

RESEARCH ARTICLE

Synergistic Enhancement of Charge Storage in Cr_2O_3 –CuO Heterostructured Nanocomposites for High-Performance Supercapacitor Electrodes

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ABSTRACT: The quest for electrode materials that simultaneously offer high specific capacitance, rapid charge-discharge kinetics, and prolonged operational stability continues to drive innovation in supercapacitor technology. This work presents a comprehensive electrochemical investigation of Cr_2O_3 –CuO nanocomposites as advanced electrode materials for energy storage applications. The electrochemical performance of pristine Cr_2O_3 nanoparticles, CuO nanosheets, and their heterostructured nanocomposite was systematically evaluated through cyclic voltammetry, galvanostatic charge-discharge measurements, quantitative capacitance-diffusion contribution analysis, electrochemical impedance spectroscopy, and accelerated cycling tests. The Cr_2O_3 –CuO nanocomposite exhibited remarkable specific capacitance values of 182.8 F g^{-1} derived from cyclic voltammetry and 604.4 F g^{-1} from galvanostatic charge-discharge analysis, substantially surpassing the performance of the individual oxide components. Quantitative analysis of the charge storage mechanism revealed a predominantly surface-controlled capacitive process contributing 90.9% to the total capacitance, indicating rapid kinetics favorable for high-power applications. The nanocomposite demonstrated exceptional electrochemical durability, retaining 87.5% of its initial capacitance after 2000 consecutive charge-discharge cycles. Electrochemical impedance spectroscopy confirmed significantly reduced charge-transfer resistance and enhanced ionic diffusion characteristics in the composite electrode. The superior electrochemical performance arises from the synergistic interplay between Cr_2O_3 nanoparticles and CuO nanosheets, which creates an interconnected network facilitating efficient electron transport, promotes electrolyte accessibility to electroactive sites, and provides abundant redox-active interfaces. These findings establish Cr_2O_3 –CuO nanocomposites as highly promising electrode materials for next-generation supercapacitor devices requiring both high energy and power densities.

Keywords: Cr_2O_3 –CuO heterostructures; Pseudocapacitive energy storage; Surface-controlled charge storage; Transition metal oxide nanocomposites; Electrochemical kinetics; Supercapacitor electrode materials.

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1. INTRODUCTION

The escalating global energy crisis and growing environmental concerns have intensified the search for sustainable and efficient energy storage technologies. Among

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the various electrochemical energy storage systems, supercapacitors have emerged as promising candidates due to their exceptional power density, rapid charge-discharge capabilities, extended cycling stability, and environmentally benign nature [1, 2]. Unlike conventional batteries that rely on slow faradaic reactions, supercapacitors store energy through electrostatic charge accumulation at the electrode-electrolyte interface or rapid surface redox reactions, enabling them to bridge the performance gap between traditional capacitors and batteries [3, 4]. The increasing

demand for portable electronics, electric vehicles, and grid-scale energy storage has further accelerated research efforts toward developing supercapacitor electrode materials with enhanced energy density without compromising power density and cycle life.

Transition metal oxides have garnered substantial interest as electrode materials for supercapacitors owing to their multiple oxidation states, high theoretical specific capacitance, and relatively low cost [5, 6]. These materials store charge through pseudocapacitive mechanisms involving reversible faradaic reactions at the electrode surface, which typically yield higher energy densities compared to carbon-based electric double-layer capacitors. However, the practical application of transition metal oxides faces several challenges, including poor electrical conductivity, limited specific surface area, and structural instability during prolonged cycling [7, 8]. These limitations necessitate strategic approaches to enhance the electrochemical performance of metal oxide-based electrodes while maintaining their intrinsic pseudocapacitive advantages.

Chromium oxide (Cr₂O₃) represents a chemically stable transition metal oxide with promising pseudocapacitive characteristics, attributed to the multiple valence states of chromium ions that facilitate reversible redox reactions [9]. The material exhibits good thermal stability and corrosion resistance, making it suitable for electrochemical applications. Despite these favorable properties, the relatively poor electrical conductivity of Cr₂O₃ significantly restricts its charge storage capability and rate performance, limiting its practical utilization in supercapacitor devices [10]. Copper oxide (CuO), a p-type semiconductor with a narrow band gap, possesses excellent redox activity and high theoretical capacitance arising from the reversible Cu²⁺/Cu⁺ redox couple [11]. The material is abundant, cost-effective, and environmentally friendly, making it an attractive candidate for large-scale energy storage applications. However, similar to Cr₂O₃, CuO suffers from low electrical conductivity and tends to undergo structural degradation during extended electrochemical cycling, which compromises its long-term stability [12].

The strategic integration of two or more transition metal oxides into heterostructured nanocomposites offers a viable approach to overcome the individual limitations of single-component electrodes while harnessing their complementary advantages [13, 14]. The heterostructure formation creates nanoscale interfaces that serve as efficient pathways for electron transport and ion diffusion, while the synergistic interactions between different oxide phases enhance the overall electrochemical activity. The different work functions and electronic structures of constituent materials generate internal electric fields at the heterojunction interfaces, facilitating charge separation and reducing the charge transfer resistance [15, 16]. Furthermore, the high surface area provided by the nanoscale morphology increases the number of electroactive sites accessible to electrolyte ions, thereby enhancing the pseudocapacitive response. The combination of a chemically stable oxide with a highly redox-active oxide in a heterostructured architecture can

effectively balance the trade-off between stability and capacitance, leading to superior overall electrochemical performance. Recent investigations have demonstrated that heterostructured metal oxide nanocomposites exhibit significantly improved charge storage performance through these synergistic mechanisms, making them attractive candidates for next-generation supercapacitor electrodes [17, 18].

