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Enhanced Supercapacitive Performance of PANI/CdCrO₃/GO Ternary Nanocomposite: A Comparative Study with GO/CdCrO₃ Superior Electrochemical Performance of the Ternary Electrode

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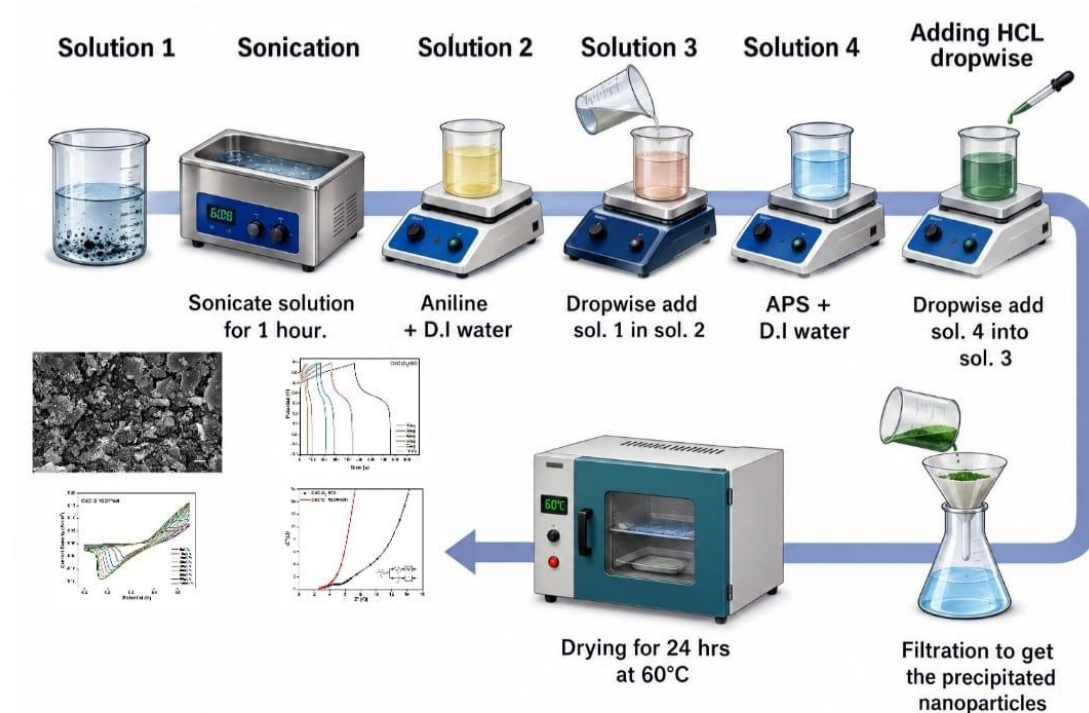
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Abstract

The advancement of high-performance supercapacitors relies strongly on the development of electrode materials capable of efficient charge storage and energy delivery. In the present study, CdCrO₃ and its graphene oxide (GO) hybrid composite with PANI were prepared using a facile and economical hydrothermal method and an in situ chemical oxidative polymerization method for potential supercapacitor applications. The structural, chemical, and morphological assessment was investigated by XRD, ATR-FTIR, and SEM techniques. Electrochemical evaluation demonstrated a remarkable improvement after GO and PANI incorporation, with the PANI/CdCrO₃/GO electrode achieving a specific capacitance of 1715 F g⁻¹ at 2 A g⁻¹, compared with 802 F g⁻¹ for the Binary CdCrO₃/GO electrode. This study demonstrates the fabrication of two electrode configurations, namely CdCrO₃/GO Binary and PANI/CdCrO₃/GO Ternary nanocomposites. Although both configurations exhibit favorable electrochemical characteristics, the Ternary device provides considerably improved charge-storage performance and maintains more than 50% capacitance retention at 1 A g⁻¹. The Ternary electrode configuration delivers a maximum energy density of 184.4 Wh kg⁻¹ along at a higher power density of 1007 W kg⁻¹, while for Binary electrode an 86.2 Wh kg⁻¹ energy density, at power density

of 995.4 W kg^{-1} . These characteristics demonstrate the excellent energy–power balance of the PANI/GO/CdCrO₃ based device. Furthermore, the electrode system exhibits remarkable long-term durability, retaining 80% of capacitance with 1000 charge/discharge cycles. Overall, the outstanding rate capability, energy-storage performance, and cycling stability make the PANI/CdCrO₃/GO supercapacitor a promising candidate for practical solid-state energy-storage applications.

