

ISSN 2250-2653



Research Fronts

A Peer-Reviewed Journal of Multiple Sciences, Arts and Commerce



Volume: XII 2026

Publisher: Govt. Digvijay Autonomous Postgraduate College Rajnandgaon
(Chhattisgarh), India 491441

Funded by: Autonomous Examination Cell of the Publisher

ISSN 2250-2653

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RESEARCH ARTICLE

Synergistic Ion-Storage Mechanisms in NiCo_2O_4 -*Typha angustifolia* Activated Carbon Hybrid Material for Next-Generation Supercapacitors

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ABSTRACT

We report the design, synthesis, structural and electrochemical characterization of a NiCo_2O_4 (NCO) — activated carbon (AC) hybrid electrode tailored to exploit synergistic ion-storage mechanisms arising from combined pseudocapacitive Faradaic reactions of NiCo_2O_4 and electrical double layer capacitance (EDLC) of activated carbon. The composite was fabricated by a controlled hydrothermal growth of NiCo_2O_4 nanostructures onto high-surface-area activated carbon followed by thermal activation. Comprehensive structural (XRD), morphological (SEM), and electrochemical (CV, GCD, EIS) analyses were performed. The hybrid electrode demonstrates improved rate capability, enhanced specific capacitance retention at high current densities, and superior cycling stability in asymmetric full devices compared to pristine NiCo_2O_4 or activated carbon electrodes. The device exhibited highest specific capacitance of 332.5 F/g at 1 A/g. Also, we got 28.67 Wh/kg energy density at 400 W/kg power density. The manufactured device exhibited good rate capacitance of 94.06 % for 5000 cycles. The study provides a pathway for hybrid electrode engineering toward high-power, durable supercapacitors.

Keywords: NiCo_2O_4 , activated carbon, hybrid electrode, supercapacitor, energy storage.

Manuscript history: Received 27-02-2026, Revision Initiated 12-03-2026, Revised & Accepted 29-03-2026
Published 30-03-2026

How to cite: Patel A, Patel SK, Singh RS. Synergistic ion-storage mechanisms in NiCo_2O_4 -*Typha angustifolia* activated carbon hybrid material for next-generation supercapacitors. Research Fronts. 2026;XII:1–13.

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1. Introduction

During a video call to her son working abroad, a housewife Anjani found that her phone was indicating low battery. But she can't charge the phone at that time. She wished if she could charge the phone within minutes and continue the conversation. Her problem can be solved by supercapacitor (electrochemical capacitors) as energy storage device in the phone. Electrochemical energy storage demands devices that combine high power density, long cycle life, and moderate energy density. Supercapacitors occupy the middle ground between batteries and conventional capacitors, and two principal storage modalities are recognized: electrochemical double layer capacitance (EDLC) and pseudocapacitance [1]. EDLCs store charge electrostatically at the electrode-electrolyte interface through a non-Faradaic mechanism. The electrode stores energy through a rapid ion adsorption-desorption process, contributing to high power density. In contrast, pseudocapacitors rely on rapid faradic redox reactions, involving the insertion and extraction of electrolyte ions on the electrode. The battery-type positive electrode stores energy through swift redox reactions, promoting high capacitance and cyclic stability. Materials such as activated carbons, graphene oxides (GOs), reduced graphene oxides (rGOs), and carbon nanotubes (CNTs) are used as EDLC-type electrodes in supercapacitors, demonstrating high power densities (approximately 15 kW/kg) [2]. However, these EDLC-type materials often exhibit poor energy density, limiting their application as advanced storage devices. Pseudocapacitive materials include conducting polymers (CPs), transition metal oxides (TMOs), transition metal sulfides, transition metal phosphides, and transition metal hydroxides. While these materials show promise as supercapacitor electrode materials, their application is constrained by factors such as toxicity and high cost. Some TMOs suffer from low specific capacitance, and CPs face challenges related to lower cyclic stability [3].

