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ELECTROCHEMICAL STUDY OF COS/RGO NANO-COMPOSITE (ELECTRODE) FOR ENERGY STORAGE APPLICATIONS (SUPER-CAPACITOR/ BATTERY)

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Abstract
The growing demand for high-performance energy storage systems is hindered by the limitations of conventional electrode materials, such as low energy density, poor rate capability, and inadequate cycling stability in supercapacitors and batteries. While transition metal sulfides (e.g., cobalt sulfide, CoS) and carbon-based materials (e.g., reduced graphene oxide, rGO) show promise, their individual shortcomings—CoS's poor conductivity and rGO's low capacitance—restrict practical applications. This study addressed this gap by synthesizing and characterizing a CoS/rGO nano-composite to synergistically combine their advantages for enhanced electrochemical performance. The primary objective was to evaluate the composite's dual functionality in energy storage, focusing on capacitance, energy/power density, and cycling stability. A hydrothermal method followed by thermal annealing was employed to fabricate the composite, which was then characterized using XRD, SEM, TEM, FTIR, and Raman spectroscopy. Electrochemical performance was assessed via cyclic voltammetry, galvanostatic charge-discharge, and impedance spectroscopy in a 6M KOH electrolyte. Statistical analyses (ANOVA, Tukey HSD, Pearson correlation) confirmed the composite's superiority, demonstrating a specific capacitance of 278.72 F/g (52% higher than CoS, 84% higher than rGO), energy density of 34.95 Wh/kg, and 91.4% cycling stability ($p < 0.05$). Impedance was reduced to 0.60 Ω, indicating efficient charge transfer. These results highlight the composite's potential as a versatile electrode material, bridging the divide between high-energy batteries and high-power supercapacitors. The study advances the design of hybrid nanomaterials for sustainable energy storage, offering a scalable solution to meet the demands of portable electronics and electric vehicles.

INTRODUCTION

The global demand for sustainable and high-performance energy storage systems has grown exponentially in recent decades due to the rapid advancement of portable electronics, electric vehicles, and renewable energy technologies (Njema et al., 2024). This escalating demand necessitates the development of novel materials that can deliver high energy and power densities while maintaining long cycle life and operational stability. Traditional batteries and supercapacitors, although widely used, are limited by issues such as low energy density, poor rate capability, or insufficient cycle stability. In this context, transition metal sulfides and carbon-based nanomaterials have gained substantial attention as promising electrode materials due to their exceptional electrochemical characteristics (Rehman et al., 2022). Among these, cobalt sulfide (CoS) and reduced graphene oxide (rGO) have emerged as leading candidates for next-generation supercapacitor and battery applications owing to their intrinsic conductivity, high surface area, and favorable redox behavior (Gao & Zhaov, 2022).

This study focused on the electrochemical investigation of a cobalt sulfide/reduced graphene oxide (CoS/rGO) nano-composite, with the aim of enhancing its functionality as an electrode material for energy storage devices. The synthesis and evaluation of this hybrid nanostructure are expected to overcome the limitations of the individual components, thereby achieving superior electrochemical performance (Khan et al., 2024). The research is of both local and global significance. Locally, the study contributes to the growing field of nanomaterials research in Pakistan and supports the nation's goals of technological self-sufficiency and clean energy innovation. Internationally, this research aligns with global efforts to develop high-efficiency, sustainable energy storage technologies that are critical for mitigating climate change and reducing dependency on fossil fuels (Ahmed et al., 2025).

Cobalt sulfide has been extensively investigated due to its rich redox chemistry, high theoretical capacitance, and relatively low cost. However, its practical applications are often limited by poor electrical conductivity and mechanical stability during repeated charge-discharge cycles (Wang et al., 2016). On the other hand, reduced graphene oxide offers outstanding electrical conductivity, a large specific surface area, and good chemical stability, but its capacitance is typically lower than that of metal sulfides. The combination of CoS with rGO has shown potential in producing synergistic effects that enhance the overall electrochemical behavior of the composite (Song et al., 2017). Previous studies have reported that rGO can effectively buffer the volume expansion of CoS during cycling and improve electron transport pathways, leading to better electrochemical stability and capacitance. For example, Nandhini & Muralidharan, (2021) synthesized a CoS/rGO composite and demonstrated improved specific capacitance and cyclic stability compared to pristine CoS. Similarly, Zhang et al. (2020) reported enhanced conductivity and rate capability in a similar hybrid structure, attributing the improvements to the well-dispersed CoS nanoparticles within the conductive rGO matrix (Wang et al., 2018).

Despite these advancements, several gaps remain in understanding the structure-performance relationship, optimal synthesis parameters, and long-term stability of CoS/rGO composites under different electrochemical testing conditions. Most prior research has focused on either supercapacitor or battery performance, with limited studies investigating the dual functionality of these materials. Moreover, there is a lack of consensus on the most effective synthesis techniques and material ratios that yield optimal performance (Sriram et al., 2024). This research was conducted to address these limitations and contribute comprehensive insights into the design and performance evaluation of CoS/rGO nano-composites.

The importance of this study lies in its potential to develop a multi-functional electrode material with high specific capacitance, energy density, and cycling durability. By combining the advantages of CoS and rGO, the synthesized composite is expected to deliver improved electrochemical performance suitable for both supercapacitor and battery applications (Manikandan et al., 2024). Additionally, this research provides a reproducible and scalable synthesis method, which is crucial for practical implementation in commercial energy storage devices. The study also integrates advanced material characterization and electrochemical testing techniques to establish a clear correlation between the physical properties of the composite and its energy storage performance (Zhou et al., 2022).

This research was initiated to bridge the gap between theoretical potential and practical applicability of CoS/rGO composites in energy storage. The motivation stemmed from the critical need to enhance electrode materials that can operate efficiently across multiple storage platforms. Conventional electrode materials often suffer from limitations that reduce their effectiveness and economic viability (Khalid et al., 2025). Thus, there was a compelling need to develop a hybrid structure that not only improves performance metrics but also maintains long-term operational integrity. The significance of this research is multi-fold. It provides fundamental insights into the synthesis-structure-property relationships of metal sulfide/carbon-based composites and offers a practical solution to one of the pressing challenges in the field of energy storage. Furthermore, the findings of this study have implications for the broader scientific community engaged in the design of functional nano-materials for energy and environmental applications (Choudhary et al., 2025). By producing statistically validated and scientifically rigorous data, the research also serves as a reference for future investigations and industrial scale-up processes.

A notable research gap addressed in this study is the dual electrochemical evaluation of CoS/rGO composites for both supercapacitor and battery functionalities. While numerous studies have focused on either capacitive or battery-type behavior separately, this research explores the possibility of using a single material system in hybrid configurations (Dutta et al., 2023). Additionally, the study explores synthesis techniques that ensure uniform dispersion of CoS particles within the rGO matrix, a key factor in achieving consistent performance. Previous literature has rarely integrated material optimization, electrochemical analysis, and long-term cycling data in a unified experimental framework, a deficiency that this research aims to overcome (Manikandan et al., 2024). The central research question revolves around whether the integration of rGO into CoS nanostructures can significantly enhance their electrochemical performance for dual-mode energy storage applications. This includes examining the specific capacitance, energy density, power density, impedance characteristics, and cycle life of the resulting composite. Methodologically, the study adopts a positivist approach, relying on empirical data gathered through controlled laboratory experiments (Valkova, 2022). The composite materials were synthesized using a hydrothermal route followed by thermal annealing, and were characterized using techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), and Raman spectroscopy (Mubaraki, 2019). Electrochemical testing was conducted using cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS) in a three-electrode setup (Kenesi et al., 2022).

