

Fabrication of MnCo₂O₄/g-CN nanohybrid electrodes for enhanced redox kinetics in supercapacitors

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Research Article

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Abstract

The inspiration for the development of specific nanophase materials comes from the increasing energy needs of the next generation. In the present work, we demonstrated the manufacturing method and evaluated the performance of a supercapacitor electrode built from manganese-cobalt (MnCo_2O_4) embedded in graphitic carbon nitride (g-CN). Hydrothermal-assisted nanohybrids demonstrated a significant increase in specific capacitance (C_s) and exceptional durability. $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanocomposite had a C_s of 1125.2 F g^{-1} , a power density (P_d) value 200 W kg^{-1} , and an energy density (E_d) of 25 Wh kg^{-1} at 1 A g^{-1} . Chronoamperometry (CA) measurements obtained after 30 hours show that the electrode has outstanding electrochemical stability. The existence of varied manganese ion oxidation states, significant specific surface area (SSA), nitrogen-rich structure, and mesoporous nature, which allows rapid ion movement, all contributed to the improved electrochemical functionality. The inclusion of electrochemically active patches inside g-CN's nanosheet design influenced its electrochemical characteristics. According to their results, adopting $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanohybrid by means of electrode material used for energy storage seems like a desirable and affordable choice.

Introduction

The world is currently experiencing an energy crisis that has an impact on almost every aspect of life. Energy is essential in modern life, and the escalating energy crisis emphasizes the critical need for reliable, environmentally friendly, and efficient energy systems. In the modern era, driven by the industrial revolution, the global energy demand has surged significantly to fulfill the basic requirements arising from increasing pollution and the development of electric vehicle innovation [1, 2]. Thus, the need for energy is always increasing, while the sources of renewable energy are limited, resulting in disasters involving an increase in emissions of greenhouse gases, an energy crisis, and a surge in pollution from fossil fuels, power, hydropower, and wind energy have become one of the world's greatest challenges [3]. The development of reliable systems to store electricity produced from renewable technologies and the use of environmentally friendly energy sources are both necessary for long-term energy conservation.[4, 5]. Effective and efficient energy storage technologies are crucial for retaining the energy produced from various sources. Batteries store chemical energy and convert it to electricity, provide portable power, and have specific voltage and capacity ratings. Although batteries have limitations because of their low power density (P_d) and high internal resistance.[6]. The capacitor's energy storage capacity is restricted by its low-slung energy density (E_d), rapid discharge rate, escape current, reliability, cost, and voltage restriction. Supercapacitors (SC_s) are at the leading edge of energy technology for environmentally benign and long-term sources of energy and storage systems. [7]. SC_s are categorized as electrochemical double-layer capacitors (EDLC_s), pseudo capacitors, and hybrid capacitors. The electrodes in EDLC_s are composed of carbon allotropes with a wide surface area, which aids in energy storage by generating a double layer on their surface. EDLC_s are typically manufactured from carbon-based materials include carbon aerogels, carbons, activated carbon, carbon nanotubes, and graphene [8,

9]. Pseudo capacitors store energy using quick, reversible faradaic processes, resulting in increased capacitance and E_d . Typical electrode materials include conducting polymers (PANI, PPy), metal oxides (RuO_2 , MnO_2), and metal sulfides (MoS_2) [10]. Hybrid capacitors combine the types of EDLC_s and pseudo capacitors, offering a balance of high E_d , P_d , and long durability [11].

The performance of supercapacitors can remain significantly boosted over the use of innovative electrode substances, as the electrode is the principal element that regulates charge storage, ion transport, and redox activity [12]. Metal oxides offer excellent chemical stability, several oxidation states, and a high theoretical capacitance, enabling effective charge storage in supercapacitors [13]. Transitional metal oxides (TMO_s) were recently recognized to be excellent applicants used for electrodes in energy storage because of their large resources of ecological compatibility, comfort of availability, and additional interesting properties that include their multiple components and shapes, broad surface area, and extremely high C_s [14, 15]. Although single metal oxides, including MnO_2 , NiO , and WO_3 , had been thoroughly investigated, their performance still falls short of the electrochemical criteria. Binary transition metal oxides (TMO_s) offer extra active areas for redox reactions, improve constitutional stability, and demonstrate superior electrical efficiency compared to single components [16]. Spinel (AB_2O_4) compound-based transition metal oxides are gaining popularity owing to high capacitance, promising electrode materials, strong electrical conductivity, and structural durability. Among several binary transition metal oxides, MnCo_2O_4 spinel oxide has gained great interest by scholars owing to its good electrochemical efficiency, high capacitance, cheap cost, and eco-friendly [17]. Researchers have synthesized MnCo_2O_4 with diverse morphologies, including nanospheres, nanowires, and nanoflowers, using hydrothermal, solvothermal, and electrodeposition techniques [18]. Yet, spinel oxides possess poor rate capability, and a limited number of available active sites, structural instability during cycling, and feasibility for scaling in SC_s applications. They are susceptible to nanoparticle aggregation and slow ion diffusion, leading to diminished surface area and impeded charge-transfer kinetics [19–21]. To address the limitations of spinel oxides, composite spinel materials are developed by incorporating multi-elemental compositions or carbon-based functional materials, including carbon aerogels, carbons, graphene, graphene oxide, reduced graphene oxide, and g-CN, which improve electron transfer, structural stability, and bifunctional capability in energy storage and catalysis uses [22]. G-CN has attracted the interest of researchers in the last decade owing to its unusual features, in additional applications are luminous photocatalysis, electrocatalysis, and storage of energy devices. The g-CN has a large surface area, exceptional electrical conductivity, affordable cost, easy fabrication, exceptional chemical/physical stability, environmental friendliness, and efficient charge transfer due to a nitrogen-rich structure [23, 24].