Contemporary research emphasizes hybrid supercapacitors, wherein one electrode is of the EDLC type, and the other is pseudocapacitive. This hybrid configuration amalgamates the characteristics of both EDLC materials and pseudocapacitive materials. There are two main types of hybrid supercapacitors: symmetric hybrids, where both the negative and positive electrodes are composed of the same material, and asymmetric hybrids, where the positive and negative electrodes are constructed from different materials. Typically, carbon-based materials are employed as the negative electrode, while transition metal oxides (MOs) or conducting polymers (CPs) serve as the positive electrode [4]. Nanostructured transition metal oxides (TMOs) are extensively utilized as positive electrodes in hybrid supercapacitors due to their favorable properties, including multiple oxidation states and high electrochemical performance. However, TMOs often exhibit suboptimal cycling performance because the electrode material may collapse during the charging/discharging process or undergo irreversible structural deformation [3].

NiCo₂O₄ has emerged as a leading TMO for pseudocapacitive electrodes because of its mixed valence and rich redox chemistry leading to high specific capacitance; however, NiCo₂O₄ alone often suffers from limited electrical conductivity at scale, structural changes on cycling, and limited rate

performance. Complementary carbonaceous materials (activated carbon, graphene, CNTs) are frequently combined with NiCo_2O_4 to realize hybrid electrodes that leverage EDLC for fast ion access and TMOs for high capacitance. Recent reviews and experimental studies highlight the benefit of NiCo_2O_4 –AC hybrids in improving conductivity, structural stability, and rate performance [5].

A supercapacitor comprises several essential components, including a substrate, electrode material, separator, and electrolyte. The overall performance of the supercapacitor is influenced by the collective effects of these components, with the electrode material playing a pivotal role. To address the challenges outlined earlier, a potential solution involves shifting towards the broader use of bio-based resources for the preparation of supercapacitor materials [6]. Consequently, the research community has focused on exploring pathways for fabricating supercapacitor components, including electrodes and gel-electrolytes, from bio-based materials. Numerous studies have already highlighted the successful fabrication of carbon electrodes derived from biomass and their applications in supercapacitors [7].

This work focuses on the deliberate engineering of NiCo_2O_4 and *Typha Angustifolia* activated carbon (NCO/TAC) hybrids, optimized to maximize the synergy between Faradaic (Ni/Co redox) and non-Faradaic (EDLC) mechanisms. We aim to synthesize a conformal, high-surface-area NCO nanostructure and activated carbon composite; comprehensively characterize structure, surface, and chemistry; quantify the separate contributions of pseudocapacitance and EDLC; and demonstrate full-cell performance in an asymmetric configuration and analyze durability. Prior reports show big performance improvements for NiCo_2O_4 /carbon hybrids but the explicit mechanistic separation and design rules for activated carbon composites remain underdeveloped.

2. Experimental Techniques

2.1 Materials

Nickel nitrate hexahydrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, reagent grade), Cobalt nitrate hexahydrate ($\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$, 99.9%), Urea ($\text{CO}(\text{NH}_2)_2$, 99%) and Citric acid (99%) were purchased from Sigma-Aldrich, while conductive carbon black (Super P) and polyvinylidene fluoride (PVDF) were obtained from Merck. Potassium hydroxide (KOH, 85%), hydrochloric acid (HCl), ethanol, deionized water and nickel foam were purchased from Finar Chemicals. Solutions were prepared using ethanol, and deionized water, while acetone was employed for washing the chemicals at various stages of the process. All chemicals utilized in the experiment were of analytical grade and were used without any additional purification.

2.2. Synthesis of NiCo_2O_4 nanoparticles

The synthesis procedure commenced with the dissolution of 1 mmol of $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and 3 mmol of $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ in 5 mL of ethanol, with vigorous stirring for 5 minutes resulting in a light pink solution. Subsequently, 6 mmol of citric acid and 12 mmol of urea were added to the dispersion, followed by stirring for 0.5 hours at 25 °C. The dispersion was then transferred to 50 ml Teflon-lined

stainless-steel autoclave. The autoclave was put into the hot air oven and hydrothermally treated at 120 °C for 12 h. After the reaction, the prepared material was washed multiple times with DI water and ethanol and then dried for another 12 h at 80 °C inside a vacuum oven. Finally, after a subsequent 12-hour period, the obtained precursor (named as NCO) underwent calcination in a muffle furnace at 350 °C for 3 hours in an air atmosphere [8]. The final NiCo₂O₄ nanoparticles emerged after gradual cooling to room temperature.