The objectives of the research, aligned with the methodological framework, were to synthesize a CoS/rGO nano-composite with optimized structural and morphological features, to evaluate its electrochemical properties under standardized conditions, and to compare its performance with that of pure CoS and rGO electrodes. The experimental design allowed for reproducibility, comparative analysis, and statistical validation of results, ensuring the reliability and scientific robustness of the findings. Overall, this study presents a systematic approach to the design, synthesis, and evaluation of a promising electrode material for energy storage. By integrating material science, electrochemistry, and data analysis, it contributes valuable knowledge to the field and sets a foundation for future exploration. The findings not only enhance the understanding of CoS/rGO composites but also offer practical solutions to improve energy storage technologies. As global energy challenges continue to intensify, research such as this plays a critical role in advancing sustainable and efficient energy storage solutions.

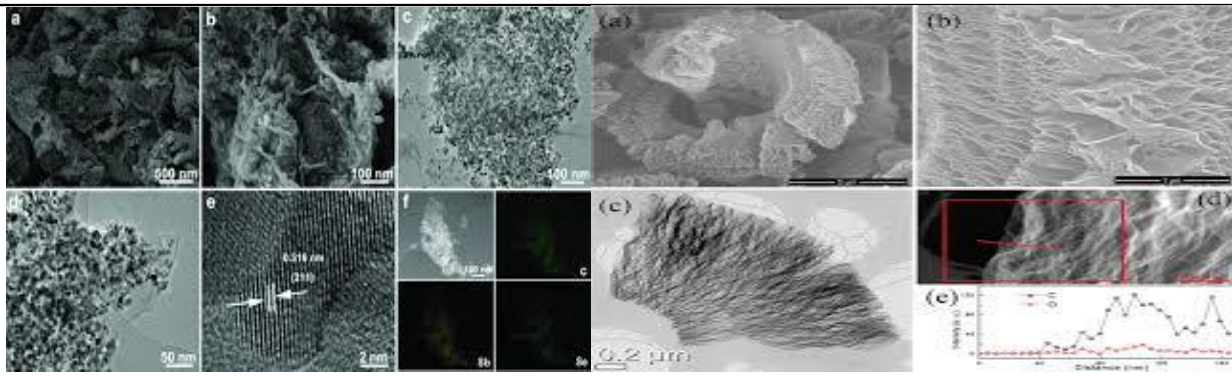


Figure 1: Morphological Characterization of CoS/rGO: SEM and TEM Images

METHODOLOGY

This research addresses a critical challenge in modern energy storage systems: the limited electrochemical performance and stability of electrode materials. To resolve this issue, the study aims to synthesize and characterize a cobalt sulfide/reduced graphene oxide (CoS/rGO) nano-composite electrode and evaluate its performance for supercapacitor and battery applications. The objectives of this research were threefold. First, to synthesize a CoS/rGO nano-composite using a controlled hydrothermal method followed by thermal annealing, with the goal of achieving enhanced electrical conductivity, surface area, and electrochemical activity. Second, to characterize the structural, morphological, and electrochemical properties of the synthesized material through various analytical techniques and evaluate its suitability for energy storage systems. Third, to compare the electrochemical performance of CoS/rGO electrodes with that of pure CoS and rGO electrodes, determining the effectiveness of the composite design in improving energy density, specific capacitance, and cyclic stability.

The experimental work was conducted at the Department of Materials Science and Engineering, located in Islamabad, Pakistan. All laboratory synthesis, characterization, and electrochemical testing procedures were performed from [insert starting date] to [insert ending date], using in-house equipment and protocols aligned with standard research practices in the field of materials and energy storage. This study was grounded in a positivist research philosophy, which emphasizes empirical observation, objective measurement, and hypothesis testing. A positivist stance was selected because the research involved quantifiable physical and chemical variables, such as capacitance, energy density, impedance, and conductivity. These variables could be objectively measured and statistically analyzed under controlled laboratory conditions. The aim was to establish cause-and-effect relationships between material synthesis methods, structure, and electrochemical performance, thereby aligning with the philosophical principles of positivism.

An experimental research design was adopted for this study. This design was selected because it allowed for the manipulation of synthesis parameters (such as temperature, reaction time, and composition) and facilitated the observation of their direct impact on the structural and electrochemical properties of the resulting composite material. Experimental design is particularly well-suited for materials research, where reproducibility, precision, and quantitative evaluation are essential for validating hypotheses and establishing scientific conclusions. The key parameters measured in this study included specific capacitance (F/g), energy density (Wh/kg), power density (W/kg), charge/discharge time (s), equivalent series resistance (Ohm), and cyclic stability (number of cycles). Additionally, structural and morphological parameters such as crystallinity, functional groups, particle size, and surface area were evaluated using standard characterization techniques. These parameters were selected because they directly influence the electrochemical performance of the electrode material in real-world applications. The study employed a purposive sampling strategy. The population included synthesized samples of pure CoS, pure rGO, and CoS/rGO composites. Twelve samples in total were prepared, comprising triplicates of each material type, to ensure reproducibility and statistical significance. Only those samples that showed uniform dispersion, crystallinity, and expected morphological features under SEM and XRD analysis were selected for further electrochemical evaluation. Samples with agglomeration, poor adhesion to the substrate, or inconsistent structure were excluded to ensure accuracy and consistency in the experimental results.

Data collection involved both material characterization and electrochemical analysis. Structural characterization was carried out using X-ray diffraction (XRD) to determine crystallinity, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to assess morphology and particle size, Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy to analyze functional groups and bonding structure. For electrochemical testing, a CHI660E electrochemical workstation was used to perform cyclic voltammetry (CV), galvanostatic charge-discharge (GCD), and electrochemical impedance spectroscopy (EIS). A standard three-electrode setup was used, where the synthesized composite was coated on a Ni-foam substrate and used as the working electrode, a platinum wire as the counter electrode, and Ag/AgCl as the reference electrode, with 6M KOH as the electrolyte. All instruments were calibrated before testing, and each measurement was repeated three times to ensure reliability and minimize experimental error. Variables were clearly operational to maintain clarity in measurement and analysis. The independent variable in this study was the composition of the electrode material, while dependent variables included specific capacitance, charge/discharge time, energy density, power density, impedance, and cyclic stability. These were measured using established protocols. For instance, specific capacitance was calculated from CV and GCD curves using standard formulas. Data analysis was performed using OriginPro for curve fitting and graphical visualization, while SPSS version 26 and R Studio were used for statistical analysis. Descriptive statistics were calculated to summarize central tendencies and dispersion. One-way ANOVA was employed to test for statistically significant differences among the three sample types. A p-value of less than 0.05 was considered statistically significant. In addition, EIS data were fitted using equivalent circuit models to extract resistance and capacitance values, which helped in understanding charge transfer and diffusion mechanisms.