Lately, nanomaterials based on spinel, including g-CN nanocomposites, were comprehensively examined and used as functional electrodes for SC_s. Tehreem et al. created $\text{MnAl}_2\text{O}_4/\text{g-CN}$ composite via the hydrothermal method and achieved C_s of 1161 F g^{-1} at 1 A g^{-1} [25]. Zheng et al. revealed that hydrothermally produced $\text{NiCo}_2\text{O}_4/\text{g-CN}$ composite material had improved durability of cycling with remarkable capacitance performance and C_s of 1127.71 F g^{-1} at 1 A g^{-1} [26]. Muhammad et al.

developed $\text{NiFe}_2\text{O}_4/\text{g-CN}$ nanosheet exhibited superior C_s of 740 F g^{-1} , E_d , and P_d had been 38 Wh Kg^{-1} and 305 W Kg^{-1} , consistently, at 1 A g^{-1} , measured by GCD. [27]. This work examines $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanohybrid by analyzing the previously documented characteristics of spinel nanostructures based on g-CN. Manganese cobalt-based g-CN may be best choice for SC_s because of its better conductivity as well as durability. The g-CN material had substantial specific surface area (SSA), which overcomes the lower cycle; improved charge transfer enhances the stability of the pristine material. The addition of magnesium increases the crystal framework, form, and life span, resulting in large C_s and remarkable cyclic durability, making it a perfect material for SC_s uses [28].

The present research explains the direct hydrothermal manufacture of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanocomposite for making a superior electrode material of supercapacitors, highlighting the outstanding properties through structural, microscopic, and electrochemical analyses using various evaluation methodologies. The $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanocomposite obtained C_s of 1125.2 F g^{-1} , maximum P_d of 200 Wh kg^{-1} at 1 A g^{-1} . CA results attained over 30 hours reveal that the electrode has remarkable electrochemical stability. As a result, $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanohybrid is recognized as a preferable applicant for supercapacitor electrode material featuring improved efficiency, affordability, and sustainability.

Experimental Information

2.1 Reagents

Chemicals used to create the $\text{MnCo}_2\text{O}_4/\text{g-CN}$ included manganese nitrate tetrahydrate ($\text{Mn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, 97%), cobalt nitrate ($\text{Co}(\text{NO}_3)_3$, 99.9%), potassium hydroxide (KOH, 85%), thiourea (NH_2CSNH_2 , ACS > 99%), and ethanol ($\text{C}_2\text{H}_6\text{O}$, ACS > 95%). The chemicals employed in the experiment appeared to be analytical grade, obtained from Sigma-Aldrich and used without additional purification. Deionized water ($\text{DI H}_2\text{O}$) was utilized in every experiment.

2.2 Preparation of MnCo_2O_4

Pristine MnCo_2O_4 had been synthesized via a controlled hydrothermal process. For the making of MnCo_2O_4 , a solution was manufactured by mixing 0.1M manganese nitrate tetrahydrate and 0.2M cobalt nitrate with 70 ml of $\text{DI H}_2\text{O}$. The mixture had been stirred using a magnetic stirrer about 30 minutes, then gradually added the solution of KOH till the pH became 9. The resultant mixture went into an autoclave, then heated at 160°C for around 5 hours before washing with ethanol and $\text{DI H}_2\text{O}$. The resulting solution was dehydrated at 60°C Over 24h.

2.3 Preparation of g-CN

Successful synthesized g-CN involved thermal-driven polymerization of thiourea. The research study entailed heating 6 g of thiourea under controlled conditions. The system's temperature was gradually boosted by 5°C per minute until exceeding 550°C . The specified temperature had been maintained for

nearly four hours. The resultant yellow product was then cooled to room temperature and powdered into a fine powder.

2.4 Preparation of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ composites

Initially, $\text{MnCo}_2\text{O}_4/\text{g-CN}$ fabricated hydrothermally via dispersing MnCo_2O_4 (1 g) within 70 ml of DI H_2O by continuous magnetic stirring for 35 minutes. Next, 1 g of g-CN was amalgamated with resultant mixture. The mixture was next added to a 100 ml Teflon-lined autoclave as well as heated at 160°C for 5 hours before being centrifuged to separate $\text{MnCo}_2\text{O}_4/\text{g-CN}$ precipitate utilizing ethanol and DI H_2O . The resulting solution dehydrated at 60°C for Over 24h, then grounded into a fine powder. The fabrication procedure can be seen in Scheme I.

2.5 Physical analysis

X-ray Diffraction (XRD, Advanced Bruker D8) spectroscopy with a Copper-K α lamp was imposed to analyze the crystalline structure of materials. Similar peaks were observed at 2θ angles ranging from 10° to 70° . Fourier transform infrared spectroscopy (FTIR, ASCO-6800) was utilized to recognize chemical bonds and functional groups in the generated molecules. Thermogravimetric analysis (TGA, DTG-60H) was carried out using equipment at temperatures ranging from $25\text{--}800^\circ\text{C}$. The Nova 2200e Quantachrome apparatus was used to quantify material surface area using the Brunauer-Emmett-Teller (BET) technique. This was accomplished by vacuuming the samples for an hour at 300°C before measuring nitrogen adsorption-desorption isotherms at 77 K.