2.3. Synthesis of Activated Carbon

The fully developed *Typha Angustifolia* leaves were gathered from a village in Durg, Chhattisgarh, India and were employed in the production of activated carbon. Initially, the Typha leaves were isolated, immersed in deionized water (DI) for a duration of 24 hours, and thoroughly rinsed in DI water multiple times to eliminate surface-bound impurities. Afterward, the cleaned leaves were dried at 120 °C for 18 hours and finely powdered using an electric blender. The resulting fine powder was dispersed in weight ratio 1:2 of KOH solution, followed by solvent evaporation. Subsequently, the dried mixture underwent carbonization under an Ar atmosphere at 800°C for 2 hours, employing an optimized condition with a heating rate of 10 °C per minute [9]. Finally, the resulting activated carbon samples were immersed in a dilute HCl solution, washed repeatedly in DI water until achieving a neutral pH, and left to dry overnight. The synthesized 1:2 activated carbon sample was designated as TAC.

2.4. Preparation of composite NCO/TAC nanoparticles

Composite NCO/TAC was prepared by simply mixing NiCo₂O₄ (NCO) and *Typha Angustifolia* derived activated carbon (TAC) in 1:1 mass ratio and grinding it with the help of mortar and pestle for 30 minutes. The composite powder, carbon black (Super P) and binder (PVDF) were taken into 8:1:1 mass ratio and mixed properly. Ethanol was used to mix all the chemicals and the slurry was directly coated onto a Nickle foam. The average mass loading was between 2-5 mg/cm.

2.5. Materials Characterization

To examine the crystalline nature of the activated carbon and metal cobaltite (TAC), the samples underwent characterization through powder X-Ray diffraction (XRD) using X'Pert³ MRD with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) at a scanning rate of $0.02^\circ \text{ s}^{-1}$ over a 2θ range of 10° to 80° . Raman spectroscopy was conducted using an alpha 300R confocal Raman imaging microscope (WITec, Germany) equipped with a 633 nm laser as the excitation source. Fourier transform infrared (FTIR) spectral analysis was conducted to identify the functional groups present in the NCO, TAC and NCO/TAC samples using a SHIMADZU FTIR-8400S spectrometer in the wavenumber range of 500 to 4000 cm^{-1} . Additionally, the microstructures and surface morphologies of the samples were examined using a scanning electron microscope (FE-SEM, ZEISS Sigma (300) equipped with energy-dispersive X-ray spectroscopy (EDAX)).

Electrochemical characterizations (Cyclic voltammetry, galvanostatic charge discharge and electrochemical impedance spectroscopy) were performed using Autolab PGSTAT302N. directly two

electrode system was used to evaluate the electrochemical performance of the device. 2 M KOH aqueous electrolyte was used.

3. Results and Discussion

3.1. Phase and structural analysis (XRD)

The XRD analysis of the NiCo₂O₄ revealed characteristic diffraction peaks at 2θ angles of 19.06° , 31.51° , 37.12° , 45.18° , 55.75° , 59.61° , and 65.42° , corresponding to the (111), (220), (311), (400), (422), (511), and (440) planes, respectively. These planes are characteristic of the cubic NiCo₂O₄ spinel structure (JCPDS No. 20-0781). Absence of any other specific peaks or noise indicates the high purity of the synthesized NCO sample. The XRD pattern of TAC activated with KOH at 750°C temperature with an alkali-carbon ratio of 3 contains the characteristic diffraction peaks are found approximately at 24.16° and 42.5° 2θ corresponding to (002) and (100) planes [10].

As shown by the red pattern in Figure 1a, XRD pattern of the composite shows characteristic diffraction peaks of spinel NiCo₂O₄ (space group Fd-3m) superimposed on the broad amorphous peak of activated carbon. The XRD pattern in Figure 1a shows that the diffraction peaks of the NCO/TAC composite are noticeably broader than those of pristine NiCo₂O₄, indicating reduced crystallinity. The characteristic TAC peak near 24° is not detected due to the relatively low content of carbon and its uniform distribution within the composite. The lack of extra diffraction peaks further confirms the high phase purity of the NCO/TAC product. Scherrer analysis (with peak indexing) provides an estimate of crystallite size, approximately 23 nm. Residual carbon signal confirms TAC preservation at optimized calcination temperatures. Representative evidence in NiCo₂O₄/carbon hybrids has been reported in multiple studies [11].