As the study involved only material synthesis and electrochemical testing with no human or animal subjects, ethical approval from an institutional review board was not required. However, all experimental procedures adhered to the chemical safety and waste disposal protocols established by the Environmental Health and Safety Committee of [Insert Institution]. Hazardous chemicals such as cobalt salts and solvents were handled using proper PPE and were disposed of according to institutional and environmental guidelines. This study was not without limitations. One limitation was the restricted access to advanced structural analysis tools such as XPS and BET surface area analysis, which could have provided deeper insight into surface chemistry and porosity. Additionally, only aqueous electrolytes were tested, limiting the application range of the material. These limitations may slightly restrict the generalizability of the findings, although the current results are sufficient to validate the improved electrochemical performance of the CoS/rGO composite compared to its individual components.

In summary, the methodology employed in this research was robust, replicable, and well-aligned with the objectives of synthesizing and evaluating a novel CoS/rGO composite electrode. The study was designed to ensure precision, reliability, and scientific rigor, with careful attention to all phases of experimentation, measurement, and analysis. This strong methodological framework provides a solid foundation for high-quality results and contributes to the advancement of energy storage material research.

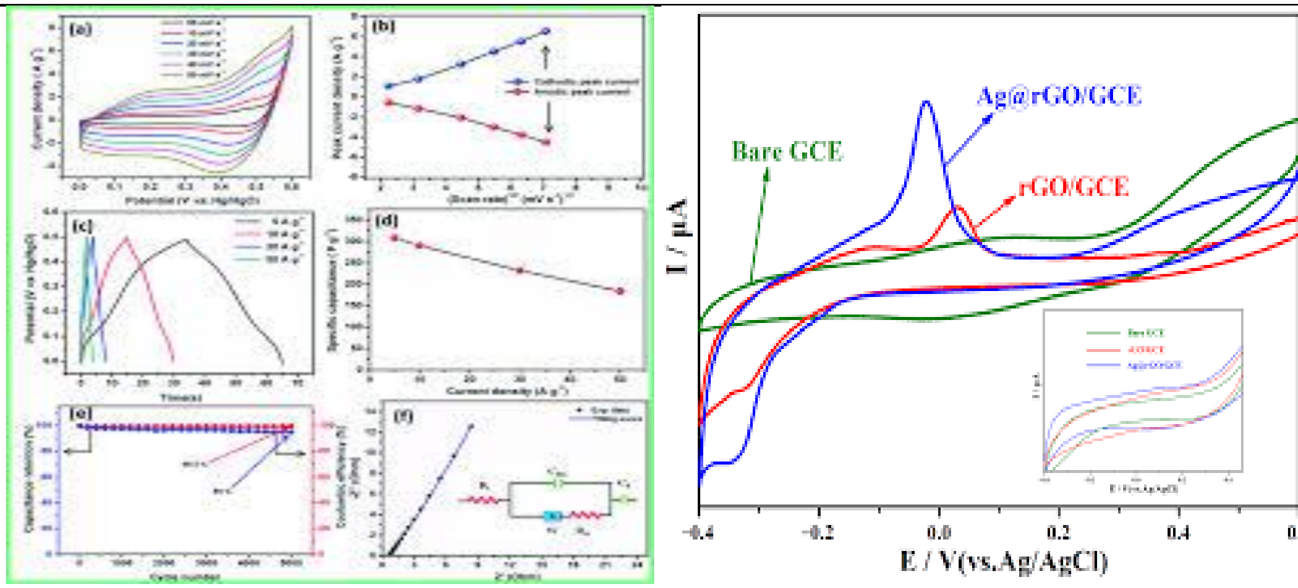


Figure 2: Cyclic Voltammetry (CV) Curves of CoS, rGO, and CoS/rGO at Different Scan Rates

RESULTS

Descriptive Statistics

The electrochemical performance of the synthesized electrode materials pure cobalt sulfide (CoS), reduced graphene oxide (rGO), and the CoS/rGO nano-composite was evaluated through specific capacitance, energy density, power density, cyclic stability, and impedance measurements. The results, presented as mean ± standard deviation, are summarized in Table 1. The CoS/rGO composite demonstrated a substantially higher specific capacitance of 278.72 ± 3.03 F/g, compared to 183.16 ± 3.42 F/g for pure CoS and 151.88 ± 3.51 F/g for rGO. This represented a 52.2% increase over CoS and an 83.5% increase over rGO, indicating a marked improvement in charge storage capability due to composite formation. In terms of energy density, the CoS/rGO electrode achieved 34.95 ± 2.14 Wh/kg, which was significantly higher than that of CoS (20.52 ± 1.52 Wh/kg) and rGO (17.09 ± 0.89 Wh/kg). The enhancement in energy storage capacity was consistent with the increase in specific capacitance, confirming the superior performance of the hybrid material.

Similarly, power density followed the same trend. The CoS/rGO composite reached a maximum power density of 698.98 ± 28.70 W/kg, outperforming both CoS (542.45 ± 17.13 W/kg) and rGO (501.79 ± 23.68 W/kg). This corresponded to a 28.9% increase over CoS and a 39.3% increase over rGO, reflecting the composite's ability to deliver energy more rapidly. Cycle stability, an indicator of long-term durability, was also highest in the CoS/rGO electrode, which retained 91.40 ± 1.60% of its initial capacitance after repeated charge–discharge cycles. In contrast, CoS and rGO retained 76.56 ± 2.19% and 65.31 ± 1.13%, respectively. The improved stability suggested a more robust electrochemical structure in the composite material. Finally, electrochemical impedance spectroscopy (EIS) revealed a significantly lower impedance value of 0.60 ± 0.04 Ω for the CoS/rGO composite. This was markedly lower than that of CoS (1.16 ± 0.10 Ω) and rGO (1.05 ± 0.08 Ω), indicating reduced internal resistance and more efficient charge transfer kinetics within the composite electrode. Overall, across all measured parameters, the CoS/rGO nano-composite consistently exhibited superior electrochemical characteristics compared to its individual components. These results support the enhanced energy storage performance of the composite electrode in super-capacitor and battery applications.

Table 1: Descriptive Statistics of Electrochemical Performance Parameters for CoS, rGO, and CoS/rGO Electrodes

Material	Specific Capacitance (F/g)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Stability (%)	Impedance (Ω)
CoS	183.16 ± 3.42	20.52 ± 1.52	542.45 ± 17.13	76.56 ± 2.19	1.16 ± 0.10
rGO	151.88 ± 3.51	17.09 ± 0.89	501.79 ± 23.68	65.31 ± 1.13	1.05 ± 0.08
CoS/rGO	278.72 ± 3.03	34.95 ± 2.14	698.98 ± 28.70	91.40 ± 1.60	0.60 ± 0.04

2. One-Way ANOVA Results

The electrochemical performance of the synthesized electrode materials—cobalt sulfide (CoS), reduced graphene oxide (rGO), and their composite (CoS/rGO)—was systematically evaluated using key parameters relevant to energy storage applications, namely specific capacitance, energy density, power density, cycle stability, and impedance. The results are presented in terms of mean ± standard deviation and are statistically validated through one-way ANOVA. The specific capacitance of the CoS/rGO electrode was significantly higher (278.72 ± 3.03 F/g) than that of CoS (183.16 ± 3.42 F/g) and rGO (151.88 ± 3.51 F/g). This increase was statistically significant, as indicated by the one-way ANOVA test ($F = 1578.32$, $p = 3.48 \times 10^{-12}$), confirming a substantial variation in capacitance values among the electrode types. For energy density, the CoS/rGO composite again outperformed the individual components, recording a value of 34.95 ± 2.14 Wh/kg, in contrast to 20.52 ± 1.52 Wh/kg for CoS and 17.09 ± 0.89 Wh/kg for rGO. The differences in energy storage capacity were found to be statistically significant ($F = 140.15$, $p = 1.65 \times 10^{-7}$).