2.6 Electrode fabrication

The fabrication of electrode material began with cleaning nickel foam (NF, $1 \times 1 \text{ cm}^2$) pieces with ethanol and DI H_2O . After cleaning, the NF had been dehydrated for three hours at 60°C inside an oven. For working electrode, a slurry as created by mixing pre-manufactured materials, PVDF (a chemical binding agent), and activated carbon, which operated as a conductive additive, in an 80:10:10 ratio, respectively. The previously cleaned NF was covered with the produced electro-catalytic ink via drop-casting, then dry at 60°C for a further 6 hours.

2.7 Electrochemical characterization

Electrochemical studies, including cyclic voltammetry (CV), galvanostatic charge/discharge (GCD), electrochemical impedance spectroscopy (EIS), and chronoamperometry (CA), have been evaluated utilizing a workstation (Corrtest-CS 350M). In three-electrode setups, the counter electrode was made of a graphite rod, the reference electrode used Ag/AgCl, and the working electrode was pre-fabricated materials. The electrolyte liquid contained a 3 M KOH solution. CV data were obtained within a potential window of 0-0.5 V at $5\text{--}50 \text{ mV s}^{-1}$. CV was used to examine redox characteristics and C_s of the produced electrodes. C_s of the material was determined using equation [1].

$$C_s = \frac{\int_{v1}^{v2} I \times dV}{m \times S \times \Delta V} [1]$$

Likewise, GCD tests were conducted at current density (J_d) between 1–3 A g⁻¹ for each electrode to C_s , E_d , and P_d are calculated using equations [2], [3], and [4], respectively.

$$C_s = \frac{I \times \Delta t}{m \times \Delta V} [2]$$

$$E_d = \frac{C_s \times \Delta V^2}{7.2} [3]$$

$$P_d = \frac{3600 \times E_d}{\Delta t} [4]$$

EIS experiments were used to estimate solution resistance (R_s) and charge transfer resistance (R_{ct}) at 0.5V as well as frequency ranges of 0.01 to 100 kHz. Additionally, CA was used for 30 hours at 0.45 volts.

Results and discussions

3.1 Physical performance

XRD analysis was conducted to confirm the crystalline structure and phase composition of manufactured material. $MnCo_2O_4$ diffraction peaks were recorded at 2θ values 18.5°, 30.8°, 36.03°, 44.2°, 58.3°, and 64.0° corresponding to planes (111), (220), (311), (400), (511), and (440) as shown in Figure (1a). $MnCo_2O_4$ /g-CN nanoparticles demonstrating the development of a face-centered cubic structure (Fd-3m) show a crystalline form, with the highest intensity peak at 36.03° (311), which is consistent with standard JCPDS Card No. 00-023-1237 [29, 30]. XRD investigation showed that the synthesized material crystallizes in a cubic lattice with unit cell parameters of $a = b = c = 8.269$ Å and interaxial angles $\alpha = \beta = \gamma = 90^\circ$, confirming its high structural symmetry and cubic phase purity. While g-CN exhibited a distinctive single diffraction peak at 27.23°, corresponding to plane (002) [31]. XRD pattern of $MnCo_2O_4$ /g-CN and pristine confirmed that all diffraction peaks were clearly determined. The formation of g-CN's distinctive diffraction peak confirmed its effective incorporation into the composite, with no observable impurity phases. The prominent and well-defined peaks associated with each constituent demonstrate the crystalline purity of the $MnCo_2O_4$ /g-CN nanocomposite.

FTIR analysis can be utilized to identify the nature of bonding and different materials functionalities group in a sample, as shown in Figure (1b) by measuring the vibrational energy level of molecules that are fundamentally within the fingerprint area of distinct molecules. The FTIR spectrum of $MnCo_2O_4$ ranges from 400 to 4000 cm⁻¹. The FTIR spectra confirm this, displaying M-O vibrations at 543 cm⁻¹ (Mn-O) and 659 cm⁻¹ (Co-O). The compound's purity is demonstrated by more bands at 790 cm⁻¹ (triazine units), 1708 cm⁻¹ (C = N stretching), 3201 cm⁻¹ (-OH stretching), and 3417 (N-H stretching) [32, 33]. XRD results of $MnCo_2O_4$ /g-CN remain in good alignment with this FTIR investigation.

TGA analysis has been used to investigate thermal characteristics of materials. Figure 2(a) displays the TGA results for MnCo₂O₄/g-CN nanohybrid. MnCo₂O₄/g-CN hybrid's TGA curve indicates a minor weight reduction at temperatures lower than 150°C, ascribed to desorption of adsorbed moisture or interlayer molecules of water [34]. The weight loss noted in the 280–330°C range is likely attributable to the initial disintegration of the g-CN structure, which entails the cleavage of C-N bonds and subsequent structural collapse. The third and largest weight loss, about 470–560°C, is attributable to the degradation of the g-CN polymeric backbone, marking the collapse of triazine units and considerable weight loss [35, 36]. MnCo₂O₄ spinel structure is thermally stable, with no substantial weight changes over 600°C.