Graphical Abstract



Keywords Nanocomposite, Perovskite doped Graphene oxide. Hybrid material. Polyaniline. Energy storage application. scharge-discharge. Electrode material . Specific capacitance .Super-capacitor. Cyclic stability.

1. Introduction

The continuously rising worldwide energy demand has emerged as one of the most pressing challenges of recent decades, driven largely by accelerated industrialization [1]. This trend has underscored the urgent need to transition toward renewable energy

resources [2] , [3]. Simultaneously, population growth, the depletion of fossil fuel reserves, and their severe environmental consequences, most notably global warming, have intensified efforts to harness and store energy from sustainable sources including solar, wind, and geothermal systems. In this context, alongside advances in energy generation technologies, the progress of efficient electrochemical energy storage (EES) devices, including batteries, fuel cells, capacitors, and supercapacitors are essential as viable alternatives to conventional fossil fuels [4]. Notably, there remains a pressing need for energy storage systems capable of bridging the deficiency of batteries and capacitors, particularly under practical operating conditions where each exhibits inherent limitations [5].

The rapid expansion of portable electronics, modern digital technologies, and renewable energy applications has created an increasing demand for efficient energy storage systems [6]. Among the various energy storage technologies, supercapacitors have gained significant attention because of their superior power delivery, fast charge–discharge characteristics, and excellent long-term cycling performance [7]. The overall electrochemical efficiency of supercapacitors largely depends on the type of electrode materials, prompting extensive research on transition metal perovskites, carbon nanomaterials, and conductive polymers as promising electrode candidates [6],[7]. According to their energy storage mechanism, supercapacitors can be divided into three major categories: electric double-layer capacitors (EDLCs), pseudocapacitors, and hybrid supercapacitors. Based on the underlying charge storage process, Sc are broadly categorized into these classes [8, 9]. EDLCs store energy through the electrostatic adsorption of ions at the electrode/electrolyte interface without involving redox reactions, whereas pseudocapacitors utilize reversible and rapid faradaic reactions occurring on or near the electrode surface [10-12]. Hybrid supercapacitors combine both electrostatic and faradaic charge storage mechanisms, resulting in enhanced energy storage capability, higher power output, and improved cycling durability compared with conventional supercapacitors [13], [14], [15].

A key advantage of perovskite oxides lies in their structurally adaptable lattice, which permits extensive compositional tuning and enables the realization of diverse functional properties [16]. The archetypal ABO_3 framework consists of two distinct cations occupying the A- and B-sites, with oxygen forming the anionic sublattice.

Structural stability is generally favored when the larger A-site cation accommodates a higher coordination environment, while the smaller B-site cation resides at the center of an oxygen octahedron [4]. The A-site can accommodate mono-, di-, or trivalent cations (e.g., Na^+ , Cd^{+2} , Fe^{3+}), while the B-site is generally populated by cations with oxidation states ranging from +3 to +5. This arrangement results in coordination numbers of 12 and 6 for the A- and B-site cations, respectively, underpinning the structural flexibility and functional diversity of perovskite materials [17] [18]. In the ideal cubic configuration, the B-site cation is centrally located within the unit cell, surrounded by oxygen anions, whereas the A-site cation occupies the corners, collectively establishing a robust [19] and versatile crystal architecture [20].

Chromite-based perovskites, including CaCrO_3 , SrCrO_3 , and BaCrO_3 , have attracted considerable interest due to their unique structural and magnetic properties. Rare-earth chromites (RCrO_3) exhibit diverse functionalities, such as magnetocaloric effects, exchange bias, and magnetization reversal [21]. The optimized CdCrO_3 crystal structure crystallizes in the cubic $\text{Pm}\bar{3}\text{m}$ phase, with Cd, Cr, and O atoms occupying the (0, 0, 0), $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$, and $(\frac{1}{2}, \frac{1}{2}, u)$ ($u \approx 0.249$) positions, respectively [22] [23]. The calculated Goldschmidt tolerance factor ($\tau = 0.97$) and formation energy confirm the structural and thermodynamic stability of the cubic phase [24], [25].