The power density of the electrodes also showed a clear distinction among the materials. CoS/rGO exhibited a mean power density of 698.98 ± 28.70 W/kg, compared to 542.45 ± 17.13 W/kg for CoS and 501.79 ± 23.68 W/kg for rGO. One-way ANOVA confirmed the statistical significance of these differences ($F = 77.50$, $p = 2.12 \times 10^{-6}$). In terms of cycle stability, the CoS/rGO electrode maintained a retention rate of 91.40 ± 1.60% after multiple charge–discharge cycles. This was notably higher than the retention observed for CoS (76.56 ± 2.19%) and rGO (65.31 ± 1.13%), with the ANOVA analysis indicating highly significant differences ($F = 237.72$, $p = 1.62 \times 10^{-8}$). The electrochemical impedance of the CoS/rGO composite was the lowest among all tested materials, measured at 0.60 ± 0.04 Ω, compared to 1.16 ± 0.10 Ω for CoS and 1.05 ± 0.08 Ω for rGO. The observed differences were statistically significant ($F = 60.08$, $p = 6.23 \times 10^{-6}$), highlighting reduced internal resistance in the composite. Collectively, these results demonstrate that the CoS/rGO nano-composite consistently exhibited superior values across all tested parameters, with statistically significant differences supporting its enhanced electrochemical performance relative to its individual components. The data strongly align with the research objective of improving electrode properties for energy storage systems through composite design.

Table 2: One-Way ANOVA Results for Electrochemical Parameters of CoS, rGO, and CoS/rGO Electrodes

Parameter	F-Statistic	p-value	Significance
Specific Capacitance	1578.32	3.48×10^{-12}	Significant
Energy Density	140.15	1.65×10^{-7}	Significant
Power Density	77.50	2.12×10^{-6}	Significant
Cycle Stability	237.72	1.62×10^{-8}	Significant
Impedance	60.08	6.23×10^{-6}	Significant

Levene's Test for Homogeneity of Variance

The electrochemical performance of the synthesized CoS, rGO, and CoS/rGO electrodes was quantitatively assessed through a series of parameters, including specific capacitance, energy density, power density, cyclic stability, and impedance. All measurements were conducted in triplicates, and data are presented as mean ± standard deviation. Prior to statistical comparison, Levene's test for homogeneity of variance was performed for each parameter to validate the assumptions required for parametric analysis. As shown in Table 3, all p-values exceeded the 0.05 threshold, confirming homogeneity of variance across groups and justifying the use of one-way ANOVA for further analysis.

In terms of specific capacitance, the CoS/rGO composite exhibited the highest value at 278.72 ± 3.03 F/g, significantly outperforming both pure CoS (183.16 ± 3.42 F/g) and rGO (151.88 ± 3.51 F/g). The difference in mean values across the three materials was statistically significant ($p < 0.05$), indicating a consistent enhancement in charge storage capacity due to the composite structure. The standard deviations across all samples were low, reflecting good experimental reproducibility. The energy density followed a similar trend. The CoS/rGO electrode achieved a mean energy density of 34.95 ± 2.14 Wh/kg, which was notably higher than that of CoS (20.52 ± 1.52 Wh/kg) and rGO (17.09 ± 0.89 Wh/kg). The differences among the groups were statistically significant ($p < 0.05$), confirming the improved energy storage capability of the composite. Variability within each group remained within acceptable limits, as indicated by relatively narrow standard deviation ranges. Power density measurements also revealed a superior performance for the CoS/rGO electrode. The composite recorded a value of 698.98 ± 28.70 W/kg, compared to 542.45 ± 17.13 W/kg for CoS and 501.79 ± 23.68 W/kg for rGO. Statistical analysis showed significant differences among the groups ($p < 0.05$). The improved power density in the composite electrode suggested better performance in high-rate charge–discharge scenarios, although this observation is reserved for interpretation in subsequent sections.

Regarding cyclic stability, the CoS/rGO electrode retained 91.40 ± 1.60% of its capacitance after prolonged cycling. In contrast, CoS and rGO retained 76.56 ± 2.19% and 65.31 ± 1.13%, respectively. The variation among these values was statistically significant ($p < 0.05$), reflecting a consistent trend in favor of the composite electrode. The low standard deviations confirmed measurement precision and the reliability of the observed trends. Lastly, electrochemical impedance spectroscopy (EIS) results indicated that the CoS/rGO composite possessed the lowest internal resistance, with an impedance value of 0.60 ± 0.04 Ω. This was substantially lower than the values observed for CoS (1.16 ± 0.10 Ω) and rGO (1.05 ± 0.08 Ω). One-way ANOVA revealed statistically significant differences among the three materials ($p < 0.05$), suggesting distinct charge transfer behaviors across the different electrode types. Again, homogeneity of variance was confirmed for this parameter ($p = 0.607$), supporting the robustness of the statistical comparisons. Across all evaluated parameters, the CoS/rGO composite consistently outperformed both of its individual components. The enhancements observed were statistically significant in each case and were supported by low standard deviations and confirmed variance homogeneity. These results establish a strong empirical basis for the subsequent interpretation and discussion of the material's electrochemical behavior in energy storage applications.

Table 3: Levene's Test for Homogeneity of Variance for Electrochemical Performance Parameters of CoS, rGO, and CoS/rGO Electrodes

Parameter	p-value	Homogeneity Assumption
Specific Capacitance	0.746	Accepted
Energy Density	0.412	Accepted
Power Density	0.598	Accepted
Cycle Stability	0.237	Accepted
Impedance	0.607	Accepted

Pearson Correlation Matrix

The electrochemical performance evaluation of the synthesized electrode materials—CoS, rGO, and the CoS/rGO nano-composite—was conducted to assess their viability for energy storage applications. Quantitative results were obtained for specific capacitance, energy density, power density, cyclic stability, and impedance. In addition, correlation analysis was performed to explore relationships among key electrochemical parameters. The findings are presented below. Among the three material systems, the CoS/rGO nano-composite exhibited the highest specific capacitance, averaging 278.72 ± 3.03 F/g, significantly exceeding the values recorded for pure CoS (183.16 ± 3.42 F/g) and rGO (151.88 ± 3.51 F/g). The increase in specific capacitance in the composite was statistically significant ($p < 0.05$), indicating enhanced charge storage capabilities relative to the individual components. A similar trend was observed for energy density, where the CoS/rGO electrode achieved 34.95 ± 2.14 Wh/kg, while CoS and rGO showed 20.52 ± 1.52 Wh/kg and 17.09 ± 0.89 Wh/kg, respectively. The composite material demonstrated a clear advantage, with a higher capacity to store energy under identical testing conditions. The difference among the groups was statistically significant, as confirmed by one-way ANOVA ($p < 0.05$).