3.2. Fourier transform infrared spectroscopy (FTIR)

Figure 1b displays the FT-IR spectra of NCO/TAC composite. The FTIR spectra of the calcined NiCo₂O₄ nanoparticles, exhibit two strong absorption bands in the regions of 616 cm^{-1} and 550 cm^{-1} . These bands correspond to the metal-oxygen stretching from tetrahedral and octahedral sites, respectively, which are characteristic of cobaltites. The spectra also reveal Co–O and Ni–O vibrations of the NiCo₂O₄ samples, along with a signal corresponding to the OH group [12]. The TAC spectrum, the broad absorption band in the range of $3300\text{--}3600\text{ cm}^{-1}$ is attributed to O–H stretching vibrations associated with hydroxyl groups from –COOH or adsorbed H₂O. The prominent peak at approximately 2944 cm^{-1} corresponds to C=O stretching vibrations of oxygen-containing functional groups. The band near 1645 cm^{-1} is associated with carboxyl group stretching modes (–COOH and/or adsorbed water). In the spectrum of the NCO/TAC nanocomposite, the characteristic metal–oxygen stretching bands at $\sim 550\text{ cm}^{-1}$ and $\sim 616\text{ cm}^{-1}$ are clearly retained, along with absorption features in the $3300\text{--}3600\text{ cm}^{-1}$ region and near $\sim 1646\text{ cm}^{-1}$, confirming the successful integration of TAC with NiCo₂O₄ [13].