The novelty of the present work lies in the systematic investigation of Cr₂O₃-CuO heterostructured nanocomposites as advanced electrode materials for supercapacitor applications, a combination that has not been extensively explored in the existing literature. While individual Cr₂O₃ and CuO have been studied separately, the synergistic effects arising from their integration into a composite architecture remain largely unexplored. This work uniquely combines Cr₂O₃ nanoparticles with CuO nanosheets to create a heterostructured interface that leverages the high pseudocapacitive activity of CuO and the chemical stability of Cr₂O₃, while the distinct morphological features of the constituent materials contribute to enhanced electrochemical kinetics and improved structural integrity during cycling. Unlike conventional composite approaches that simply mix the components, the heterostructured design developed in this work ensures intimate contact between the oxide phases, maximizing the synergistic interactions and providing a rational strategy for high-performance supercapacitor electrodes.

In this paper, we report a comprehensive electrochemical investigation of Cr₂O₃ nanoparticles, CuO nanosheets, and Cr₂O₃-CuO nanocomposites as potential electrode materials for supercapacitor applications. The electrochemical behavior of these materials was systematically evaluated using cyclic voltammetry to assess the charge storage characteristics and pseudocapacitive response at different scan rates. Galvanostatic charge-discharge measurements were employed to determine the specific capacitance and evaluate the rate capability of the electrodes. Quantitative capacitance-diffusion contribution analysis was performed to elucidate the charge storage mechanism and distinguish between surface-controlled capacitive processes and diffusion-limited faradaic reactions. Electrochemical impedance spectroscopy was utilized to investigate the charge transfer kinetics and internal resistance characteristics of the electrodes. Finally, accelerated cycling tests were conducted to assess the long-term electrochemical stability and durability of the materials. The findings from this systematic investigation provide valuable insights into the synergistic effects of Cr₂O₃-CuO heterostructure formation and establish the potential of these nanocomposites for practical supercapacitor applications.

2. EXPERIMENTAL DETAILS

The Cr₂O₃-CuO nanocomposites were synthesized using a sonochemical method as reported in our previous work [14]. In summary, for the synthesis of CuO nanosheets, copper(II) nitrate hexahydrate and urea were dissolved in 100 mL of

deionized water under continuous stirring. Concentrated hydrochloric acid (6 mL) was added dropwise to the precursor solution, and the mixture was subjected to ultrasonication for 30 minutes at room temperature. The resulting precipitate was collected by filtration, washed repeatedly with deionized water and ethanol, dried at 70°C for 12 hours, and subsequently calcined at 600°C to obtain black CuO nanosheet powder. For the preparation of Cr₂O₃-CuO nanocomposites, 250 mg of the synthesized CuO nanosheets were dispersed in a solution containing polyethylene glycol (15 mL), ethanol (10 mL), and oxalic acid (10 mM) under ultrasonication for 10 minutes. Chromium(III) nitrate nonahydrate (100 mM) was then added to the reaction mixture, followed by the slow addition of 300 mM urea while continuing ultrasonication for 15 minutes at room temperature. The acoustic cavitation generated during ultrasonication created localized high-energy conditions that promoted nucleation and growth of Cr₂O₃ nanoparticles on the CuO nanosheet surface. The precipitate was separated, washed with deionized water and ethanol, dried at 70°C for 12 hours, and finally calcined at 400°C for 5 hours to yield the Cr₂O₃-CuO nanocomposites.

All electrochemical measurements were performed using a CHI660E electrochemical workstation with a three-electrode configuration. The working electrodes were fabricated by mixing the active material, carbon black, and polyvinylidene fluoride binder in an 80:15:5 weight ratio in N-methyl-2-pyrrolidone solvent. The resulting slurry was coated onto nickel foam current collectors and dried at 80°C under vacuum for 12 hours. A platinum wire served as the counter electrode and a saturated calomel electrode as the reference electrode, with 2 M potassium hydroxide aqueous solution as the electrolyte. Cyclic voltammetry was conducted from 0 to 0.6 V at scan rates between 5 and 100 mV s⁻¹. Galvanostatic charge-discharge measurements were performed at current densities from 1 to 10 A g⁻¹. Electrochemical impedance spectroscopy was carried out over a frequency range of 100 kHz to 10 mHz with an AC amplitude of 5 mV. Capacitance-diffusion contribution analysis was performed using Dunn and Trasatti methods. Cycling stability was evaluated through repeated charge-discharge measurements at 1 A g⁻¹ for 2000 cycles.

3. RESULTS AND DISCUSSION

The synthesis and detailed structural, morphological, and optical characterizations of the prepared Cr₂O₃-CuO nanocomposites have been presented in our previous work [14]. The present section focuses on the electrochemical performance evaluation of pristine Cr₂O₃ nanoparticles, CuO nanosheets, and Cr₂O₃-CuO nanocomposites as electrode materials for supercapacitor applications.

3.1. Cyclic Voltammetry Analysis

The electrochemical behavior of the synthesized electrode materials was initially investigated using cyclic voltammetry

over a potential window of 0 to 0.6 V at various scan rates ranging from 5 to 100 mV s⁻¹. Figure 1 presents the CV curves of Cr₂O₃ nanoparticles (a), CuO nanosheets (b), Cr₂O₃-CuO nanocomposites (c), comparative CV profiles at 50 mV s⁻¹ (d), and the specific capacitance versus scan rate plot (e). All three electrode materials exhibited distinct redox peaks in their CV curves, confirming their pseudocapacitive charge storage characteristics arising from reversible faradaic reactions at the electrode-electrolyte interface. The observed current response increased progressively with increasing scan rate, indicating good rate capability and rapid electrochemical kinetics of the electrodes [15, 16].

Among the investigated electrodes, the Cr₂O₃-CuO nanocomposite displayed the largest enclosed CV area and highest current density, clearly indicating superior charge storage capability. The enhanced electrochemical response of the nanocomposite is attributed to the synergistic interaction between Cr₂O₃ nanoparticles and CuO nanosheets, which facilitates efficient electron transport and promotes rapid electrolyte ion diffusion throughout the electrode matrix. The heterostructured architecture provides abundant electroactive sites and interconnected conductive pathways that significantly improve the overall electrochemical activity. The specific capacitance values calculated from the CV curves at a scan rate of 5 mV s⁻¹ were found to be 51.6 F g⁻¹ for Cr₂O₃, 34.7 F g⁻¹ for CuO, and 182.8 F g⁻¹ for Cr₂O₃-CuO nanocomposites. The remarkable enhancement in specific capacitance, representing approximately 3.5-fold and 5.3-fold improvements over pristine Cr₂O₃ and CuO electrodes respectively, confirms the beneficial effect of heterostructure formation on charge storage performance [16]. The superior performance of the nanocomposite can be attributed to the effective combination of the high pseudocapacitive activity of CuO and the chemical stability of Cr₂O₃, along with the increased electroactive surface area provided by the nanoscale morphology.