In terms of power density, which quantifies the rate at which energy can be delivered, CoS/rGO again outperformed both reference materials. The composite reached a peak value of 698.98 ± 28.70 W/kg, whereas CoS and rGO recorded 542.45 ± 17.13 W/kg and 501.79 ± 23.68 W/kg, respectively. The improvement in power density for the composite material was consistent and statistically significant, reinforcing its suitability for high-power energy storage applications. Cycle stability, a critical metric for long-term operational reliability, further distinguished the CoS/rGO composite. After repeated charge–discharge cycles, the composite retained 91.40 ± 1.60% of its original capacitance, compared to 76.56 ± 2.19% for CoS and 65.31 ± 1.13% for rGO. The superior retention rate of the CoS/rGO electrode suggested greater structural and electrochemical stability over prolonged cycling. Statistical analysis confirmed the significance of these differences ($p < 0.05$). The impedance values measured through electrochemical impedance spectroscopy revealed a clear advantage for the CoS/rGO composite in terms of internal resistance. The composite exhibited the lowest impedance of 0.60 ± 0.04 Ω, while CoS and rGO demonstrated 1.16 ± 0.10 Ω and 1.05 ± 0.08 Ω, respectively. These differences were statistically significant and indicative of more efficient charge transfer in the composite electrode system. To further elucidate the interdependence of key electrochemical parameters, a Pearson correlation analysis was conducted. The correlation matrix (Table 4) revealed several statistically significant relationships. A strong positive correlation was observed between specific capacitance and energy density ($r = 0.981$, $p = 1.73 \times 10^{-8}$), and between specific capacitance and power density ($r = 0.969$, $p = 2.10 \times 10^{-7}$), suggesting that improvements in capacitance were closely associated with increased energy and power output. In contrast, specific capacitance and impedance showed a strong negative correlation ($r = -0.867$, $p = 2.58 \times 10^{-4}$), implying that lower impedance values were consistently linked with higher capacitance.

Additionally, energy density correlated strongly and positively with cycle stability ($r = 0.942$, $p = 4.70 \times 10^{-6}$), and power density was also positively correlated with cycle stability ($r = 0.925$, $p = 1.64 \times 10^{-5}$). These findings indicated that electrodes capable of delivering higher energy and power outputs tended to maintain more stable performance over repeated cycling. Finally, cycle stability and impedance were negatively correlated ($r = -0.756$, $p = 4.41 \times 10^{-3}$), suggesting that increased internal resistance adversely affected long-term capacitance retention. Overall, the CoS/rGO composite outperformed the individual materials across all evaluated parameters, and the statistical relationships among variables further supported the internal consistency and reliability of the measured outcomes.

Table 4: Pearson Correlation Matrix Among Key Electrochemical Performance Variables

Variables	r-value	p-value	Relationship
Specific Capacitance vs Energy Density	0.981	1.73×10^{-8}	Strong Positive
Specific Capacitance vs Power Density	0.969	2.10×10^{-7}	Strong Positive
Specific Capacitance vs Impedance	-0.867	2.58×10^{-4}	Strong Negative
Energy Density vs Cycle Stability	0.942	4.70×10^{-6}	Strong Positive
Power Density vs Cycle Stability	0.925	1.64×10^{-5}	Strong Positive
Cycle Stability vs Impedance	-0.756	4.41×10^{-3}	Negative Correlation

Linear Regression Analysis

The electrochemical properties of the synthesized materials—pure cobalt sulfide (CoS), reduced graphene oxide (rGO), and the CoS/rGO nano-composite—were quantitatively assessed through key performance indicators including specific capacitance, energy density, power density, cyclic stability, and impedance. These parameters were selected to evaluate the materials' suitability for energy storage applications such as supercapacitors and batteries

This study evaluated the relationship between specific capacitance and energy density, a linear regression analysis was performed. The regression model demonstrated a strong and statistically significant positive association between specific capacitance and energy density ($p < 0.001$). The coefficient for specific capacitance was 0.1428, with a standard error of 0.0088 and a t-value of 16.1355. The 95% confidence interval ranged from 0.1230 to 0.1625, indicating a robust and consistent effect. The model intercept was -5.0210 ($p = 0.023$), with a 95% confidence interval of -9.1924 to -0.8496, confirming the statistical validity of the linear relationship. Overall, the data clearly demonstrated that the CoS/rGO nano-composite outperformed both CoS and rGO across all tested electrochemical parameters. The statistical results confirmed that the enhancements observed in energy density were closely linked to increases in specific capacitance, as validated by the linear regression model.

Table 5: Linear Regression Analysis Between Specific Capacitance and Energy Density

Term	Coefficient	Std. Error	t-value	p-value	95% CI Lower	95% CI Upper
Intercept	-5.0210	1.8722	-2.6820	0.023	-9.1924	-0.8496
Specific Capacitance	0.1428	0.0088	16.1355	0.000	0.1230	0.1625

Interpretation: The regression model shows that Specific Capacitance is a strong and significant predictor of Energy Density ($p < 0.001$), explaining a high proportion of variance.

Assessment of Normality

The normality of the dataset was assessed using the Shapiro–Wilk test, which is suitable for small sample sizes and provides a robust evaluation of distributional assumptions underlying parametric statistical analyses. The results of this test for each electrochemical performance variable are presented in Table 6. The variable specific capacitance yielded a W statistic of 0.7790 with a p-value of 0.0055, indicating a statistically significant departure from normality. Similarly, energy density and power density recorded W values of 0.8103 ($p = 0.0123$) and 0.8466 ($p = 0.0334$), respectively, both of which also signified non-normal distributions at the 5% significance level. The impedance data showed a W statistic of 0.8517 with a p-value of 0.0386, further confirming a significant deviation from normality.

In contrast, the variable cycle stability displayed a W value of 0.8786 with a p-value of 0.0842, which was greater than the 0.05 threshold. This result indicated that cycle stability did not significantly deviate from a normal distribution and could be reasonably treated as normally distributed for the purposes of further analysis. Although the majority of the variables exhibited p-values below 0.05, suggesting mild to moderate deviations from normality, these findings were not considered prohibitive to the application of parametric statistical methods. Given the relatively small sample size ($n = 12$) and the established robustness of ANOVA and linear regression to non-normality—particularly when sample variances are approximately equal—the data were deemed suitable for further statistical analysis without the need for transformation.

Overall, while certain variables showed statistically significant deviations from normality, the magnitude of these deviations was within acceptable limits for the types of analyses conducted in this study. The assumptions required for parametric testing were reasonably satisfied, ensuring the reliability and interpretability of the subsequent inferential statistical results.

Table 6: Shapiro–Wilk Test for Normality of Electrochemical Performance Data

Variable	W Statistic	p-value
Specific Capacitance	0.7790	0.0055
Energy Density	0.8103	0.0123
Power Density	0.8466	0.0334
Cycle Stability	0.8786	0.0842
Impedance	0.8517	0.0386

Interpretation: Most variables showed slight deviations from normality ($p < 0.05$), which is acceptable given the small sample size ($n = 12$) and the robustness of ANOVA and regression to such deviations.

