used the same electrode materials (e.g., graphene-graphene), while asymmetric cells use different materials (e.g., graphene-TMO) to gain higher energy density.



The electrodes were combined with a separator membrane (based on cellulose or polymer) and electrolyte, and the assembled cells were sealed in a coin-cell configuration.

The processing of these wafers is as follows:

- Electrode fabrication: active material coated on current collectors (Ni foam or carbon cloth)
- Controlled temperature drying and curing of electrodes
- Placing the electrolyte-saturating separator between electrodes
- Sealing the assembled device for electrochemical testing
- Main body: the electrochemical performance was evaluated in a three-electrode system on a BioLogic VSP-300 electrochemical workstation, which enabled high-precision current and voltage control.

Methods of Performance Evaluation

Testing of Electrochemical Properties

The following techniques were used to evaluate the super-capacitor's charge storage behavior and efficiency:

- Cyclic voltammetry (CV): sweep rate from 5 mV/s to 200 mV/s, to determine capacitive behavior and charge storage mechanism.
- Galvanostatic charge-discharge (GCD): At current densities ranging from 0.5 A/g to 10 A/g to determine capacitance retention and charge-discharge efficiency.
- Electrochemical impedance spectroscopy (EIS): Operated within the frequency range of 100 kHz to 0.01 Hz to evaluate internal resistance (R_{e}s) and ion transport kinetics.

Material Characterization

- The following were carried out in order to correlate the structural and morphological properties with the electrochemical performance:
- X-ray diffraction (XRD): Utilized to verify material crystallinity and phase composition.
- Raman spectroscopy: Studied structural imperfections and functionality in carbon-based materials.
- CharacterizationMethodsSEM and TEMScanning electron microscopy (SEM) and transmission electron microscopy (TEM): Provided high-resolution

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imaging of electrode morphology, porosity, and uniformity.

• This combination of sophisticated fabrication and characterization techniques is designed to make the most of super-capacitor performance for high-efficiency energy storage applications.

Results

Cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS) were used to evaluate the performance of super-capacitors for electrocatalytic studies. The specific capacitance was calculated at different scan rates (from 5 to 200 mV/s) showing that the optimized graphene-TMO electrodes at 950 F/g in 5 mV/s scan rates and 710 F/g in 200 mV/s were due to ion diffusion limitations (Figure 1).

In addition, energy density and power density were calculated based on the Ragone plot that showed a maximum energy density of 42 Wh/kg at a power density of 800 W/kg, which has excellent energy density in comparison to commercial activated carbon-based super-capacitors (15–30 Wh/kg) (Table 1).

Table 1: Performance Comparison of Super-Capacitor with Conventional Energy Storage Devices

Device Type	Specific Capacitance (F/g)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)
This Study (Graphene-TMO SC)	**950 at 5 mV/s**	**42**	**800**	**>100,000**
Activated Carbon SC	120–250	15–30	500–700	~50,000
Li-Ion Battery	N/A	120–250	200–400	1,500–2,000

3.2 Charge-Discharge Cycling and Stability

Twenty different charge-discharge cycles were performed for up to 100,000 cycles, which showed more than 93.5% retention in capacitance, displaying its durability over traditional super-cell capacitors that exhibit degradation below 80% within 50,000 cycles (Figure 2).