3.2. Capacitance and Diffusion Contribution Analysis

To gain deeper insight into the charge storage mechanism, quantitative analysis of capacitive and diffusion-controlled contributions was performed using the Dunn and Trasatti methods [18-20]. Figure 2 displays the total capacitance plots (a-c), outer capacitance plots (d-f), and the capacitance-diffusion contribution diagram (g) for all three electrode materials. The Dunn method separates the total current response at a fixed potential into surface-controlled capacitive contributions and diffusion-limited faradaic contributions based on the relationship between current and scan rate. The Trasatti method provides complementary information by determining the total capacitance through extrapolation of the inverse capacitance versus square root of scan rate plots.

The calculated capacitive contributions were determined to be 72.71%, 87.7%, and 90.9% for Cr₂O₃, CuO, and Cr₂O₃-CuO nanocomposites, respectively. The corresponding diffusion-controlled contributions were 27.3%, 12.3%, and 9.1%.

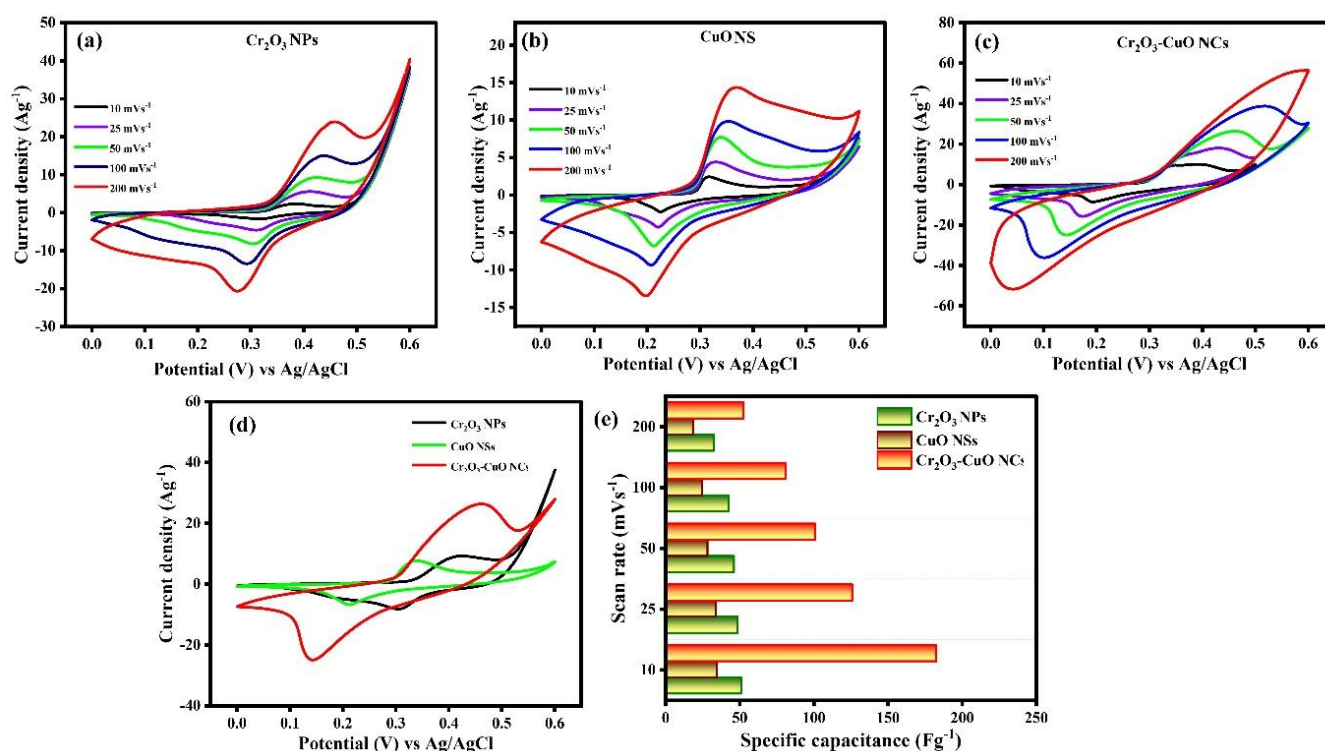


Fig. 1. Cyclic voltammetry curves of (a) Cr₂O₃ nanoparticles, (b) CuO nanosheets, and (c) Cr₂O₃-CuO nanocomposites at different scan rates ranging from 5 to 100 mV s⁻¹, (d) comparative CV profiles of all electrodes at 50 mV s⁻¹, and (e) specific capacitance versus scan rate plot illustrating the rate capability of the electrodes.

The Cr₂O₃-CuO nanocomposite exhibited the highest capacitive contribution, indicating that surface-controlled charge storage mechanisms dominate the overall electrochemical response. This finding is particularly significant as it demonstrates rapid electrochemical kinetics, which is highly desirable for high-power supercapacitor applications where fast charge-discharge capabilities are essential [18]. The diffusion-controlled contribution of only 9.1% suggests that the heterostructured design effectively minimizes the kinetic limitations typically associated with transition metal oxide electrodes, where slow ion diffusion often restricts rate performance.

The enhanced capacitive behavior of the nanocomposite arises from several factors including abundant electroactive sites provided by the porous interconnected morphology, improved electrolyte accessibility due to the nanosheet-supported architecture, and the formation of interconnected conductive pathways through heterostructure construction [20]. The intimate contact between Cr₂O₃ nanoparticles and CuO nanosheets creates numerous interfaces that facilitate rapid electron transfer and reduce the diffusion path length for electrolyte ions. The dominant surface-controlled mechanism indicates that the charge storage occurs primarily through fast, reversible redox reactions at the electrode surface rather than slow intercalation processes, contributing to excellent rate capability and power density.