BET analysis has been employed for estimating specific surface area and porosity in MnCo₂O₄/g-CN composite, as displayed in Figure (2b). The BET surface area of the generated electrode material was examined utilizing N₂ adsorption-desorption isotherms at 77 K. The N₂ adsorption-desorption isotherms show a type-IV plot through different hysteresis loops, demonstrating the existence of mesoporous structures. Such a mesoporous framework allows for fast passage of electrolyte ions, which improves material's overall electrochemical efficiency [37]. The MnCo₂O₄/g-CN nanocomposite has a greater BET specific surface area (113 m² g⁻¹). This is owing to the layered g-CN structure, which increases porosity and reduces particle agglomeration. MnCo₂O₄ nanoparticles are evenly distributed on stacked g-CN material, preventing agglomeration and exposing more electroactive sites. This synergistic architecture improves ion diffusion and charge transfer, yielding higher pseudocapacitive performance than the separate components [38, 39].

3.2 Electrochemical Performance

CV tests were conducted to study the charge storage capability for MnCo₂O₄, g-CN, and MnCo₂O₄/g-CN through three-electrode arrangement with 3 M KOH electrolyte at scan speed ranging from 5 to 50 mV s⁻¹ across voltage range of 0-0.5 V, as shown in Figure (3a-c). Electrodes showed pseudocapacitive characteristics (Fig. 3a, c), including the presence of a redox peak from MnCo₂O₄ nanoparticles. The redox peak levels of electrode CV plots move toward increased anodic and decreased cathodic potentials as the scan rate rises. This change was induced by the interior resistance and complex dispersion channel of H⁺ ions within electrodes [40]. MnCo₂O₄/g-CN electrode has a greater redox peak than the g-CN and MnCo₂O₄ electrodes of the supercapacitor. MnCo₂O₄/g-CN supercapacitor electrode demonstrated amalgamation sites compared to MnCo₂O₄ and g-CN supercapacitor electrodes (Fig. 3c) at 5 mVs⁻¹. The MnCo₂O₄/g-CN supercapacitor electrode demonstrated electrochemical energy-storing capabilities. Figures (3c) shows that CV plots of MnCo₂O₄/g-CN supercapacitor were more symmetric, indicating a more extensive reversible process at the electrode. At redox peak values, the following reactions occurred: [41, 42].



MnCo₂O₄ exhibits pseudocapacitive behavior through reversible surface redox reactions involving Co and Mn active centers. The alkaline electrolyte's OH⁻ ions promote rapid Faradaic charge transfer, resulting in higher C_s [42]. The anode (I_{pa}) and cathode (I_{pc}) maximum currents of MnCo₂O₄/g-CN nanohybrids rise with scan rate as shown in Figure (3d), and their R² values (0.978 and 0.989, correspondingly) evaluated using linearly fitted. The C_s of every material falls with higher sweep rates, since ions have limited time to integrate towards the core of each electrode. According to test results, C_s of MnCo₂O₄, g-CN, and MnCo₂O₄/g-CN nanohybrids obtained 387.7, 672.3, and 855.4 F g⁻¹, accordingly as shown in Figure (3e). Thus, superior C_s of the composite material is notably greater compared to the pristine material; this may be related to the synergistic interaction, enhanced charge transfer, as well as improved electrolyte ion diffusion.

Figure 5(a-c) shows GCD plots for MnCo₂O₄, g-CN, as well as MnCo₂O₄/g-CN nanohybrid at 1–3 A g⁻¹ and 0–0.5 V (Ag/AgCl), correspondingly. A GCD test has been utilized to examine sample's capacity to store electrochemical energy at varied J_d levels (1–3 A g⁻¹). MnCo₂O₄/g-CN SC_s electrode's discharge duration was noticeably superior to both g-CN and MnCo₂O₄ electrodes of SC_s at equivalent charge and discharge currents. The MnCo₂O₄/g-CN material exhibits considerably higher energy storage capacity than the pristine material. C_s of all materials with various J_d (1–3 A g⁻¹) are displayed in Fig. 4d. Due to greater internal resistance and a shorter ion transport time to the electrode's surface, C_s of synthesized electrode fell since J_d increased [20]. The C_s of MnCo₂O₄/g-CN was 1125.2 F g⁻¹ at 1 A g⁻¹, pristine MnCo₂O₄ exhibited a lower C_s value, 664.1 F g⁻¹ at 1 A g⁻¹, and the C_s of g-CN calculated 875.9 at 1 A g⁻¹. MnCo₂O₄/g-CN combination outperforms at all higher J_d levels. Furthermore, Ragone plot demonstrates the association between E_d and P_d, with E_d decreasing as P_d increases, as illustrated in Figure (4e). MnCo₂O₄/g-CN exhibits an E_d value of 25 Wh kg⁻¹ and P_d value of 200 W kg⁻¹, respectively. Although pristine MnCo₂O₄ has a lower E_d value, 11.95 Wh kg⁻¹, and P_d value 180 W kg⁻¹ at 1 A g⁻¹, and g-CN has an E_d of 17.5 Wh kg⁻¹, as well as P_d value 190 at 1 A g⁻¹ determined (Eq. 3–4). The g-CN framework increased the redox kinetics, ion transport, power performance, and charge collection efficiency of the MnCo₂O₄/g-CN composite, resulting in greater E_d at higher P_d [43]. MnCo₂O₄/g-CN nanohybrids have higher C_s, rate performance, and thermal durability. The result is because of the successful integration of g-CN with MnCo₂O₄, which enhances SSA as well as conductivity. Table 1 represents a comparison of C_s for g-CN-based nanomaterials.