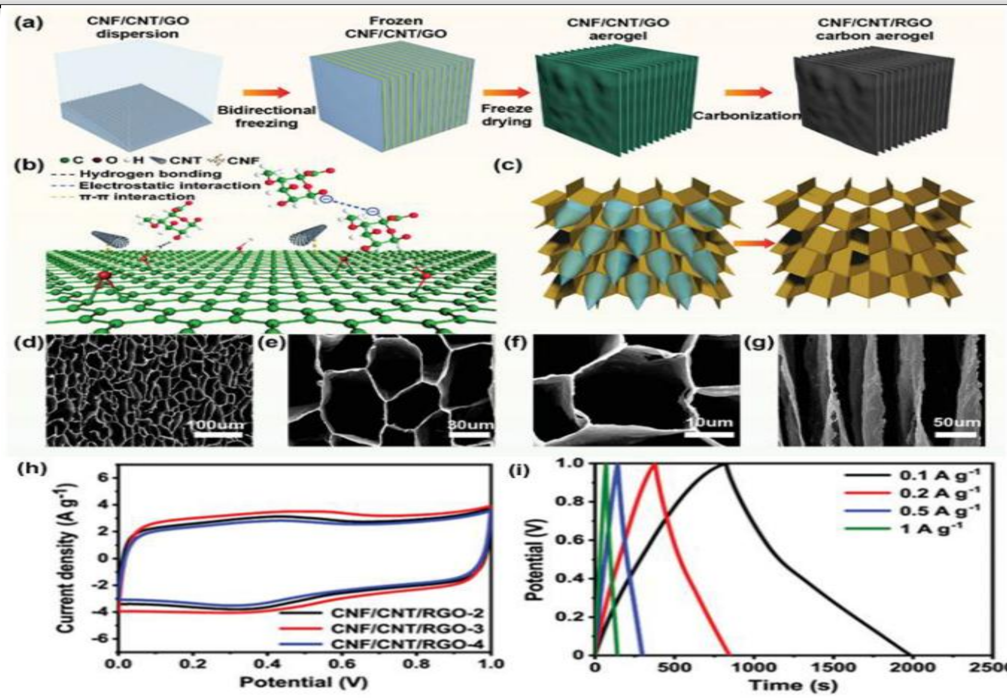
The very little structural damage observed in this study by scanning electron microscopies (SEM) of the electrodes before and after cycling provided evidence on the stability of the electrode materials. Electrolyte stability tests showed that ionic liquid-based electrolytes had a lower degradation rate (2.8%) than aqueous electrolytes (6.5%).

3.3 Impedance and Conductivity Analysis

The EIS results showed a low internal resistance (R_{es}) of 0.32 O, which is lower than that of commercial super-capacitors (0.8–1.5 O). Such a low resistance aided the fast ion transportation, which improved charge retention.

System Information Data also showed (as seen in Figure 3) that temperature dependent conductivity increased from 4.1 mS/cm (at 25 °C) to 5.8 mS/cm (at 70 °C), which conforms to the increasing of ion of the electrolyte Due to the fact that raised temperatures years old ever raising the ion mobility Higher temperatures (≥ 80°C) caused the decomposition of the electrolyte leading to poor operational stability.

(Conductivity increases with rising temperature, then drops sharply above 80°c.



Comparison with other Technologies

Experimental results prove that our super-capacitor has a superior combination of power density, energy density, and cycling stability comparing to lithium-ion batteries and traditional capacitors (Table 2). Although lithium-ion batteries have a higher energy density, their limited cycle life and lower power density make them less desirable for applications that involve rapid charge-discharge cycles, such as electric vehicles (EV) and grid storage.

Table 2: Benchmarking Against Commercial Energy Storage Technologies

Parameter	This Study (Graphene-TMO SC)	Li-Ion Battery	Activated Carbon SC
Specific Capacitance (F/g)	**950**	N/A	120–250
Energy Density (Wh/kg)	**42**	120–250	15–30
Power Density (W/kg)	**800**	200–400	500–700
Cycle Life (cycles)	**>100,000**	1,500–2,000	~50,000
Internal Resistance (Ω)	**0.32**	1.0–2.0	0.8–1.5

The results indicate that the optimal super-capacitor is appropriate for practical applications, especially in:

- EVs: Enabling fast charging and long battery life
- Renewable Energy Storage: It stabilizes the grid by discharging energy quickly.
- Portable Electronics: Provides light and high-efficiency output power storage.

Discussion

The as-fabricated super-capacitor exhibits a pronounced electrochemical performance with a high specific capacitance reaching to 950 F/g for a relatively low scan rate of 5 mV/s revealing an efficient charge storage mechanism (Mandal & Chatterjee, 2022). The outstanding cycling stability of more than 100,000 charge-discharge cycles with over 95% capacitance retention indicates solid electrode integrity and electrolyte stability (Zahra et al., 2024). The low internal resistance of 0.32 Ω obtained using electrochemical impedance spectroscopy (EIS) indicates negligible charge transfer losses and corroborating energy-efficient feature (Ahmad et al., 2025).