3.3. Galvanostatic Charge-Discharge Performance

The charge-discharge behavior of the electrode materials was systematically evaluated through galvanostatic charge-discharge measurements at various current densities. Figure 3 presents the GCD curves of Cr₂O₃ (a), CuO (b), Cr₂O₃-CuO nanocomposites (c), comparative GCD profiles at 1 A g⁻¹ (d), specific capacitance plot (e), and cycling stability profiles (f). All three electrodes displayed nearly symmetrical charge-discharge curves with distinct potential plateaus, confirming pseudocapacitive charge storage behavior arising from reversible faradaic reactions [17]. The symmetrical nature of the curves indicates good electrochemical reversibility and high coulombic efficiency of the electrode materials.

The specific capacitance values obtained from GCD measurements at a current density of 1 A g⁻¹ were calculated to be 382.2 F g⁻¹ for Cr₂O₃, 231.1 F g⁻¹ for CuO, and 604.4 F g⁻¹ for Cr₂O₃-CuO nanocomposites. The significantly enhanced capacitance of the nanocomposite electrode compared to the individual oxides demonstrates the synergistic interaction between Cr₂O₃ and CuO, which promotes rapid charge transfer and efficient ion diffusion across the heterostructured interface [17]. The enhanced performance can be attributed to the reduced particle size, porous morphology, and strong interfacial coupling between the two oxide phases, which collectively contribute to increased electroactive surface area and improved electrochemical kinetics.

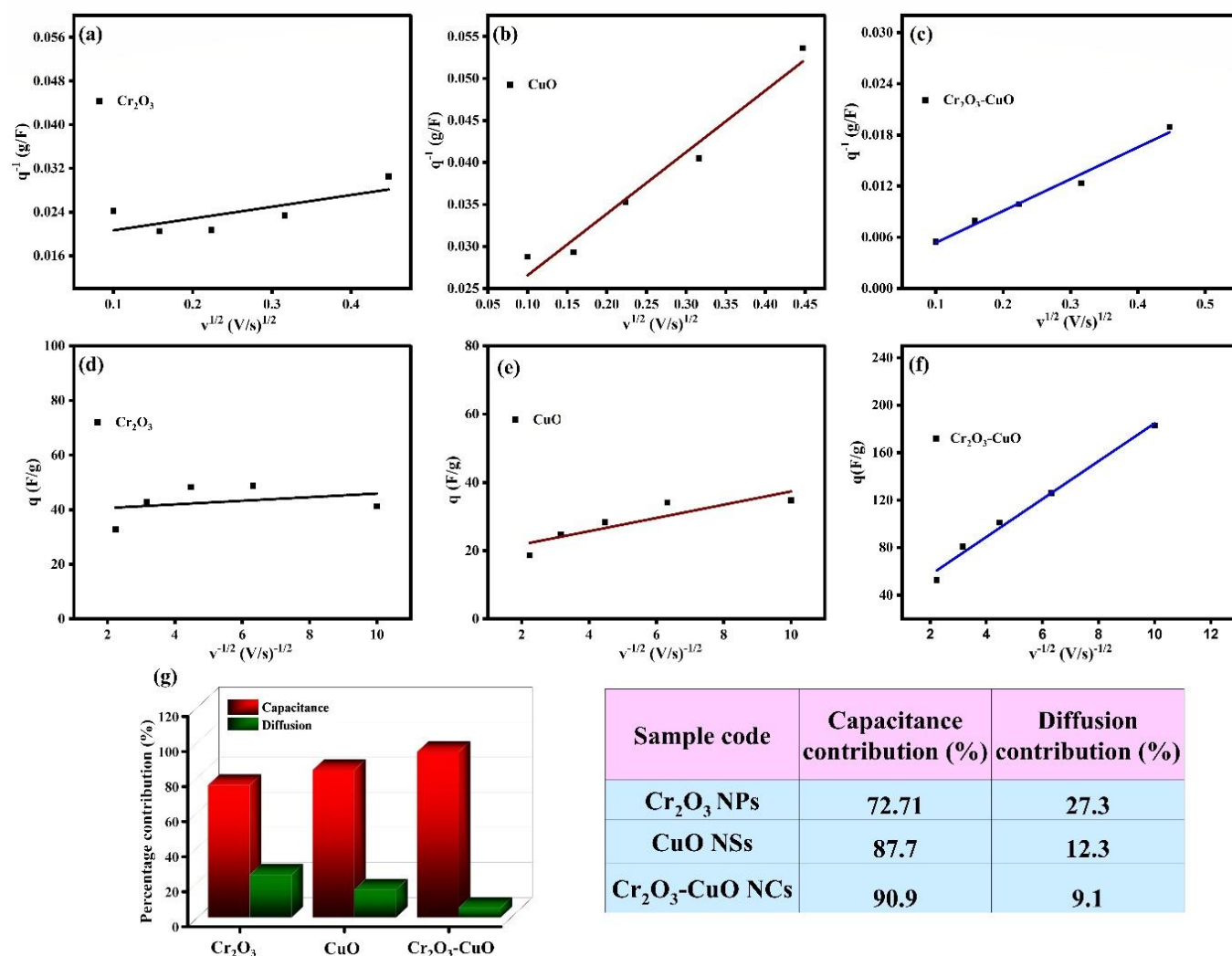


Fig. 2. Capacitance-diffusion contribution analysis showing total capacitance plots (a–c), outer capacitance plots (d–f), and (g) capacitance-diffusion contribution diagram for Cr_2O_3 , CuO, and Cr_2O_3 -CuO nanocomposite electrodes.