Table 1
Comparative C_s of $MnCo_2O_4/g-CN$ electrodes via previously fabricated g-CN nanohybrid

Sr. No.	Materials	J_d ($A\ g^{-1}$)	C_s ($F\ g^{-1}$)	Electrolyte (KOH)	Reference
1	$NiCo_2O_4/g-CN$	1	1127	6 M	[26]
2	$ZnFe_2O_4/g-CN$	1	103	6 M	[44]
3	$MnAl_2O_4/g-CN$	1	1161	2 M	[45]
4	$FeAl_2O_4/g-CN$	1	1049	3 M	[46]
5	$CuMnO_2/g-CN$	0.025	817.85	0.5 M	[47]
6	$BiFe_2O_3/g-CN$	1	1164	2 M	[48]
7	$NiAl_2O_4/g-CN$	1	768	3 M	[49]
8	$CoFe_2O_4/g-CN$	2	157.5	2 M	[50]
9	$MnCo_2O_4/g-CN$	2	654	6 M	[28]
10	$MnCo_2O_4/g-CN$	1	1125.2	3 M	Present Work

EIS is an electrochemical technique aimed at assessing characteristics of electrochemical energy-storage devices. The Nyquist plots for $MnCo_2O_4$, g-CN, and $MnCo_2O_4/g-CN$ as shown in Figure (5a). The solution resistance (R_s) is the x-axis point of contact that represents the resistance between electrode and electrolyte. Presence of semi-circle impedance plots is typically attributed to resistance charge transfer (R_{ct}), which occurs throughout the electrode material at higher frequency ranges. Compared to $MnCo_2O_4$ and g-CN electrodes, $MnCo_2O_4/g-CN$ electrode exhibits a steeper linear curve at lower frequency ranges. Evaluations of EIS show R_{ct} values of 1.89 ($MnCo_2O_4$), 1.83 (g-CN), and 1.68 Ω ($MnCo_2O_4/g-CN$), indicating enhanced charge-transfer properties of the nanohybrid. The R_{ct} values for $MnCo_2O_4$, g-CN, and $MnCo_2O_4/g-CN$ were 0.09, 0.084, and 0.07 Ω , respectively. This result indicated $MnCo_2O_4/g-CN$ nanomaterial had greater conductivity than the pure $MnCo_2O_4$ and g-CN materials. Using EIS reduced electrochemical impedance, indicating improved electron mobility in the $MnCo_2O_4/g-CN$ composite.

The electrochemical durability exhibited by the $MnCo_2O_4/g-CN$ electrode was identified using CA at 0.45 V, as seen in Fig. 5(b). CA study demonstrated the electrode's outstanding electrochemical performance and exceptional durability, with a constant current response even after 30 hours of continuous operation. Fast charge movement, along with efficient transfer of ions, is made feasible by the addition of several active sites and increased electrode interface, which improves dependability. Such functional properties

demonstrate the electrode's morphological stability, enhanced redox kinetics, and suitability for long-term energy storage uses.

Conclusion

This research employed a hydrothermal process to assess the potential applications of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ composites as novel electrode materials for SCs in energy storage. To describe the materials synthesized, the SSA of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ was examined using the BET method. The $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanohybrid electrode has a C_s of 1125.2 F g^{-1} as compared to pure MnCo_2O_4 664.1 F g^{-1} at 1 A g^{-1} via GCD study. Furthermore, it takes a low R_{ct} of 0.07Ω and can sustain over 30 hours. Thus, the functionalization of g-CN within the MnCo_2O_4 scaffold significantly improved overall electrochemical characteristics. The use of g-CN improves ion transport by significantly increasing the electrode's SSA. The electrochemical results given in current research revealed that the use of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ electrodes has tremendous promise for a variety of energy storage uses. This study offers ideas for creating novel electrode materials for the next-generation SCs that are more efficient and stable over time.

Declarations

Declarations

Compliance with ethical standards

Yes, this article compliance with ethical standards of journal

Competing interests

There is no conflict of interest in any form for this manuscript

Conflict of Interest

The authors declare that they have no conflict of interest.

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Author Contribution

Aman Ullah wrote the main manuscript text, Ali prepared the figures, Samira prepared the graph, and Reda perform electrochemical data.

Data Availability statements

Data will be available on reasonable request.

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Scheme 1

Scheme 1 is available in the Supplementary Files section.