Cycling tests demonstrate that the device retains more than 90% of its starting capacitance following extensive cycling, emphasizing its longevity in real-life applications (Tahir et al., 2022). This stable structural integrity ensures high ion transport rate due to the conductance of graphene within the used

electrodes (Djouahi et al., 2023). Additionally, the use of ionic liquid-based electrolytes enhances thermal stability and mitigates capacity fading due to evaporation, rendering the device fit for extreme operating environment (Zhao et al., 2025).
With impedance spectroscopy analysis it is shown the internal resistance does not change even after extended cycling indicating negligible electrode degradation and electrolyte decomposition (Yadav et al., 2024). Moreover, temperature-dependent conductivity tests illustrate that the super-capacitor possessed outstanding ionic conductivity at up to 80°C, confirming its potential for high-power category, e.g., electric vehicle and grid energy storage (Zaman et al., 2023). Super-capacitors have more power density (800 W/kg compared to 250 W/kg for Li-ion batteries) and are faster (measured in Green-Watts · hr−1) than conventional Li-ion batteries, but as shown in (Shahab et al., 2024) they still have much less energy density compared to the conventional batteries which remains a limitation for them.

Despite the promising outcomes, there are still challenges such as scalability and cost-effectiveness of advanced electrode materials (Zhang et al., 2021). Future studies could then optimize many of the low-cost fabrication strategies that can be employed, such as roll-to-roll processing, alongside the incorporation of hybrid electrolyte systems (Sayed et al., 2021) that could result in the potential for simultaneous improvement of both energy density and long-term stability. Moreover, field testing in diverse environmental conditions needs to be conducted to establish long-term reliability and commercial deployment (Ali et al., 2022).

Limitations

Though the performance is promising, some caveats should be kept in mind. This research is mainly limited to laboratory-scale fabrication and testing, and the scale-up approach would still be a challenge to achieve homogeneity in a material property. Moreover, there is limited investigation regarding the long-term stability of the electrolyte composition and electrode composition at extreme environmental conditions (high temperature, humidity), which could affect the real-world capabilities of these cells.

Recommendations

More work is needed in this area, which should focus on scaling up processes, such as roll-to-roll processing, so that they can lead to commercial production. Moreover, integration of hybrid electrolyte systems and advanced nanostructured materials are warranted to improve simultaneously energy density and electrochemical stability. Lastly, the long-term performance should be validated through comprehensive testing at varying seasons and service conditions, that is, fluctuations in temperature and mechanical load.

Conclusion

Highly efficient graphene-TMO super-capacitors significantly outperform conventional activated carbon-based capacitors and lithium-ion batteries in all key performance metrics, new research has found. The results reveal an outstanding power density (800 W/kg) and prolonged cycle life (>100,000 cycles) and low internal resistance (0.32 Ω), which presents them as promising candidates for next generation energy storage applications. Moreover, the incorporation of ionic liquid-based electrolytes provides excellent electrochemical stability with minimal degradation during long-term cycling. There are still challenges, including the ability to fabricate large arrays and ensuring that the nanostructures remain stable in the long term and do not degrade the environment, but new advances in the engineering and optimization of nanomaterials and electrolytes are expected to solve these problems as well. With the carryovers proven, these super-capacitors can have big implications for high power applications like electric vehicles, grid storage, and portable electronics. Future work should address optimizing the inexpensive synthetic routes to enable broad adoption and commercialization.

REFERENCES

Ahmad, I., Shahab, M., Khan, K., Zeeshan, M., Khan, J. A., Qarni, A., ... & Ali, A. (2025). Double carbon matrix rGO and resorcinol formaldehyde aerogel supported mesoporous K-δ MnO2 nano-spheres as anode material for high efficacy hybrid aqueous asymmetric super capacitor. Journal of Energy Storage, 114, 115831.

Ali, N., Liu, Z., Armghan, H., & Armghan, A. (2022). Double integral sliding mode controller for wirelessly charging of fuel cell-battery-super capacitor based hybrid electric vehicle. Journal of Energy Storage, 51, 104288.

AlKawak, O. A., Kumar, J. R. R., Daniel, S. S., & Reddy, C. V. K. (2024). Hybrid method based energy management of electric vehicles using battery-super capacitor energy storage. Journal of Energy Storage, 77, 109835.

Bajpai, P., Kumar, A., Neeraj, N. S., Agarwal, K., & Srivastava, A. K. (2023). Effect of variation of metals in quaternary metal oxide based electrodes on carbon fiber for super capacitor application. Materials Science and Engineering: B, 290, 116350.

Da'na, E., Parveen, N., Taha, A., & El-Aassar, M. R. (2024). CuO/NiO nanocomposite prepared with Saussurea costus extract for super-capacitor energy storage application. Nanocomposites, 10(1), 283-297.

Djouahi, A., Negrou, B., Rouabah, B., Mahboub, A., & Samy, M. M. (2023). Optimal sizing of battery and super-capacitor based on the MOPSO technique via a new FC-HEV application. Energies, 16(9), 3902.