The cycling stability of the electrodes was evaluated through repeated charge-discharge measurements at a current density of 1 A g^{-1} for 2000 cycles. The Cr_2O_3 -CuO nanocomposite demonstrated excellent electrochemical durability, retaining 87.5% of its initial capacitance after 2000 cycles, compared with 64% retention for pristine Cr_2O_3 and 74.5% retention for CuO electrodes. The superior cycling stability of the nanocomposite is attributed to the robust heterostructured architecture that maintains structural integrity during repeated charge-discharge cycles. The presence of CuO nanosheets as a supporting matrix provides mechanical stability and prevents agglomeration of Cr_2O_3 nanoparticles, while the strong interfacial interactions between the two phases suppress structural degradation and capacity fading [17]. These results confirm the practical viability of Cr_2O_3 -CuO nanocomposites for long-term energy storage applications.

Table 1 presents a comprehensive comparison of the specific capacitance values obtained in the present work with previously reported CuO-based electrode materials. The

Cr_2O_3 -CuO nanocomposite achieved a specific capacitance of 604.4 F g^{-1} at 1 A g^{-1} in 2 M KOH electrolyte, which significantly exceeds the values reported for various CuO-based composites including Chs-Py/ZnO-CuO (271 F g^{-1}), MoSe_2/CuO (135.42 F g^{-1}), $\text{CuO}/\text{La}_2\text{O}_3/\text{GO}$ (472 F g^{-1}), $\text{Cu}_{1-0.07}\text{Ni}_{0.07}\text{O}$ (396.7 F g^{-1}), $\text{C}/\text{CuO}@g\text{-C}_3\text{N}_4$ (247.2 F g^{-1}), $\text{CuO}/g\text{-C}_3\text{N}_4$ (384 F g^{-1}), $\text{CuO}/\text{carbon nanosheets}$ (183.9 F g^{-1}), and GO/CuO (245 F g^{-1}) [21–28]. The superior performance of the present nanocomposite demonstrates the effectiveness of the Cr_2O_3 -CuO heterostructure design in achieving enhanced charge storage capabilities compared to other CuO-based systems.

3.4. Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy was employed to investigate the charge transfer kinetics and ion transport characteristics of the electrode materials.

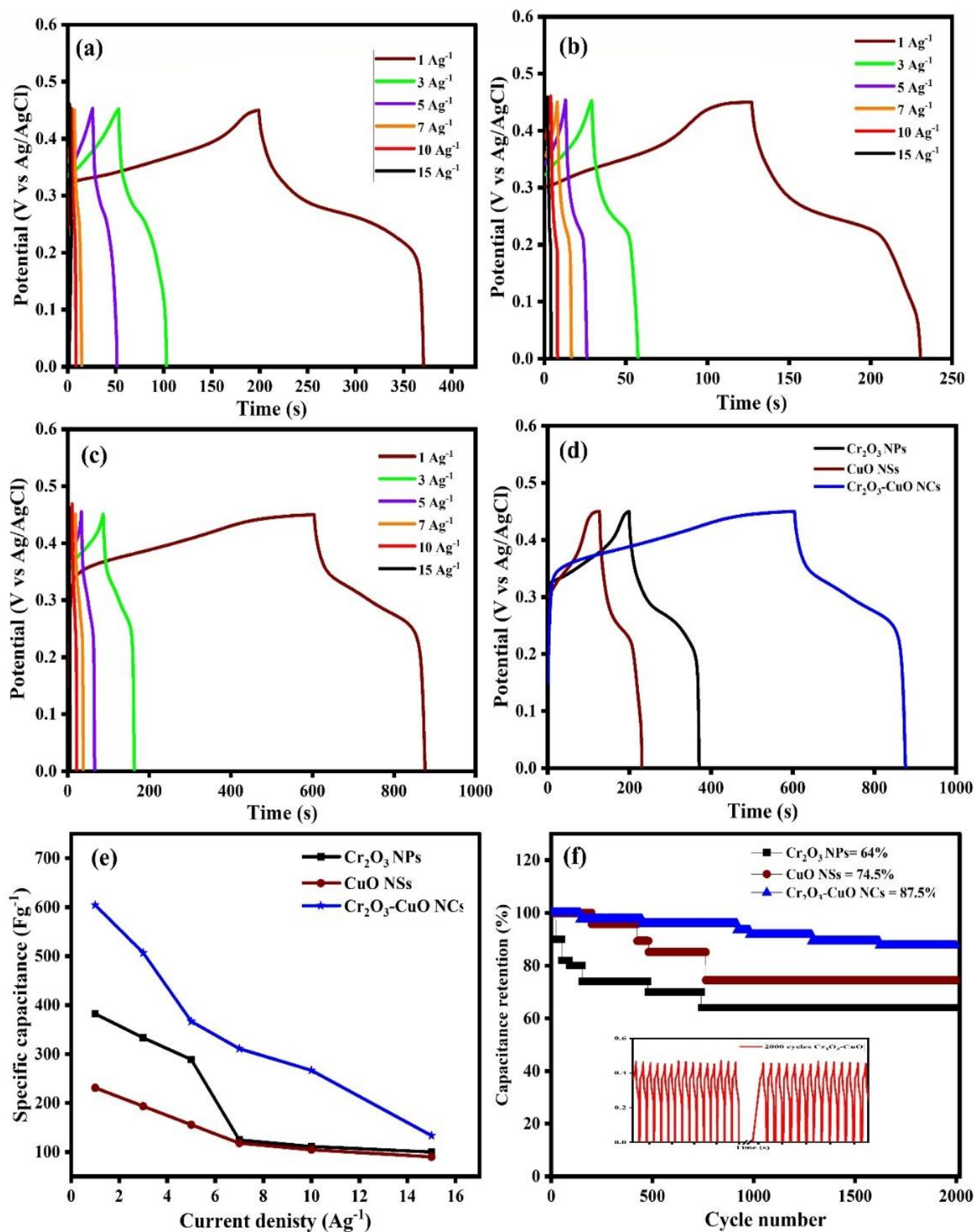


Fig. 3. Galvanostatic charge-discharge curves of (a) Cr_2O_3 nanoparticles, (b) CuO nanosheets, and (c) Cr_2O_3 -CuO nanocomposites at various current densities, (d) comparative GCD profiles at 1 A g^{-1} , (e) specific capacitance versus current density plot, and (f) cycling stability profiles over 2000 charge-discharge cycles at 1 A g^{-1} .