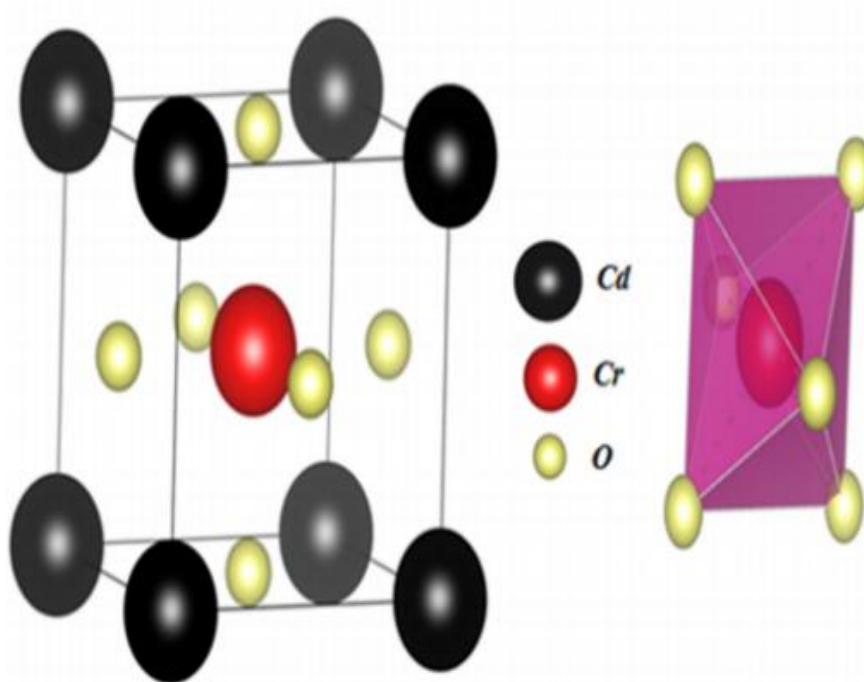


Figure 1: Computed crystal structure of cubic CdCrO₃. [21]

Conductive polymers and transition metal perovskites are widely found as pseudocapacitive electrode materials for the rapid and reversible nature of their faradaic charge-storage mechanisms [26], [27]. Among conductive polymers, polyaniline (PANI), polypyrrole, and polythiophene have attained significance owing to their high electrical conductivity, low cost, and straightforward synthesis routes [27], [28]. In particular, PANI is considered among the most promising candidates because of its valuable theoretical capacitance and wonderful redox activity [29]. Despite that, its practical application is constrained by low capacity retention resulting from structural degradation during repeated charge–discharge processes [28, 30]. To address this limitation, PANI is frequently hybridized with metal oxides and carbonaceous materials, which enhance electrical conductivity, provide additional electroactive sites, and improve the structural integrity of the electrode [31]. Graphene oxide (GO), a 2D carbon-based material with an sp²-hybridized framework and abundant oxygen-containing functional groups, facilitates efficient electron transport and ion diffusion, thereby improving the specific capacitance and cycling durability of composite electrodes [32]. These unique characteristics have driven extensive research into graphene and graphene oxide (GO)-based nanocomposites for applications in nanoelectronics, photovoltaic technologies, sensing, catalysis, and energy storage systems [33], [34]. Graphene oxide is particularly valued for its outstanding electrical properties, including efficient charge transport, high carrier mobility, and an extended π -conjugated structure. In metal oxide/GO composites, these characteristics facilitate rapid electron migration and effective charge separation, thereby suppressing electron–hole recombination and enhancing the overall functional performance of the composite materials [35].

Consequently, PANI/CdCrO₃/GO ternary nanocomposites have appeared as potential electrode materials for high-performance supercapacitors.

2. Experimentation

2.1. Reagents and Materials

Analytical-grade chemicals were employed throughout this work without any additional purification. Cadmium nitrates (Cd (NO₃)₂ · 4H₂O), citric acid, aniline, potassium permanganate (KMnO₄), chromium nitrate, hydrogen peroxide (H₂O₂),

graphite powder, deionized (DI) water, ethylene glycol, sulfuric acid (H_2SO_4), nitric acid (HNO_3), hydrochloric acid (HCl), acetic acid, ethanol, and ammonium persulfate ($(\text{NH}_4)_2\text{S}_2\text{O}_8$ (97.0%) (APS), were obtained from Sigma Aldrich, directly used as supplied.