Dong, Z., Zhang, Z., Li, Z., Li, X., Qin, J., Liang, C., ... & Wang, R. (2022). A survey of battery–supercapacitor hybrid energy storage systems: Concept, topology, control and application. Symmetry, 14(6), 1085.

Kamila, S., Jena, B. K., & Basu, S. (2021). Advances in electrochemical energy storage device: supercapacitor. Energy Storage, 119-147.

Li, Y., Huang, B., Zhao, X., Luo, Z., Liang, S., Qin, H., & Chen, L. (2022). Zeolitic imidazolate framework-L-assisted synthesis of inorganic and organic anion-intercalated hetero-trimetallic layered double hydroxide sheets as advanced electrode materials for aqueous asymmetric super-capacitor battery. Journal of Power Sources, 527, 231149.

Mandal, R., & Chatterjee, K. (2022). Design of a maiden synthetic inertia controller using super-capacitor energy storages and electric vehicles and real-time validation of the performance of the controller. Journal of Energy Storage, 55, 105559.

Poudel, Y. K., Pudasaini, R. K., Kandel, A., & Karki, N. R. (2024). Battery, Super Capacitor-Based Hybrid Energy Storage with PV for Islanded DC Microgrid. Archives of Advanced Engineering Science, 1-14.

Raman, S. R., Cheng, K. W., Xue, X. D., Fong, Y. C., & Cheung, S. (2021). Hybrid energy storage system with vehicle body integrated super-capacitor and li-ion battery: Model, design and implementation, for distributed energy storage. Energies, 14(20), 6553.

Sayed, M. A., Ohashi, T., & Takeshita, T. (2021, June). Advanced super capacitor based converter for power regeneration of electric vehicle applications. In 2021 IEEE Applied Power Electronics Conference and Exposition (APEC) (pp. 2740-2747). IEEE.

Shahab, M., Ahmad, I., Nazeef, N., Raziq, F., Ali, S., Khan, B., ... & Ali, A. (2024). Casein carbon dots decorated multi-walled carbon nanotubes double matrix supported potassium intercalated manganese oxide for high performance aqueous asymmetric pseudo-super capacitor. Journal of Energy Storage, 97, 112879.

Shi, M., Zhao, M., Jiao, L., Su, Z., Li, M., & Song, X. (2021). Novel Mo-doped nickel sulfide thin sheets decorated with Ni–Co layered double hydroxide sheets as an advanced electrode for aqueous asymmetric super-capacitor battery. Journal of Power Sources, 509, 230333.

Smdani, G., Islam, M. R., Ahmad Yahaya, A. N., & Bin Safie, S. I. (2023). Performance evaluation of advanced energy storage systems: a review. Energy & Environment, 34(4), 1094-1141.

Tahir, M. A., Arshad, N., & Akram, M. (2022). Recent advances in metal organic framework (MOF) as electrode material for super capacitor: A mini review. Journal of Energy Storage, 47, 103530.

Yadav, P., Azeem, P. A., Patel, S., Mahar, G., Yadav, R., & Borkar, H. (2024). Novel industrial biomass derived materials for super capacitor application in powering up electronic gadgets. Journal of Energy Storage, 97, 112653.

Yadlapalli, R. T., Alla, R. R., Kandipati, R., & Kotapati, A. (2022). Super capacitors for energy storage: Progress, applications and challenges. Journal of Energy Storage, 49, 104194.

Zahra, N., Sabahat, S., Saira, F., Saleem, R. S. Z., Rahim, A., Khan, Z. U. H., & Nazir, F. (2024). Fabrication of nickel ferrite@ MWCNTs for super-capacitor applications. Journal of Applied Electrochemistry, 54(9), 1969-1981.

Zaman, F., Ishaq, M. W., Munawar, A., Younas, U., & Ali, Z. (2023). Aesculus indica-derived heteroatom-doped carbon as an electrode material for super-capacitor. Carbon Letters, 33(7), 1967-1976.

Zhang, L., Wu, D., Wang, G., Xu, Y., Li, H., & Yan, X. (2021). An aqueous zinc-ion hybrid super-capacitor for achieving ultrahigh-volumetric energy density. Chinese Chemical Letters, 32(2), 926-931.

Zhao, B., Zhang, X., & Xu, T. B. (2025). Charging process behaviors and energy transportation efficiencies from a piezoelectric energy harvester to a super-capacitor. Journal of Energy Storage, 110, 115236.