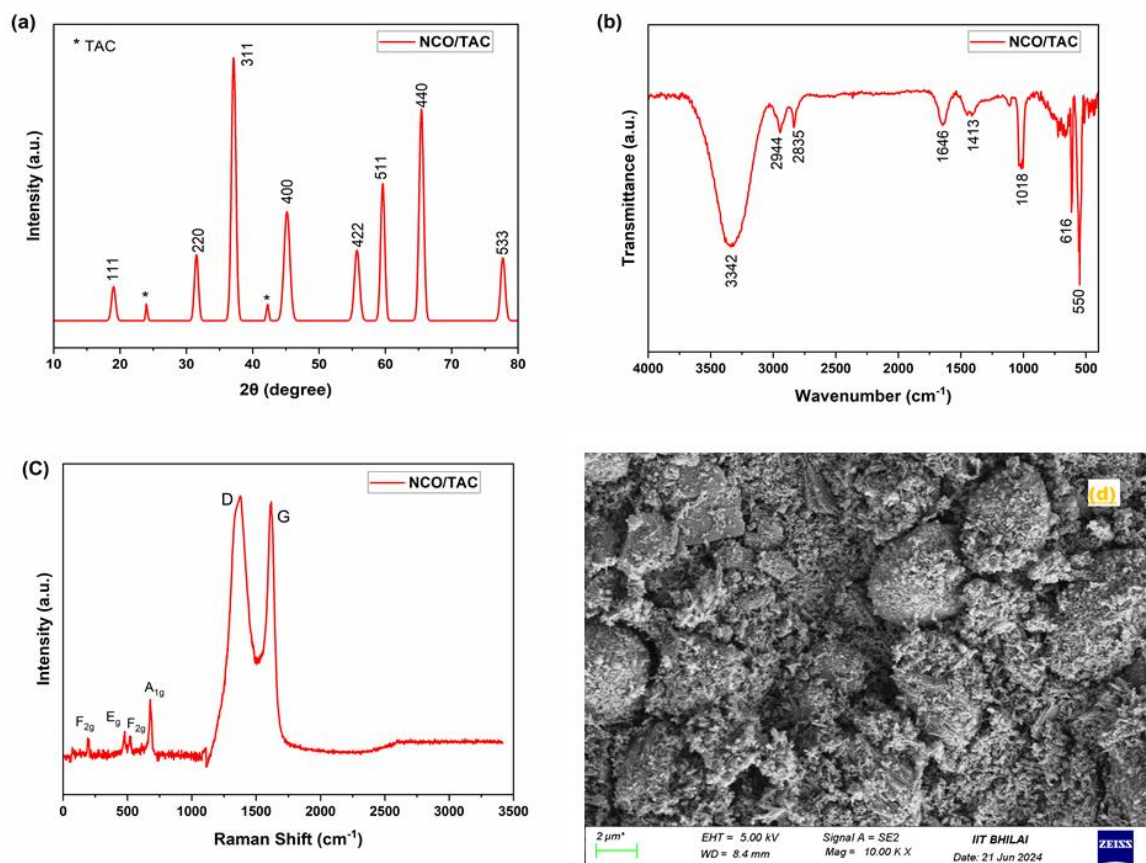


Figure 1. X-ray diffraction (XRD) patterns of the composite (NCO/TAC) nanoparticles (a), FTIR spectra (b) and Raman spectra of the composite (NCO/TAC) nanocomposites (c). FE-SEM image of the composite (d).

3.3. Raman spectroscopy

Raman spectroscopy was employed to further analyze the structural characteristics, particularly the degree of order/disorder and compositional features of the samples. Figure 1c presents the Raman spectra of NCO/TAC composite. The spectrum of TAC displays two distinct vibrational bands at approximately 1365 cm^{-1} and 1687 cm^{-1} , corresponding to the D band (A_{1g} breathing mode) and G band (E_{2g} mode of sp^2 -hybridized carbon), respectively [6]. The degree of graphitization and defect density was assessed by evaluating the intensity ratio (I_D/I_G) of these bands. The I_D/I_G ratio of NCO/TAC is lower than that of TAC, indicating a higher degree of structural defects and the partial restoration of graphitic domains upon compositing, in NCO/TAC. Additionally, the NCO/TAC spectrum exhibits a weak peak near 662 cm^{-1} , which is attributed to the characteristic vibrational modes of the NiCo_2O_4 spinel phase. Notably, both the D and G bands in the NCO/TAC composite exhibit a blue shift relative to TAC. This shift is likely associated with charge transfer interactions between TAC and NiCo_2O_4 nanoparticles, a phenomenon consistent with previous reports [14].

3.4. Morphology and microstructure (FE-SEM spectroscopy)

SEM images typically show NiCo_2O_4 nanospheres conformally grown on the TAC surface, forming a hierarchical porous network that retains TAC macroporosity while adding NCO nanoscale

pseudocapacitive sites. Conformal coverage without blocking mesopores is crucial for ion accessibility and EDLC contribution. The microstructural characteristics of the NCO, TAC and NCO/TAC samples were examined using FESEM. Figure 1d displays FESEM image of the as-synthesized NCO/TAC nanocomposite, which possess a uniform spherical morphology with an average diameter of approximately 500 nm. In the NCO/TAC composite where TAC nanosheets are observed to be uniformly covered by the NCO spheres and effectively interconnect the nanospheres [15].

3.5. Electrochemical performance

3.5.1. Electrode fabrication and cell assembly

Active material (NCO/TAC composite) mixed with 5 wt% PVDF and 10 wt% Super P in N-methyl-2-pyrrolidone (NMP), uniformly cast on nickel foam and dried. mass loading was 1–3 mg cm⁻² and this was used as working electrode. A platinum wire was used as counter electrode and Ag/AgCl (aqueous) was used as reference electrode. 2 M KOH (aqueous) was used as electrolyte. An asymmetric device was also assembled using NCO/TAC as positive and high-surface-area activated carbon (AC) with matching mass calculated by charge balance ($q^+ = q^-$) using capacitance and potential window. Operating voltage window was kept 0–0.8 V in 2 M aqueous KOH [7].