Figures

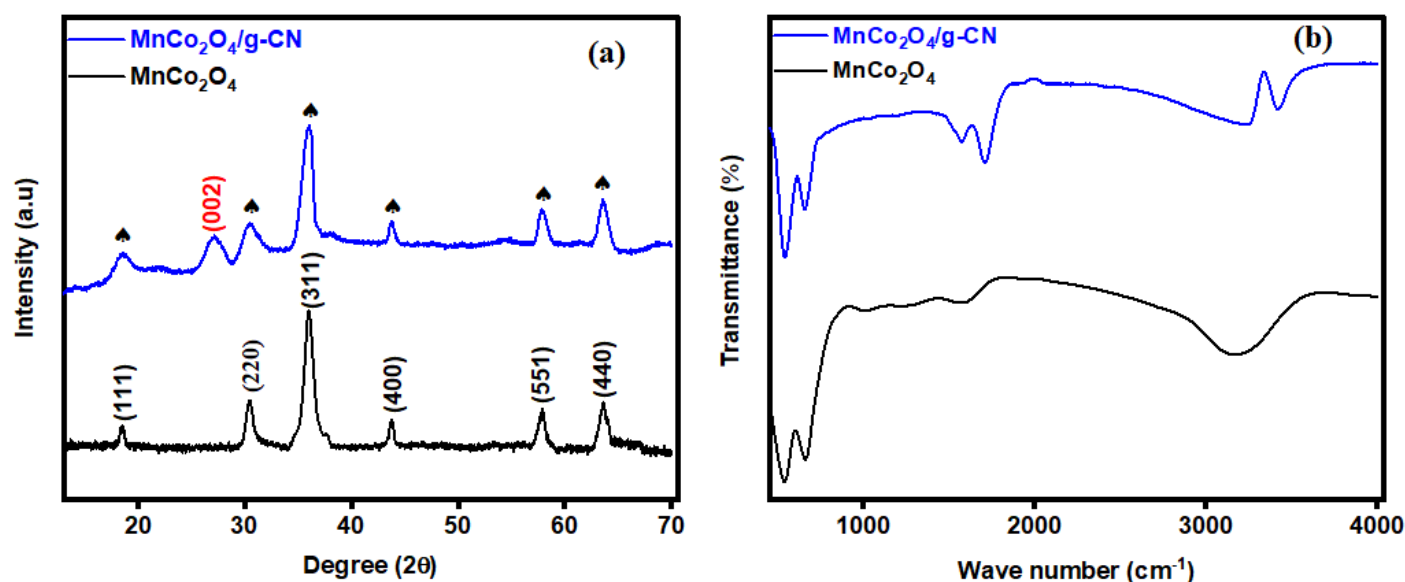


Figure 1

(a) XRD spectrum of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ (b) FTIR spectrum of $\text{MnCo}_2\text{O}_4/\text{g-CN}$

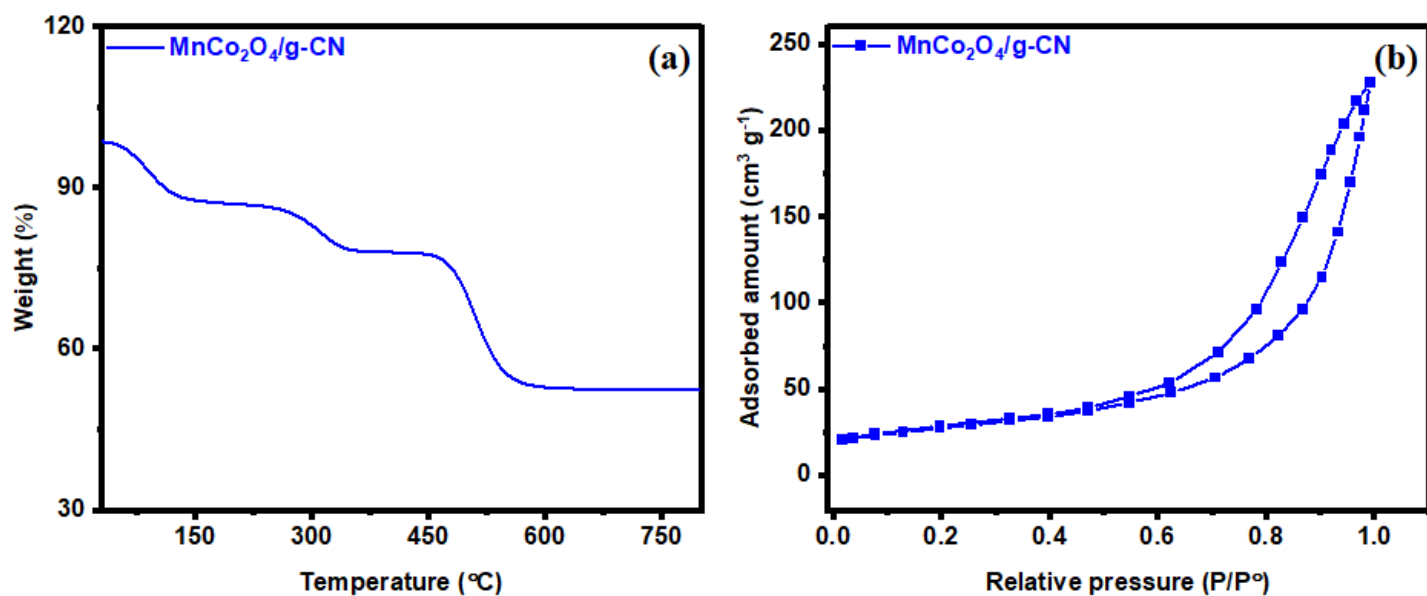


Figure 2

(a) TGA of $\text{MnCo}_2\text{O}_4/\text{g-CN}$, (b) BET of $\text{MnCo}_2\text{O}_4/\text{g-CN}$ nanohybrid