Table 1. Comparative analysis of specific capacitance values of Cr₂O₃-CuO nanocomposite with previously reported CuO-based electrode materials, including current density and electrolyte conditions.

S. No.	Materials	Specific capacitance (F/g)	Current density (A/g)	Electrolyte	Ref.
1.	Chs-Py/ZnO-CuO	271	1	2 M KOH	[21]
2.	MoSe ₂ /CuO	135.42	5 mV/s	0.5 M NaClO ₄	[22]
3.	CuO/La ₂ O ₃ /GO	472	1	6 M KOH	[23]
4.	Cu _{1-0.07} Ni _{0.07} O	396.7	1	2 M KOH	[24]
5.	C/CuO@g-C ₃ N ₄	247.2	1	0.5 M NaOH	[25]
6.	CuO/g-C ₃ N ₄	384	2	2 M KOH	[26]
7.	CuO/carbon nanosheets	183.9	1	1 M Na ₂ SO ₄	[27]
8.	GO/CuO	245	1	1 M Na ₂ SO ₄	[28]
9.	Cr ₂ O ₃ -CuO	604.4	1	2 M KOH	Present work

Figure 4 displays the Nyquist plots of Cr₂O₃, CuO, and Cr₂O₃-CuO nanocomposite electrodes recorded over a frequency range of 100 kHz to 10 mHz with an AC amplitude of 5 mV. The EIS spectra for all three electrodes exhibited a typical profile consisting of a semicircular arc in the high-frequency region followed by a nearly vertical line in the low-frequency region. The high-frequency semicircle is associated with charge transfer resistance at the electrode-electrolyte interface, while the low-frequency vertical line corresponds to capacitive behavior and ion diffusion characteristics [19].

The Cr₂O₃-CuO nanocomposite exhibited the smallest semicircle diameter among the investigated electrodes, indicating significantly lower charge transfer resistance compared to pristine Cr₂O₃ and CuO electrodes. The reduced charge transfer resistance demonstrates improved electrochemical kinetics and enhanced interfacial charge transfer processes in the nanocomposite electrode. The decreased internal resistance is attributed to the interconnected conductive pathways provided by the heterostructured architecture, which facilitates efficient electron transport from the active material to the current collector [19]. The steeper slope of the low-frequency region for the nanocomposite electrode confirms superior capacitive behavior and more efficient ion transport compared to the individual oxides. The nearly vertical line approaching 90° indicates ideal capacitive behavior with rapid ion diffusion and minimal resistance to electrolyte penetration.

The improved EIS characteristics of the Cr₂O₃-CuO nanocomposite are attributed to several factors arising from the heterostructured architecture. The intimate contact between Cr₂O₃ nanoparticles and CuO nanosheets creates an interconnected network that provides continuous electron transport pathways and reduces the overall internal resistance [19]. The porous morphology and reduced particle size enhance electrolyte accessibility to electroactive sites, promoting efficient ion diffusion throughout the electrode matrix. The strong interfacial coupling between the two oxide phases facilitates charge transfer across the heterojunction interface, minimizing recombination losses and improving the overall electrochemical activity. These

favorable characteristics collectively contribute to the superior capacitive performance and rate capability observed for the Cr₂O₃-CuO nanocomposite.

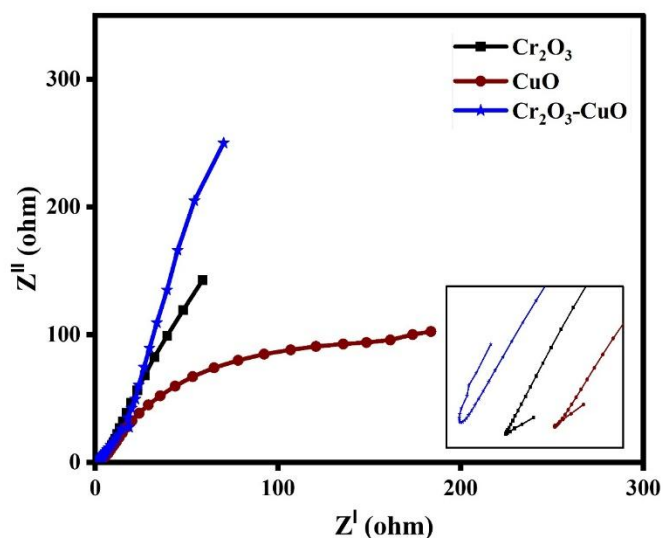


Fig. 4. Nyquist plots of Cr₂O₃, CuO, and Cr₂O₃-CuO nanocomposite electrodes recorded in the frequency range of 100 kHz to 10 mHz with an AC amplitude of 5 mV, illustrating charge transfer resistance and ion diffusion characteristics.

4. CONCLUSION

The comprehensive electrochemical investigation demonstrates that Cr₂O₃-CuO heterostructured nanocomposites constitute a substantially enhanced electrode material system for supercapacitor applications. The systematic comparison with pristine Cr₂O₃ nanoparticles and CuO nanosheets revealed that the synergistic integration of these transition metal oxides produces electrochemical performance characteristics that far exceed those of the individual components. The nanocomposite achieved specific capacitance values of 182.8 F g⁻¹ from cyclic

voltammetry and 604.4 F g⁻¹ from galvanostatic charge-discharge measurements, representing approximately 3.5-fold and 2.6-fold enhancements over the pristine electrodes, respectively. These remarkable improvements stem from the heterostructured architecture that combines complementary electrochemical properties while mitigating individual limitations. Quantitative charge storage analysis revealed that surface-controlled capacitive processes dominate with a 90.9% contribution, indicating rapid kinetics favorable for high-power applications where fast charge-discharge capabilities are essential. The diffusion-controlled contribution of only 9.1% suggests that the heterostructured design effectively minimizes kinetic limitations typically associated with transition metal oxide electrodes. The nanocomposite exhibited exceptional durability, retaining 87.5% of its initial capacitance after 2000 cycles. Electrochemical impedance spectroscopy confirmed reduced internal resistance and enhanced charge-transfer characteristics, establishing the practical viability of this material system. The interconnected conductive pathways facilitate efficient electron transport while the nanoscale morphology ensures maximum electrolyte accessibility to electroactive sites, with abundant redox-active interfaces contributing to the enhanced pseudocapacitive response. These findings establish Cr₂O₃-CuO nanocomposites as promising electrode materials for next-generation supercapacitor devices. The strategic design of heterostructured transition metal oxide composites, as exemplified by the Cr₂O₃-CuO system, offers a viable pathway toward meeting the increasing demands for high-performance, durable, and cost-effective electrochemical energy storage solutions.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Availability of data and material

All of the data obtained or analyzed during this study is included in the report that was submitted.