2.2. Synthesis of CdCrO_3

CdCrO_3 perovskite was prepared using the sol-gel technique owing to its facile, economical, and environmentally benign approach [36] , [37] , [38]. Initially, 3.08 g of Cadmium nitrate and 7.0 g of chromium nitrate were dissolved in 50 mL of ethanol under continuous stirring for 5 min to obtain a uniform precursor solution. Subsequently, 6.634 g of citric acid ($\text{C}_6\text{H}_8\text{O}_7$, 99% purity, Merck) was introduced as a complexing agent in a 1:1:2 molar ratio relative to the metal ions. The solution was heated with constant stirring for nearly 2 h until a viscous gel was formed. The pH was then adjusted and maintained at 8 by the gradual addition of ammonia solution (NH_4OH , 99%) [19] . The gel thus obtained was calcined at 452 °C for 2 hrs and then annealed at 750 °C to achieve the crystalline CdCrO_3 phase. Finally, the obtained powder was ground into a fine material and stored for subsequent characterization studies [24].

2.3. Synthesis of GO

Graphene oxide (GO) was synthesized by modified Hummers' method as reported previously [39]. Firstly, we mixed Sodium nitrate (NaNO_3) and graphite powder with concentrated H_2SO_4 in a 2:2 ratio. The reaction mixture was maintained at 0–5 °C in an ice bath and stirred for 20 min. Subsequently, 12 g KMnO_4 was added gradually over 2 h, followed by stirring for 20 min. The mixture was then heated to 50 °C and stirred for 30 min. Next, 100 mL distilled water was added slowly, followed by 1 h of stirring. Afterward, 200 mL distilled water was added, and the mixture was heated at 98 °C for 30 min. Upon cooling, 20 mL H_2O_2 was added dropwise, producing a bright-yellow suspension. The mixture was stirred for 20 min and left for 24 h. The HCl and deionized water are used to wash the resulting suspension repeatedly, until a neutral pH was attained, ultrasonicated for 2 hrs, and for 24 h at 65 °C, it undergoes vacuum-dried to obtain purified GO [40]. .

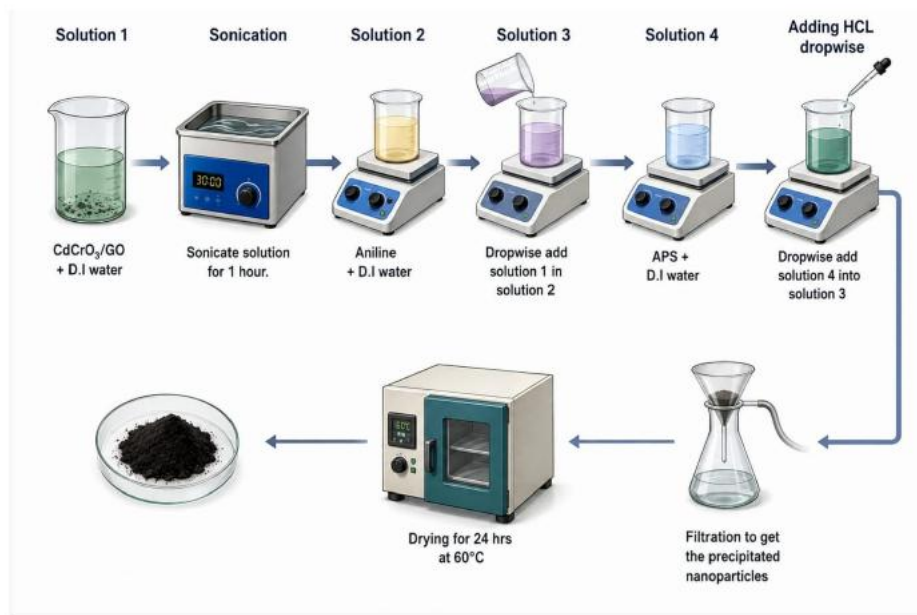
2.4. Synthesis of CdCrO_3/GO Nanocomposite

To prepare the CdCrO₃/GO nanocomposite, 0.05 g of graphene oxide (GO) was ultrasonicated for 10 min after dispersed in 50 mL of deionized water, to achieve a well-dispersed suspension. In a separate container, CdCrO₃ nanoparticles were suspended in a solution of 1:1 (v/v) ethylene glycol–acetic acid and sonicated for 1 h. The suspension of CdCrO₃ was then mixed with the GO dispersion and continuously stirred at 85 °C for 1 hour to ensure effective interaction of two components [15]. The resulting product was isolated by centrifugation at 3500 rpm for 10 min, repeatedly washed with deionized water to remove any remaining impurities, and then dried at 70 °C overnight to obtain the final GO/CdCrO₃ nanocomposite [41], [42].