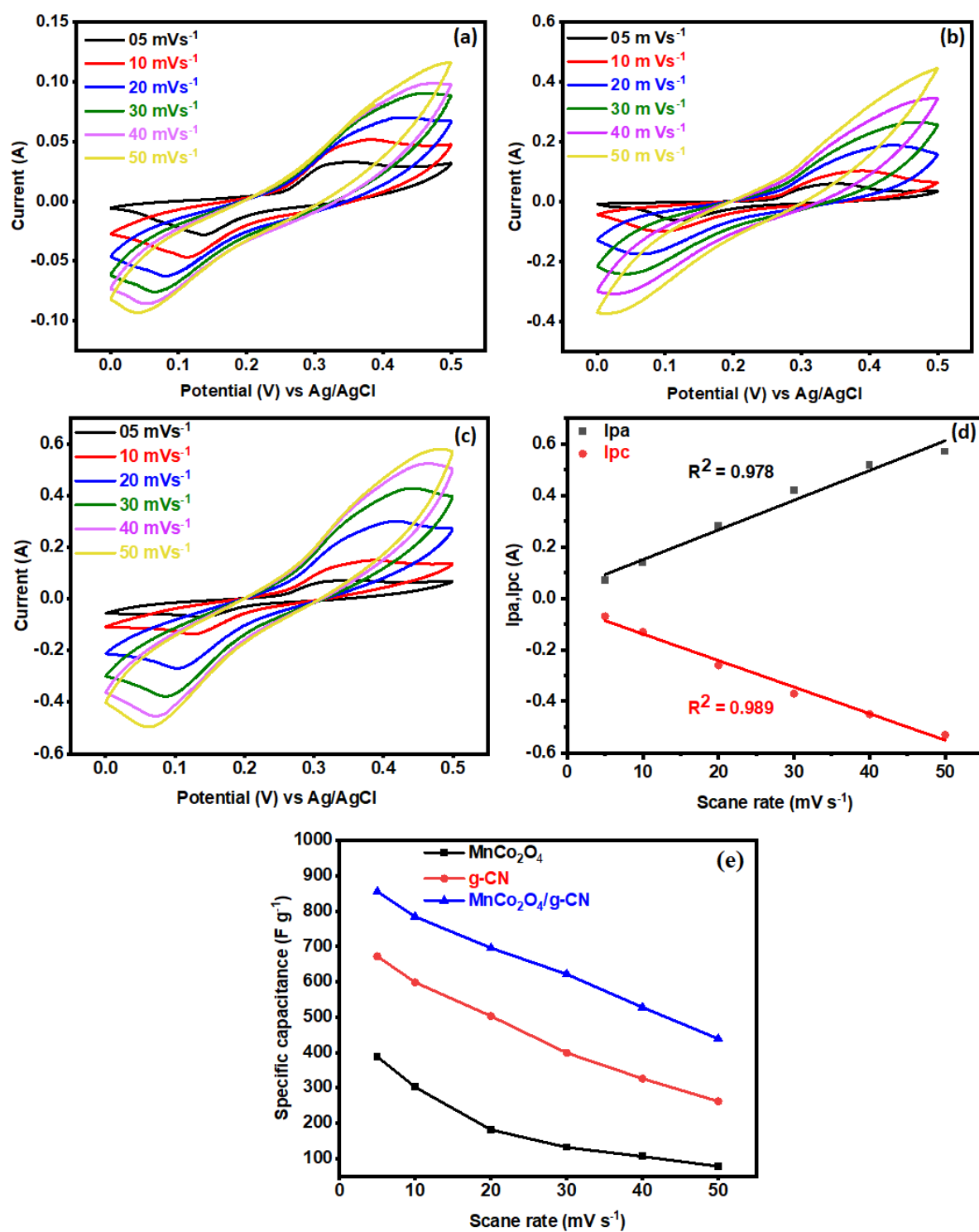


Figure 3

CV plots for (a) MnCo₂O₄, (b) g-CN, as well as (c) MnCo₂O₄/g-CN at 5-50 mVs⁻¹, (d) I_{pa} and I_{pc} peaks currents vs scan rate, and (e) C_s vs all materials' scan rates