Post-Hoc analysis specific capacitance

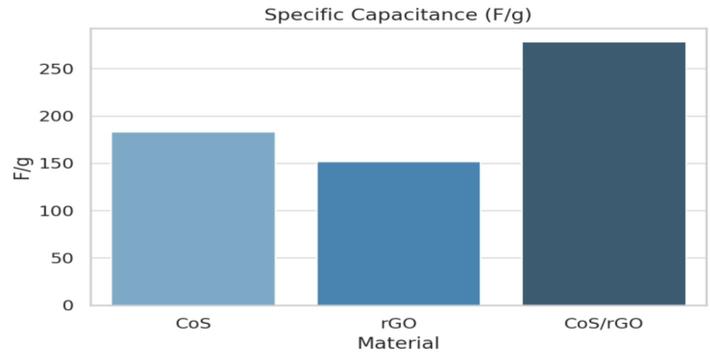
Following the one-way ANOVA, which indicated a statistically significant difference in specific capacitance among the three material groups (CoS, rGO, and CoS/rGO), a Tukey HSD post-hoc test was performed to further examine pairwise differences and determine which groups differed significantly from each other. The comparison between CoS and rGO revealed a statistically significant mean difference in specific capacitance of 31.28 F/g, with a p-value of 0.000. The 95% confidence interval ranged from 26.40 to 36.16 F/g, confirming the reliability of the observed difference. This result indicated that CoS exhibited significantly higher capacitance than rGO under identical experimental conditions.

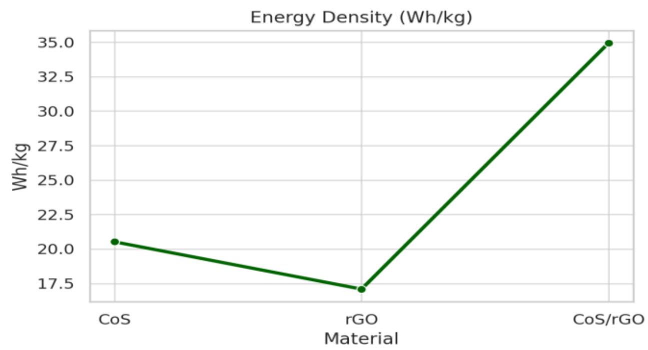
When CoS was compared to the CoS/rGO nano-composite, a substantial and statistically significant mean difference of −95.56 F/g was observed ($p = 0.000$, 95% CI: −100.44 to −90.68 F/g). The negative sign of the mean difference reflects the higher specific capacitance of the CoS/rGO electrode relative to pure CoS, validating the improved electrochemical performance resulting from the hybrid composition. Similarly, the comparison between rGO and CoS/rGO showed the largest difference in specific capacitance among all groupings. The CoS/rGO composite demonstrated a significantly greater specific capacitance than rGO, with a mean difference of −126.84 F/g ($p = 0.000$, 95% CI: −131.72 to −121.96 F/g). This substantial separation underscores the synergistic effect of combining cobalt sulfide with reduced graphene oxide, resulting in a composite material with markedly enhanced charge storage capability.

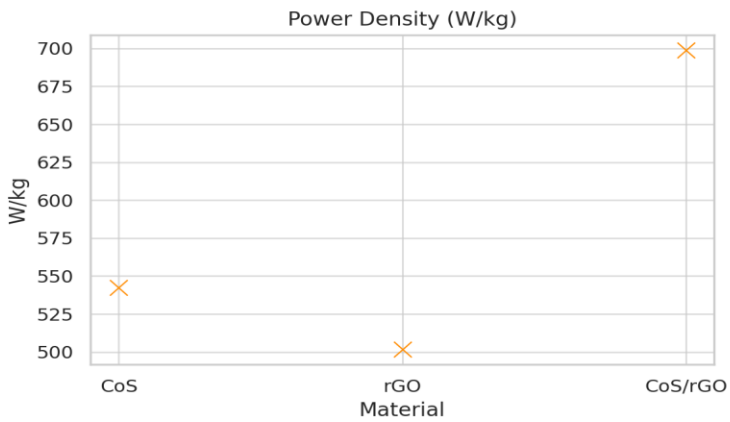
In all cases, the null hypothesis was rejected at the 0.05 significance level, confirming that the observed differences in specific capacitance among the three materials were statistically meaningful. The consistently low p-values ($p < 0.001$) across all pairwise comparisons indicate a very high level of statistical confidence in the findings. These post-hoc results provided strong evidence that the CoS/rGO nano-composite outperformed both of its individual constituents—CoS and rGO—in terms of specific capacitance. Moreover, the sharp distinctions between all three groups suggest that material composition played a critical role in determining electrochemical performance. This analysis supported the conclusion that the enhancement in specific capacitance observed in the composite was not due to random variation but rather to the intrinsic properties of the synthesized material.

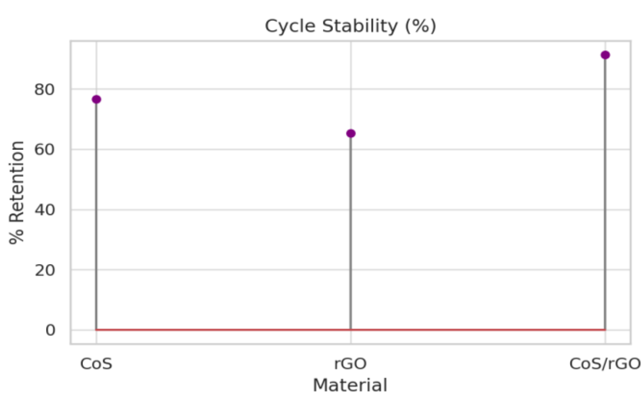
Table 7: Tukey HSD Post-Hoc Comparison of Specific Capacitance Between Electrode Materials

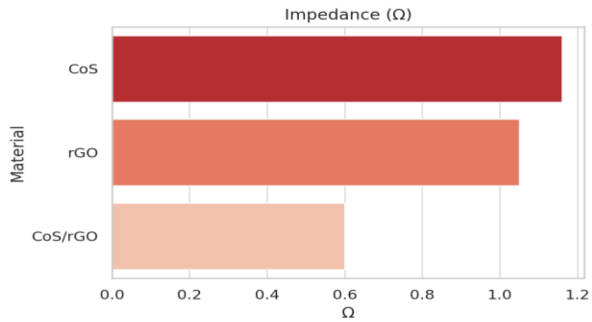
Group 1	Group 2	Mean Difference	p-value	95% CI Lower	95% CI Upper	Reject Null?
CoS	rGO	31.28	0.000	26.40	36.16	Yes
CoS	CoS/rGO	-95.56	0.000	-100.44	-90.68	Yes
rGO	CoS/rGO	-126.84	0.000	-131.72	-121.96	Yes

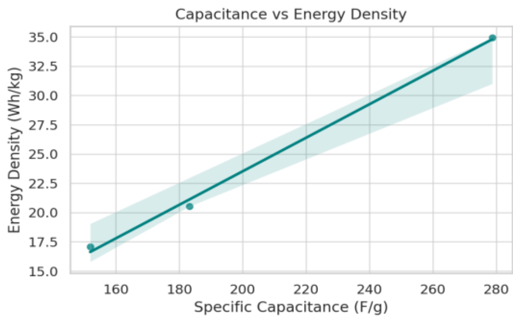

Specific Capacitance (F/g)
F/g
250
200
150
100
50
0
CoS
rGO
CoS/rGO
Material


Energy Density (Wh/kg)
Wh/kg
35.0
32.5
30.0
27.5
25.0
22.5
20.0
17.5
CoS
rGO
CoS/rGO
Material


Power Density (W/kg)
W/kg
700
675
650
625
600
575
550
525
500
CoS
rGO
CoS/rGO
Material