The specific capacitance (C_s) was determined from cyclic voltammetry (CV) data using the following equation:

$$C_s = \int \frac{IdV}{ms(V_2 - V_1)} \quad (1)$$

Where $\int IdV$ represents the integral area under the CV curve, m is the mass of active material deposited on the Ni-foam, s is the scan rate, and $(V_2 - V_1)$ denotes the applied potential window of the electrolyte. Similarly, the specific capacities, energy densities and power densities were calculated using the following equations:

$$C_s = \frac{I \times \Delta t}{m \times \Delta V} \quad (2)$$

$$Ed = \frac{C_s \times (\Delta V)^2}{7.2} \quad (3)$$

$$Pd = \frac{Ed \times 3600}{\Delta t} \quad (4)$$

Where C_s is the specific capacitance, Δt is the discharging time, m is the mass of the active material, ΔV is the potential window, Ed is energy density and Pd is power density [1].

The scanning rates of CV tests were 5, 10, 20, 50 and 100 mV/s performed in the voltage scope of 0 to 0.8 V. GCD experiments were carried out in the potential range of 0–0.8 V with current densities of 1, 2, 3, 4 and 5 A/g, respectively.

3.5.2. Cyclic voltammetry (CV)

The electrochemical properties of the NCO/TAC electrode were evaluated using a two-electrode configuration. Figure 2a presents the cyclic voltammetry (CV) profiles of the composite recorded at scan rates of 5, 10, 20, 50, and 100 mV/s in the negative positive potential range. The sample exhibited quasi-rectangular CV curve with noticeable humps between 0.7 and 0.2 V, indicating

the coexistence of electric double-layer capacitance (EDLC) and pseudocapacitive contributions. The more pronounced pseudocapacitive behavior observed in NCO/TAC suggests a higher degree of crystallinity relative to the other samples. The peaks in the 0.7 to 0.2 V region are likely associated with redox transitions involving $\text{Ni}^{2+}/\text{Ni}^{3+}$ and $\text{Co}^{2+}/\text{Co}^{3+}$ couples [16]. Increasing the scan rate from 5 to 100 mV/s induces a cathodic shift across the sample. Additionally, figure 2a shows the CV curves in the voltage window of 0 to 0.8 V, clearly demonstrating pseudocapacitive behavior in the positive region (0–0.8 V).

The specific capacitances of the electrode were calculated using Equation (1). Figure 2a summarizes the capacitance values at different scan rates. At 5 mV/s, the specific capacitance obtained was 435 F/g. The significantly enhanced capacitance of NCO/TAC arise from the conversion of hydroxides to oxides at higher calcination temperatures, thereby improving pseudocapacitive behavior and EDLC contribution. The cross-linked nanoflake morphology of NCO/TAC further promotes ion accessibility and charge storage. The capacitance values obtained in this study surpass those reported in our previous works involving biogas-derived mesoporous carbon and are comparable to other reported results [17].