2.5. Preparation of PANI/GO/CdCrO₃ Nanocomposite

The GO/CdCrO₃/PANI ternary nanocomposite is synthesized using an in-situ chemical oxidative polymerization approach. Initially, 0.050 g of graphene oxide (GO) and 0.1 g of CdCrO₃ in 20 mL of deionized water and ultrasonicated for 60 min to produce (Solution 1) to disperse the nanoparticles. Separately, Solution 2 was prepared by dissolving 3 mL of aniline in 60 mL of deionized water while stirring the mixture continuously for 30 min. Solution 1 was then introduced slowly into Solution 2 under constant stirring, and the resulting suspension (Solution 3) was stirred for an additional 10 min. Then Polymerization was initiated gradually by adding 60 mL of a chilled ammonium persulfate (APS, 0.68 g) solution while maintaining vigorous agitation. The reaction mixture immediately changed to a black color. Further, the dropwise addition of 1.50 mL of hydrochloric acid (HCl) was done after 15 min, until the suspension exhibited a greenish-black coloration. The reaction was left undisturbed overnight to allow complete polymerization [43] .

After completion of the reaction, the synthesized composite was separated, repeatedly rinsed with deionized water until the washings became clear, and vacuum dried for 24 hrs at 70 °C to obtain the final PANI/GO/CdCrO₃ nanocomposite [2].



2.6. Electrode Preparation and Electrochemical Measurements

Nickel foam ($1.5 \times 1 \text{ cm}^2$) was employed as the current collector after sequential cleaning with deionized water, 5% HCl, ethanol, acetone, and followed by oven drying. The homogeneity of the suspension was obtained by electrode slurry, which was fabricated by dispersing 10 %wt activated carbon, 80 %wt of the active material, and 10 %wt polyvinylidene fluoride (PVDF) in N-methyl-2-pyrrolidone (NMP) under ultrasonication. The prepared slurry was evenly drop-cast onto pretreated nickel foam and dried process at 40°C to get the working electrode [44].

Electrochemical experiments were carried out in 2.00 molar KOH electrolyte with a Teflon-lined Pyrex electrochemical cell [44]. Before each experiment, the cell was cleaned with acetone, deionized water, and aqua regia thoroughly, followed by oven drying to eliminate residual contaminants and ensure measurement reproducibility.

The electrochemical characteristics of the prepared materials were investigated through cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and galvanostatic charge–discharge (GCD). Specific capacitance (C_s , F/g) was estimated from the CV as well as from GCD profiles according to Eqs. (1) and (2), respectively.

$$C_s = \frac{1}{ms\Delta V} \int_{V_a}^{V_c} IdV \quad (1)$$

In Eq. (1), $\int dV$ indicates the total enclosed area of the cyclic voltammogram, m refers to the mass (g) of the electroactive material deposited on the glassy carbon electrode, ΔV is the applied potential window, and v represents the scan rate (mV s^{-1}).

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

where I denotes discharge current (Amp), Δt is discharge time (sec), m is the active electrode material's mass (g), and ΔV is the operating potential window (V).

The EIS was conducted within a frequency range of 1 Hz to 10^5 Hz using a sinusoidal AC signal with an amplitude of 10 mV. The coulombic efficiency (η) of the prepared electrodes was obtained from the GCD profiles using Eq. (3):

$$E = \frac{1}{7.2} Cs(\Delta V)^2 \quad (3)$$

$$P = 3600 \frac{E}{\Delta t} \quad (4)$$

Here, the variables “ Cs ” is the specific capacitance (F g^{-1}), “ ΔV ” is the voltage window (V), and “ Δt ” is the discharge time (s) obtained from the GCD curves.

$$\eta = \frac{td}{tc} \times 100 \quad (5)$$

where t_c and t_d represent the discharge and charge times (s), [45] respectively. In addition, the energy density (Wh kg^{-1}) and power density (W kg^{-1}) of the fabricated supercapacitor electrodes were calculated using Eqs. (3), (4) and (5), respectively [46].

3. Physiochemical characterizations

3.1 X-ray Diffraction

To examine the structural characteristics of the synthesized samples, X-ray diffraction (XRD) analysis was performed to assess their crystallinity and phase composition. The diffraction profiles of pure CdCrO_3 , the binary GO/CdCrO_3 hybrid, and the ternary PANI/GO/CdCrO_3 nanocomposite were systematically recorded and compared.