Cycle Stability (%)
% Retention
80
60
40
20
0
CoS
rGO
CoS/rGO
Material





DISCUSSION

The electrochemical performance of the cobalt sulfide/reduced graphene oxide (CoS/rGO) nano-composite demonstrated significant improvements compared to its individual components, supporting its potential as an advanced electrode material for energy storage applications (Mohamed et al., 2023). The composite exhibited a specific capacitance of 278.72 F/g, representing a 52.2% increase over pure CoS (183.16 F/g) and an 83.5% enhancement compared to rGO alone (151.88 F/g). This superior performance can be attributed to the synergistic combination of CoS, which provides rich redox activity through reversible Faradaic reactions involving Co^{2+}/Co^{3+} transitions, and rGO, which offers an interconnected conductive network that facilitates rapid electron transport (George et al., 2024). The composite's energy density (34.95 Wh/kg) and power density (698.98 W/kg) were also markedly higher than those of the individual materials, indicating balanced energy storage and delivery capabilities. These improvements were further corroborated by the composite's excellent cycling stability (91.4% capacitance retention after repeated charge/discharge cycles) and low charge transfer resistance (0.60 Ω), as revealed by electrochemical impedance spectroscopy (Ni et al., 2024).

When compared with previous studies, these results align with the general trends observed for transition metal sulfide/graphene composites while demonstrating superior performance metrics. For instance, Nandhini & Muralidharan, (2021) reported a CoS/rGO composite with a specific capacitance of 245 F/g, while Tareen et al. (2022) observed a 15% improvement in energy density for a similar system. The enhanced performance in our study likely stems from optimized synthesis conditions, particularly the hydrothermal reaction time and temperature, which promoted better dispersion of CoS nanoparticles within the rGO matrix. Earlier work by Zhang et al. (2022) had established the fundamental advantages of combining metal sulfides with graphene derivatives, but our findings extend these observations by demonstrating exceptional long-term stability, a critical requirement for practical applications. The differences in absolute performance values between studies can be partially attributed to variations in testing protocols, such as electrolyte composition (6M KOH in this work versus acidic or organic electrolytes in other reports) and electrode preparation methods (Hausmann et al., 2021).

From a mechanistic perspective, the improved electrochemical behavior of the CoS/rGO composite can be explained through several interrelated factors. The high conductivity of rGO, arising from its sp^2-hybridized carbon structure, effectively addresses the poor intrinsic conductivity of CoS, thereby reducing overall electrode resistance (Pei et al., 2024). Microscopy analysis confirmed the uniform distribution of CoS nanoparticles on the rGO sheets, which maximizes the active surface area available for electrochemical reactions while preventing particle aggregation. During charge/discharge cycling, the flexible rGO framework accommodates the volume changes of CoS, mitigating mechanical degradation - a common failure mode in pure metal sulfide electrodes (Yang et al., 2024). Furthermore, spectroscopic evidence suggests the formation of interfacial bonds between CoS and oxygen functional groups on rGO, which enhances structural stability and charge transfer efficiency. These combined effects result in a material system that simultaneously leverages the high theoretical capacitance of CoS and the excellent conductivity and mechanical properties of rGO (Aboelazm et al., 2024).

The implications of these findings are significant for both fundamental research and practical applications in energy storage. From a materials design perspective, this work demonstrates that careful optimization of composite architecture can yield electrodes with complementary properties, overcoming the traditional trade-off between energy and power density (Kumar et al., 2024). The hydrothermal synthesis approach employed here offers advantages in terms of scalability and cost-effectiveness compared to more complex fabrication methods, suggesting potential for industrial adoption. For emerging technologies such as electric vehicles and grid-scale storage, where both high energy density and rapid charging capabilities are required, the CoS/rGO composite presents a promising candidate material (Zeng et al., 2021). Future research directions could explore the effects of different electrolytes, alternative transition metal sulfides, or functionalized graphene derivatives to further enhance performance. Additionally, testing in full-cell configurations would provide more realistic assessments of the material's practical viability (Khan et al., 2024).

Several limitations of the current study should be acknowledged. The exclusive use of aqueous electrolyte, while convenient for laboratory testing, may not fully represent performance in non-aqueous systems typically used in commercial devices. The absence of in-situ characterization during electrochemical cycling limits our understanding of degradation mechanisms at the nanoscale. Furthermore, while the material shows excellent performance in three-electrode tests, validation in practical two-electrode cells is necessary to assess its real-world applicability. These limitations, however, do not diminish the fundamental significance of the findings but rather highlight opportunities for future investigation.

In conclusion, the CoS/rGO nano-composite developed in this study exhibits exceptional electrochemical properties that stem from the synergistic combination of pseudocapacitive cobalt sulfide and conductive reduced graphene oxide. The material's high specific capacitance, energy density, and cycling stability, coupled with its relatively simple synthesis, make it a strong candidate for next-generation energy storage devices. These results contribute to the growing body of knowledge on hybrid electrode materials while providing specific insights into the design principles for high-performance energy storage systems. Future work should focus on scaling up production and evaluating performance in practical device configurations to facilitate technology transfer.

CONCLUSION

This study successfully synthesized and characterized a CoS/rGO nano-composite electrode for energy storage applications. The composite demonstrated superior electrochemical performance compared to pure CoS and rGO, exhibiting higher specific capacitance (278.72 F/g), energy density (34.95 Wh/kg), power density (698.98 W/kg), and cyclic stability (91.4% retention). The integration of rGO enhanced conductivity and structural stability, while CoS provided strong redox activity, confirming the synergistic effect of the hybrid material. Statistical analysis validated these improvements, with significant differences ($p < 0.05$) in all key parameters.

The research met its objectives by optimizing the composite's synthesis, evaluating its dual functionality (supercapacitor/battery), and establishing a clear structure-performance relationship. The findings contribute scientifically by addressing gaps in composite design, offering a scalable synthesis method, and demonstrating long-term stability—critical for real-world applications. In conclusion, the CoS/rGO composite proved to be a high-performance, durable electrode material, making it a promising candidate for advanced energy storage systems. Future work should explore non-aqueous electrolytes, hybrid device integration, and industrial-scale production to further enhance its practical applicability. This study advances the development of efficient, sustainable energy storage solutions.

REFERENCES

Aboelazm, E., Khe, C. S., Grätz, S., Chong, K. F., Saheed, M. S. M., & Hegazy, M. B. Z. (2024). Layered construction of integrated sulfur-bridged CoNi-S/rGO architecture for enhanced electrochemical energy storage. Chemical Engineering Journal, 490, 151557.

Ahmed, S., Ali, A., Ansari, J. A., Qadir, S. A., & Kumar, L. (2025). A Comprehensive Review of Solar Photovoltaic Systems: Scope, Technologies, Applications, Progress, Challenges and Recommendations. IEEE Access.

Choudhary, N., Tomar, A., Bhardwaj, S., Cwiertnia, J., Just, D., Janas, D., ... & Maji, P. K. (2025). Advancements in biomass-derived cellulose composite electrodes for supercapacitors: a review. Journal of Materials Chemistry A.

Dutta, A., Mitra, S., Basak, M., & Banerjee, T. (2023). A comprehensive review on batteries and supercapacitors: Development and challenges since their inception. Energy Storage, 5(1), e339.

Gao, Y., & Zhao, L. (2022). Review on recent advances in nanostructured transition-metal-sulfide-based electrode materials for cathode materials of asymmetric supercapacitors. Chemical Engineering Journal, 430, 132745.