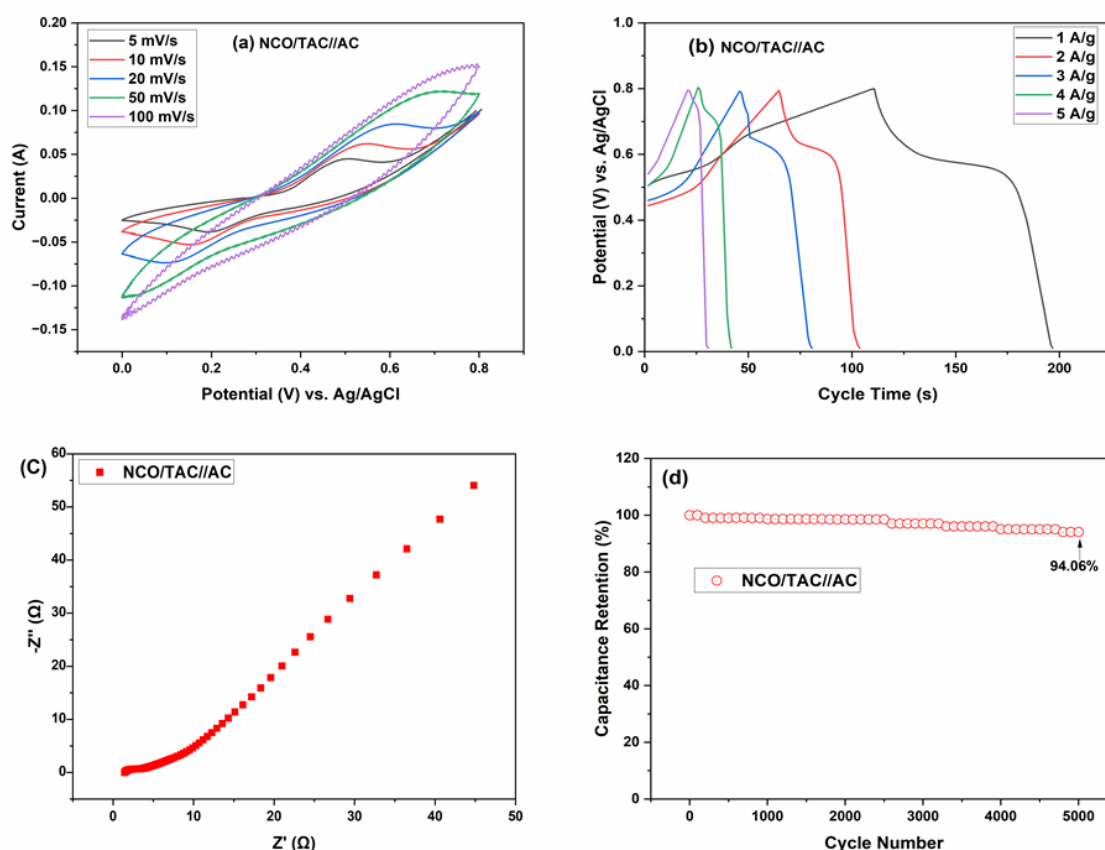


Figure 2. Cyclic voltammetry curves of the device for different scan rates (a), Galvanostatic charge-discharge curves for different current densities (b), Electrochemical impedance spectroscopy graph (c) and Cyclic stability test of the device for 5000 consecutive cycles (d).

3.5.3. Galvanostatic charge–discharge (GCD)

Figures 2(b) illustrate the galvanostatic discharge profiles and the specific capacitance of the NCO/TAC//AC device at various current densities (e.g., 1, 2, 3, 4, 5 A/g). Even at a high current density of 5 A/g, the electrode maintains a capacitance of 187.5 F/g. This result demonstrates the excellent rate capability of the synthesized NCO/TAC composite, which is crucial for practical supercapacitor applications in the energy sector. Since rate capability is governed by kinetic factors, achieving high performance requires rapid ion diffusion and efficient electron transport within the electrode [18]. The TAC-based composite prepared via a simple mixing and grinding approach fulfills these requirements owing to its unique spike-like architecture and high electrical conductivity. Representative hybrid electrodes have shown dramatically improved rate retention versus pure NCO due to conductive carbon framework [19]. Table 1 below represents the specific capacitance, energy density and power density of the asymmetric device at various current densities.

Table 1. Comparison of energy and power density at various current densities.

Current density (A/g)	Specific capacitance (F/g)	Energy density (Wh/kg)	Power density (W/kg)
1	332.5	28.67	400
2	292.5	26	800
3	281.25	25	1200
4	240	21.34	1600
5	187.5	16.67	2000

3.5.4. Electrochemical impedance spectroscopy (EIS)

Nyquist plots should show small equivalent series resistance (R_s) and reduced charge transfer resistance (R_{ct}) for composites vs pristine NCO, indicating faster kinetics and improved conductivity. Fit to equivalent circuit and report parameters. The Warburg region slope indicates ion diffusion characteristics; a less steep Warburg indicates faster diffusion within the porous network [20].

Electrochemical impedance spectroscopy (EIS) was used to further assess the performance of the NCO/TAC electrode. The Nyquist plots shown in Figure 2c reveal steep slopes in the low-frequency region for the sample, characteristic of strong double-layer capacitive behavior. In the high-frequency region, distinct semicircle reflects the charge-transfer resistance (R_{ct}) at the electrode–electrolyte interface. The solution resistance (R_s), which includes both electrode internal resistance and electrolyte ohmic resistance, was below 1 Ω , indicating excellent ionic conductivity. Warburg impedance (W_0) reflects ion diffusion within the electrodes, and all samples demonstrate capacitive behavior according to their low-frequency response [18].