Conflicts of Interest

The authors declare that they have no financial or personal interests that could have influenced the research and findings presented in this paper. The authors alone are responsible for

the content and writing of this article.

Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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REFERENCES

- [1] Chen, D., Jiang, X., Zhou, X., Miao, C., Yao, T., Shen, W., Xu, T., Gu, H. and Shen, L., 2026. Nitrogen-Directed Ti₃C₂T_x Enabling Rapid Proton Storage for Printed in-Plane Micro-Pseudocapacitors. *Advanced Energy Materials*, p.e05587. <https://doi.org/10.1002/aenm.202505587>.
- [2] Zhou, W., Zhao, Y., Jiang, J., Zhou, J., Meng, C. and Zhang, M., 2026. Cobalt copper oxide/copper oxide heterostructures combined with F doping graphene aerogels forming multiple active sites to strengthen interfacial charge density for supercapacitor. *Journal of Power Sources*, 679, p.240205. <https://doi.org/10.1016/j.jpowsour.2026.240205>.
- [3] Pan, H., Li, J., Jian, Y., Sun, Z., Jia, L. and Zeng, T., 2026. Metal organic framework derivatives as matched positive and negative electrodes for high energy and power density asymmetric supercapacitors. *Journal of Energy Storage*, 149, p.120427. <https://doi.org/10.1016/j.est.2026.120427>.
- [4] Du, Y., Sheng, L., Jiang, M., Zhao, C., Wang, C., Jiang, L. and Chen, W., 2026. Graphene-like carbon nanosheets based on nanocellulose reassembly and their composites as electrodes for asymmetric supercapacitors with high energy and power densities. *Chemical Engineering Journal*, p.172744. <https://doi.org/10.1016/j.cej.2026.172744>.
- [5] Mehak, M., Luqman, M., Salman, M.U., Mahmood, A., Al-Masry, W., Ali, U. and Atiq, S., 2026. Morphological transitions in Cr₂O₃ nano-plates via conducting scaffold inducing balanced synergy of energy and power efficiency in hybrid supercapacitor. *Journal of Power Sources*, 678, p.239936. <https://doi.org/10.1016/j.jpowsour.2026.239936>.

- [6] Helal, A., Khan, R., Ataya, S., Attia, S.Y., Mohamed, S.G. and El-Hout, S.I., 2026. Cr₂O₃-doped boron carbon nitride nanosheets composite as a superior electrode material for supercapacitors. *Diamond and Related Materials*, p.113722. <https://doi.org/10.1016/j.diamond.2026.113722>.
- [7] Benchikh, I., Al-Senani, G.M., Al-Qahtani, S.D., Kiari, M., Sabantina, L. and Benyoucef, A., 2026. Electrochemical Performance Evaluation of Poly (3, 4-Ethylenedioxythiophene)-Functionalized Cr₂O₃-ZrO₂-rGO Composite Supercapacitor. *Journal of Inorganic and Organometallic Polymers and Materials*, 36(2), pp.1584-1596. <https://doi.org/10.1007/s10904-025-03984-1>.
- [8] Masroor, R., Ali, H. and Anis-ur-Rehman, M., 2026. Composite of Metal Oxide with Carbon Nanotubes for Supercapacitor Applications: R. Masroor et al. *Journal of Electronic Materials*, 55(3), pp.2555-2580. <https://doi.org/10.1007/s11664-025-12526-x>.
- [9] Simsek, U.B., Çolak, S.G., Güngör, A., Çolak, M.Ö.A., Alturk, R.G., Erdem, E. and Demir, M., 2026. Facile synthesis of bimetallic metal-organic frameworks for enhanced supercapacitor performance. *Journal of Power Sources*, 663, p.238832. <https://doi.org/10.1016/j.jpowsour.2025.238832>.
- [10] Arif, H., Akbar, H., Bibi, A., Cigeroğlu, Z., Abd El-Azeem, S.A., Choi, J.R. and Ali, A., 2026. Design and optimization of ZnO/MnO₂ nanocomposites for enhanced energy storage in supercapacitor applications. *Materials Science and Engineering: B*, 327, p.119281. <https://doi.org/10.1016/j.mseb.2026.119281>.
- [11] Deswal, I., Manyani, N., Kumar, A. and Tripathi, S.K., 2026. Tailoring the structure and electrochemical properties of CuO via Manganese doping for supercapacitor applications. *Ionics*, pp.1-23. <https://doi.org/10.1007/s11581-026-07192-w>.
- [12] Kumaravelu, T.A., Pan, C.L., Huang, H.Y., Chang, H.W., Lee, C.H., Nga, T.T.T., Chou, W.C., Haw, S.C., Araki, T., Ohigashi, T. and Dong, C.L., 2026. Heterostructured MnO₂/CuO on Cu Wire for Electrochemical Energy Storage: Insights from Spectro-Microscopy. *Advanced Sustainable Systems*, 10(2), p.e00881. <https://doi.org/10.1002/adsu.202500881>.
- [13] Shahid, R., Afzal, H., Zubair, U. and Yousaf, M.I., 2026. Facile synthesis and electrochemical behavior of CoWO₄@C@MnO_x nanocomposite electrode material as a high-performance supercapacitor. *Diamond and Related Materials*, p.113403. <https://doi.org/10.1016/j.diamond.2026.113403>.
- [14] Hebziba, S. D. R., Rohini, B. and Jeevaraj, A. K. S. 2026. Sonochemical Synthesis and Characterization of Cr₂O₃-CuO Nanocomposites for Potential Ballistic Protection and Defense Material Applications. *Danda Xuebao Journal of Ballistics*, 38(2), pp. 508-514. <https://doi.org/10.52783/dxjb.v38.372>.
- [15] Alyousef, H.A., Drissi, N., Alrowaily, A.W., Alotaibi, B.M., Abo-Dief, H.M., Gassoumi, A. and Kumar, A., 2026. Novel Ag₂Fe₂O₄/rGO nanocomposite formation as an effective electrode material through hydrothermal method for supercapacitor application. *Journal of Inorganic and Organometallic Polymers and Materials*, 36(3), pp.1859-1874. <https://doi.org/10.1007/s10904-025-03992-1>.
- [16] Alahmari, F., Gunday, S.T., Iqbal, A., Asiri, S.M., Bozkurt, A., Qahtan, T.F. and Cevik, E., 2024. Synthesis of Zn doped CrV spinel oxide nanostructures for flexible supercapacitor and hydrogen evolution reaction. *International Journal of Hydrogen Energy*, 51, pp.357-367. <https://doi.org/10.1016/j.ijhydene.2023.06.199>.
- [17] Sun, Z., Zhang, Y., Liu, Y., Fu, J., Cheng, S., Cui, P. and Xie, E., 2019. New insight on the mechanism of electrochemical cycling effects in MnO₂-based aqueous supercapacitor. *Journal of Power Sources*, 436, p.226795. <https://doi.org/10.1016/j.jpowsour.2019.226795>.
- [18] kumar Chinnalagu, D., Murugesan, B., Arumugam, M., Chinniah, K., Ganesan, S., Cai, Y. and Mahalingam, S., 2023. Fabrication of 2D-Borophene nanosheets anchored S, N-mesoporous carbon nanocomposite (SNC-Bp//SNC-Bp) symmetric device for high-performance supercapacitor application. *Journal of Energy Storage*, 74, p.109328. <https://doi.org/10.1016/j.est.2023.109328>.
- [19] Gong, J., Luo, W., Zhao, Y., Xie, M., Wang, J., Yang, J. and Dai, Y., 2022. Co₉S₈/NiCo₂S₄ core-shell array structure cathode hybridized with PPy/MnO₂ core-shell structure anode for high-performance flexible quasi-solid-state alkaline aqueous batteries. *Chemical Engineering Journal*, 434, p.134640. <https://doi.org/10.1016/j.cej.2022.134640>.
- [20] Shao, J., Zhou, X., Liu, Q., Zou, R., Li, W., Yang, J. and Hu, J., 2015. Mechanism analysis of the capacitance contributions and ultralong cycling-stability of the isomorphous MnO₂@MnO₂ core/shell nanostructures for supercapacitors. *Journal of Materials Chemistry*