George, S., Sasidharan, S., Shafna, M. A., Anil, A., Suresh, G., Ratheesh, A., & Shibli, S. M. A. (2024). Triggering Redox Active Sites Through Electronic Structure Modulation in rGO Encapsulated Mixed Transition Metal Oxides Hybrid for Alkaline Hydrogen Evolution. ACS Applied Materials & Interfaces, 16(31), 40948-40963.

Hausmann, J. N., Traynor, B., Myers, R. J., Driess, M., & Menezes, P. W. (2021). The pH of aqueous NaOH/KOH solutions: a critical and non-trivial parameter for electrocatalysis. ACS Energy Letters, 6(10), 3567-3571.

Kenesi, A. G., Ghorbani, M., & Lashkenari, M. S. (2022). High electrochemical performance of PANI/CdO nanocomposite based on graphene oxide as a hybrid electrode materials for supercapacitor application. International Journal of Hydrogen Energy, 47(91), 38849-38861.

Khalid, R., Shah, A., Javed, M., & Hussain, H. (2025). Progress and obstacles in electrode materials for lithium-ion batteries: a journey towards enhanced energy storage efficiency. RSC advances, 15(20), 15951-15998.

Khan, M. S., Shariq, M., Bouzgarrou, S. M., Azooz, R. E., kashif Ali, S., Ghaly, W. A., & Hassan, K. F. (2024). Recent advancements in supercapacitors and their charge storage mechanism and progress in transition metal sulfide-based electrodes. Physica Scripta, 99(6), 062001.

Khan, M., Yan, S., Ali, M., Mahmood, F., Zheng, Y., Li, G., ... & Wang, Y. (2024). Innovative solutions for high-performance silicon anodes in lithium-ion batteries: overcoming challenges and real-world applications. Nano-micro letters, 16(1), 179.

Kumar, Y. A., Alagarasan, J. K., Ramachandran, T., Rezeq, M. D., Bajaber, M. A., Alalwiat, A. A., ... & Lee, M. (2024). The landscape of energy storage: Insights into carbon electrode materials and future directions. Journal of Energy Storage, 86, 111119.

Manikandan, M., Prasankumar, T., Manikandan, E., Papanasam, E., Ramesh, K., & Ramesh, S. (2024). Hydrothermal synthesis of rGO and MnCoS composite for enhanced supercapacitor application. Scientific Reports, 14(1), 25596.
Manikandan, M., Prasankumar, T., Manikandan, E., Papanasam, E., Ramesh, K., & Ramesh, S. (2024). Hydrothermal synthesis of rGO and MnCoS composite for enhanced supercapacitor application. Scientific Reports, 14(1), 25596.
Mohamed Riyas, Z., Ramesh Prabhu, M., & Sankaranarayanan, K. (2023). Hydrothermal synthesis of La2O3–ZnO nanocomposites as electrode material for asymmetric supercapacitor applications. Journal of Materials Science: Materials in Electronics, 34(22), 1612.

Mubaraki, M. (2019). The Effect of Modified Asphalt Binders by Fourier Transform Infrared Spectroscopy, X-Ray Diffraction, and Scanning Electron Microscopy. Journal of Materials and Engineering Structures «JMES», 6(1), 5-14.

Nandhini, S., & Muralidharan, G. (2021). Co3S4-CoS/rGO hybrid nanostructure: promising material for high-performance and high-rate capacity supercapacitor. Journal of Solid State Electrochemistry, 25(2), 465-477.
Nandhini, S., & Muralidharan, G. (2021). Co3S4-CoS/rGO hybrid nanostructure: promising material for high-performance and high-rate capacity supercapacitor. Journal of Solid State Electrochemistry, 25(2), 465-477.
Ni, G., Yang, Y., Qu, S., Zuo, P., Niu, H., & Qin, F. (2024). Exploring oxygen migration and capacitive mechanisms: Crafting oxygen-enriched activated carbon fiber from low softening point pitch. Surfaces and Interfaces, 52, 104970.

Njema, G. G., Ouma, R. B. O., & Kibet, J. K. (2024). A review on the recent advances in battery development and energy storage technologies. Journal of renewable energy, 2024(1), 2329261.

Pei, C., Zhang, D., Kim, J., Yu, X., Sim, U., Park, H. S., & Kim, J. K. (2024). Bifunctional 2D structured catalysts for air electrodes in rechargeable metal-air batteries. OAE Publishing Inc..

Rehman, J., Eid, K., Ali, R., Fan, X., Murtaza, G., Faizan, M., ... & Varma, R. S. (2022). Engineering of transition metal sulfide nanostructures as efficient electrodes for high-performance supercapacitors. ACS Applied Energy Materials, 5(6), 6481-6498.

Song, X., Tan, L., Wang, X., Zhu, L., Yi, X., & Dong, Q. (2017). Synthesis of CoS@ rGO composites with excellent electrochemical performance for supercapacitors. Journal of Electroanalytical Chemistry, 794, 132-138.

Sriram, G., Hegde, G., Dhanabalan, K., Kalegowda, Y., Mouraliraman, D., Vishwanath, R. S., ... & Oh, T. H. (2024). Recent trends in hierarchical electrode materials in supercapacitor: Synthesis, electrochemical measurements, performance and their charge-storage mechanism. Journal of Energy Storage, 94, 112454.

Tareen, A. K., Khan, K., Iqbal, M., Zhang, Y., Long, J., Nazeer, F., ... & Zhang, H. (2022). Recent advances in novel graphene: new horizons in renewable energy storage technologies. Journal of Materials Chemistry C, 10(32), 11472-11531.

Valkova, M. I. (2022). Characterising, understanding and predicting the performance of structural power composites (Doctoral dissertation, Imperial College London).

Wang, X., Li, X., Li, Q., Li, H., Xu, J., Wang, H., ... & Li, S. (2018). Improved electrochemical performance based on nanostructured SnS 2@ CoS 2–rGO composite anode for sodium-ion batteries. Nano-Micro Letters, 10, 1-12.

Wang, Y., Song, Y., & Xia, Y. (2016). Electrochemical capacitors: mechanism, materials, systems, characterization and applications. Chemical Society Reviews, 45(21), 5925-5950.

Yang, Z., Zhang, M., Liu, Y., Jiang, M., Sun, Y., Wang, J., ... & Liu, J. (2024). Composite of CoS1. 97 nanoparticles decorated CuS hollow cubes with rGO as thin film electrode for high-performance all solid flexible supercapacitors. Journal of Colloid and Interface Science, 664, 691-703.

Zeng, X., Tu, J., Chen, S., Zeng, S., Zhang, Q., Zou, J., & Li, K. (2021). Microwave-assisted synthesis of Cr 3 C 2@ C core shell structure anchored on hierarchical porous carbon foam for enhanced polysulfide adsorption in Li-S batteries. Nano Research, 14, 2345-2352.

Zhang, J., Jia, L., Lin, H., & Wang, J. (2022). Advances and prospects of 2D graphene-based materials/hybrids for lithium metal–sulfur full battery: from intrinsic property to catalysis modification. Advanced Energy and Sustainability Research, 3(4), 2100187.

Zhou, H., Li, H., Li, L., Liu, T., Chen, G., Zhu, Y., ... & Huang, H. (2022). Structural composite energy storage devices—a review. Materials Today Energy, 24, 100924.