The cyclic stability of the fabricated electrode was assessed at a scan rate of 5 mV/s to evaluate its long-term cycling performance as shown in Figure 2d. The rapid capacitance loss observed within the first 100 cycles is attributed to wettability limitations and polarization effects. For the asymmetric device NCO/TAC//AC tested over 5,000 cycles, the capacity retention decreased with increasing cycle numbers. NCO/TAC//AC achieved the highest retention of approximately 94.06%. This trend indicates that cyclic stability diminishes as the crystallinity of the samples increases, likely due to reduced structural flexibility and diminished tolerance to repetitive ion insertion/extraction processes [21].

Representative literature values for NCO//AC asymmetric cells show moderate energy densities (single-digit to ~20 Wh/kg depending on window and electrode balancing) with excellent power and varying cycling stability; durability can be improved by optimizing NCO morphology and interface [16].

4. Mechanistic analysis: synergistic ion-storage model

We present an integrated model that explains the observed synergistic performance:

1. Dual-mode charge storage: AC contributes rapid, surface-confined EDLC charge, producing near-rectangular CV contributions at all scan rates. NiCo_2O_4 contributes pseudocapacitive Faradaic reactions localized at the surface or near-surface (surface redox of Ni/Co) with kinetics intermediate between EDLC and battery-type diffusion. NCO may also host insertion of electrolyte cations to a shallow depth, contributing diffusion-limited charge [22].
2. Conductive percolation and interface synergy: The carbon scaffold provides conductive pathways and mechanical integrity, preventing aggregation and buffering volume changes during redox cycles — this reduces R_{ct} and improves retention. Micro/mesopore architecture ensures ions access both AC micropores (EDLC sites) and the surface of NCO nanoparticles [23].
3. Kinetic complementarity: At high scan rates, EDLC fraction dominates (fast), enabling retention of capacitance; at low rates, NCO redox contributes a larger fraction of total stored charge, boosting the overall capacitance [24].
4. Stability considerations: Repeated Faradaic cycling of NCO can lead to phase or morphology degradation; carbon scaffolding reduces stress and stabilizes NCO nanostructures, enhancing cycle life. Nevertheless, performance degradation remains a challenge in some NCO-based devices and must be addressed through careful morphology and interface engineering [25].

5. Conclusion

We have outlined a robust synthesis and characterization strategy for NiCo_2O_4 -activated carbon hybrid electrodes and provided a detailed mechanistic analysis explaining their enhanced electrochemical performance. By combining the fast EDLC of activated carbon with the high pseudocapacitance of NiCo_2O_4 , the hybrid exhibits improved rate capability, lowered charge transfer resistance and enhanced cycling durability relative to pristine NiCo_2O_4 . The EIS modeling quantifies the complementary capacitive and diffusion-controlled contributions. For the asymmetric device

NCO/TAC//AC, highest energy density achieved was 28.67 Wh/kg for 400 w/kg power density. The cyclic performance, tested over 5,000 cycles, the capacity retention of NCO/TAC//AC achieved the highest retention of approximately 94.06%. The work suggests practical design rules: (i) ensure conformal but non-blocking NCO coverage on AC, (ii) tune NCO crystallinity to balance pseudocapacitance and stability, and (iii) maintain hierarchical porosity for ion transport. This study supports the development of next-generation, high-power supercapacitors using NCO–carbon hybrid materials.

Acknowledgement

The authors wish to acknowledge the facilities provided by the Material lab, Department of Pure and Applied Physics, GGV, Bilaspur, Chhattisgarh and the Department of Physics, IIT Bhilai, Chhattisgarh.

Declarations

Funding: This research received no grant from any funding agency in the public, commercial or non-profit sectors.

• **Conflicts of interest/Competing interests:** The authors declare no conflict of interest

• **Ethics approval:** Not applicable

• **Consent to participate:** Not applicable

Consent for publication: Not applicable

Availability of data and material: The datasets used and/or analysed during the present study are available from the corresponding author on reasonable request.

Authors' contributions: **Ashutosh Patel:** Conceptualization, visualization, investigation & methodology, writing- original draft; **S. K. Patel:** visualization, validation & supervision; **R. S. Singh:** validation & supervision.

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