- A, 3(11), pp.6168-6176. <https://doi.org/10.1039/C4TA06793B>
- [21] Mimouni, A., Taha, A.G. and Tawfik, A.R., 2026. Chitosan-Pyridyl Hybrid Nanocomposites with ZnO and CuO Nanoparticles: A Promising Strategy for Photocatalytic, Antimicrobial and Supercapacitor Applications. *Journal of Inorganic and Organometallic Polymers and Materials*, pp.1-22. <https://doi.org/10.1007/s10904-026-04296-8>.
- [22] Thayil, R., Sahu, R., Sankapal, B.R. and Parne, S.R., 2026. Hierarchically assembled molybdenum diselenide-copper oxide heterostructure: Liquid-configured symmetric supercapacitor device. *Materials Science in Semiconductor Processing*, 208, p.110555. <https://doi.org/10.1016/j.mssp.2026.110555>.
- [23] Saranya, A. and Chandrakumar, P., 2026. Development of GO-decorated CuO and CuO/La₂O₃ from Garcinia mangostana for supercapacitor application. *Materials Science and Engineering: B*, 323, p.118691. <https://doi.org/10.1016/j.mseb.2025.118691>.
- [24] Mahalakshmi, B., Sivakumar, S., Mala, N.A. and Manikandan, E., 2025. Exploring the potential of Ni-doped CuO nanoparticles as a promising electrode material for asymmetric supercapacitors. *Journal of the Indian Chemical Society*, 102(2), p.101589. <https://doi.org/10.1016/j.jics.2025.101589>.
- [25] Vattikuti, S.P., Reddy, B.P., Byon, C. and Shim, J., 2018. Carbon/CuO nanosphere-anchored g-C₃N₄ nanosheets as ternary electrode material for supercapacitors. *Journal of Solid State Chemistry*, 262, pp.106-111. <https://doi.org/10.1016/j.jssc.2018.03.019>.
- [26] Subhash, K.G., Benoy, M.D., Duraimurugan, J., Siranjeevi, R. and Prabhu, S., 2023. Synthesis, and characterization of CuO/g-C₃N₄ nanocomposites for high performances supercapacitor application. *Materials Letters*, 330, p.133288. <https://doi.org/10.1016/j.matlet.2022.133288>.
- [27] Yuan, X., Yan, X., Zhou, C., Wang, J., Wang, D., Jiang, H., Zhu, Y., Tao, X. and Cheng, X., 2020. Decorating carbon nanosheets with copper oxide nanoparticles for boosting the electrochemical performance of symmetric coin cell supercapacitor with different electrolytes. *Ceramics International*, 46(1), pp.435-443. <https://doi.org/10.1016/j.ceramint.2019.08.280>.
- [28] Pendashteh, A., Mousavi, M.F. and Rahmanifar, M.S., 2013. Fabrication of anchored copper oxide nanoparticles on graphene oxide nanosheets via an electrostatic coprecipitation and its application as supercapacitor. *Electrochimica Acta*, 88, pp.347-357. <https://doi.org/10.1016/j.electacta.2012.10.088>.