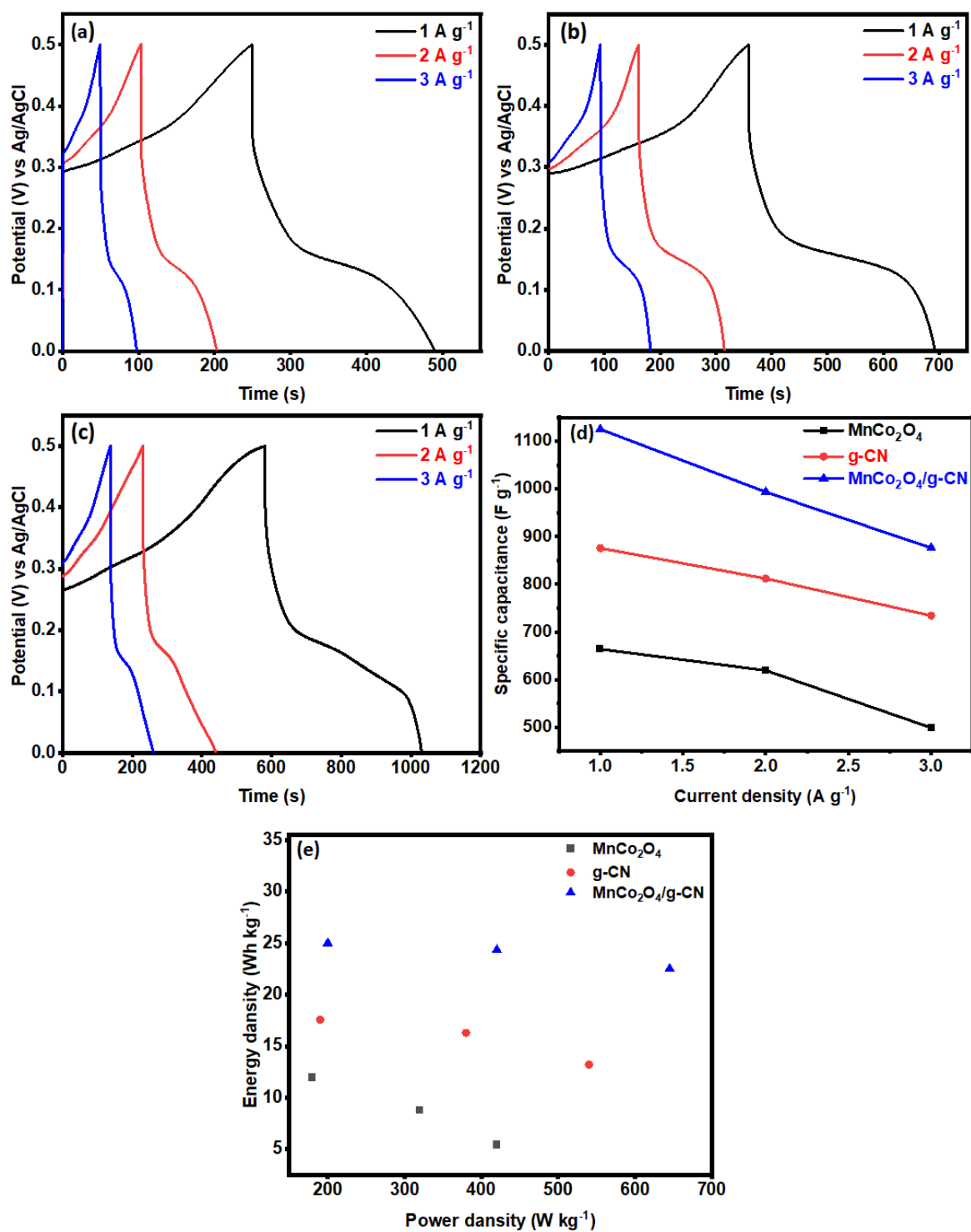


Figure 4

GCD plots for (a) MnCo_2O_4 , (b) g-CN , and (c) $\text{MnCo}_2\text{O}_4/\text{g-CN}$ at 1-3 A g^{-1} (d) J_d vs. C_s value of all materials, as well as (e) P_d vs E_d value of all materials

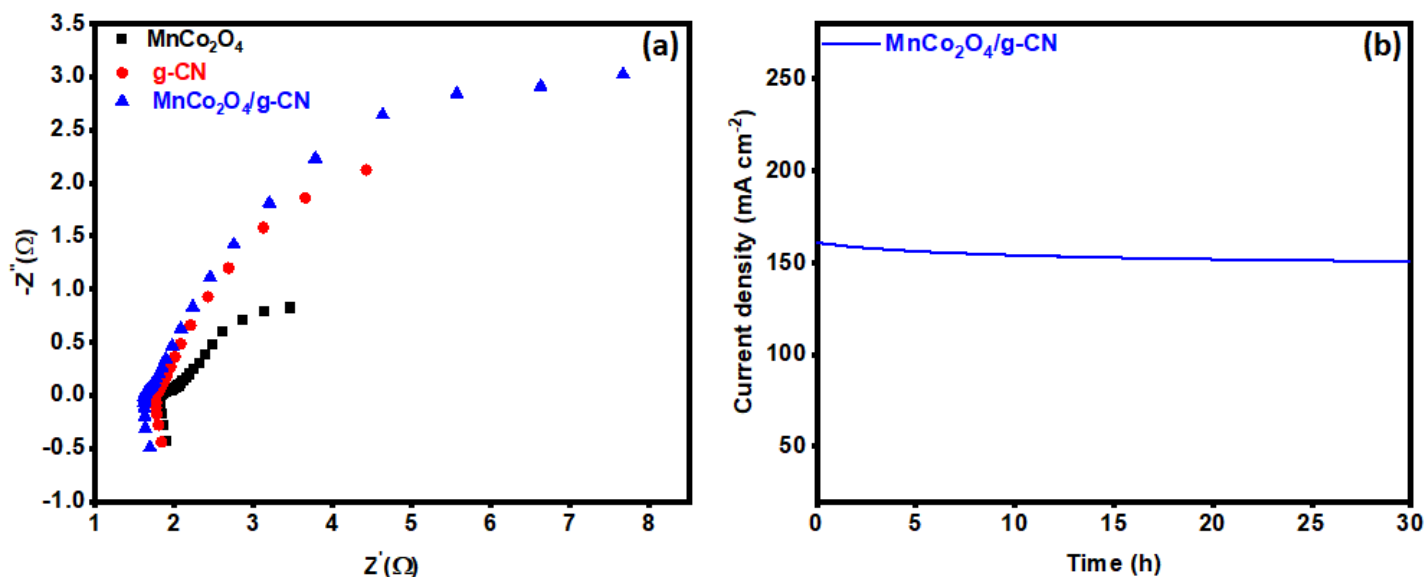


Figure 5

(a) EIS for MnCo_2O_4 , g-CN, and $\text{MnCo}_2\text{O}_4/\text{g-CN}$, (b) Chronoamperometry of $\text{MnCo}_2\text{O}_4/\text{g-CN}$

Supplementary Files

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