As illustrated in Fig. 2 (a), pure CdCrO_3 displays distinct Orthorhombic Crystal system [47] with diffraction peaks at 18.63° , 31.94° , 34.63° , 37.77° , 43.62° , 62.81° ,

75.09° and 79.63° are 2θ values, which can be indexed to the (110), (112), (130), (220), (132), (204) (314) and (352) crystallographic planes, respectively of a cubic phase. These reflections are consistent with an orthorhombic perovskite structure of CdCrO_3 belonging to the Cmcm (63) space group, in agreement with standard data (JCPDS No. 96-100-8085).

In the case of graphene oxide, a characteristic broadened reflection centered at $2\theta \approx 24.1^\circ$, corresponding to the (002) plane, is observed in Fig. 2 (b), indicating partial reduction of GO [48], [16]. For the ternary PANI/GO/ CdCrO_3 composite, the diffraction pattern retains the dominant peaks associated with CdCrO_3 , along with additional broad features at $2\theta \approx 25.6^\circ$ and 16° , [48] indexed to the (200) plane and (011) plane of PANI [31], [2]. Importantly, no extraneous or impurity-related peaks are detected, demonstrating the high phase purity of the synthesized PANI/GO/ CdCrO_3 nanocomposite [31]. The XRD pattern of PANI exhibits a predominantly amorphous nature and arises from the periodic arrangement of benzenoid and quinoid units along the polymer backbone [49]. This confirms the successive incorporation and coexistence of GO and PANI within the composite matrix CdCrO_3 phases. These results collectively verify the successful formation of the nanocomposite via the in-situ polymerization method [31].

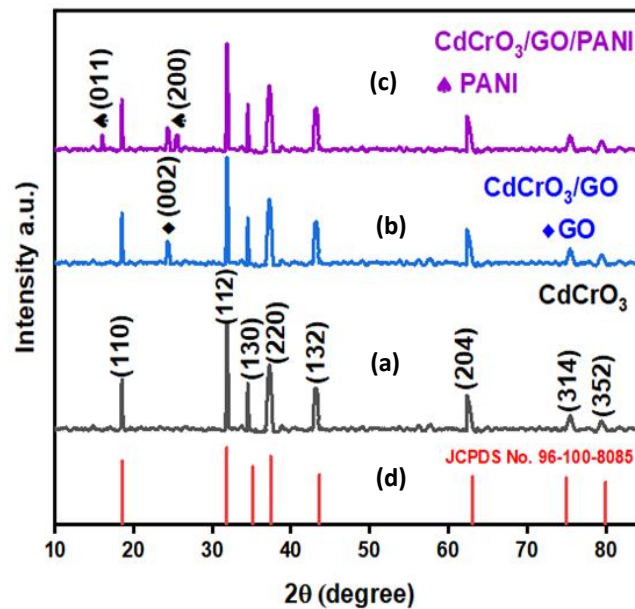


Figure 3: XRD spectra of nanocomposites (a) CdCrO_3 (b) GO/ CdCrO_3 binary (c) PANI/GO/ CdCrO_3 ternary (d) JCPDS of CdCrO_3 perovskite.

The microstructural characteristics of the PANI/CdCrO₃/GO composite were quantified from the XRD data by determining the lattice microstrain, crystallite size, and degree of crystallinity. These parameters were derived primarily from the well-resolved reflections of the CdCrO₃ perovskite phase, as both GO and PANI are largely amorphous and therefore unsuitable for precise peak-based analysis.

$$\text{Crystalline Size} = K\lambda / \beta \cos \theta$$

$$d = 0.5 n\lambda / \sin \theta$$

Where, $n = 1$ [50].

Microstrain ' ϵ ' is computed by utilizing the equation [51].

$$\epsilon = 0.25 \beta / \tan \theta$$

The size of the crystallite, denoted by 'D' and lattice strain (ϵ) [52] were estimated utilizing standard XRD-based relations, where the shape factor (K) was taken as 0.9, the wavelength of Cu K α radiation (λ) as 0.154 nm, the full width at half maximum is β (FWHM) in radians after instrumental correction, and θ corresponds to half of the diffraction angle. The interplanar spacing (d) was computed from Bragg's Law, which relates diffraction angle to lattice spacing. The crystallinity of the sample is calculated using the formula,

$$\% \text{ Crystallinity} = \text{Sum of Area of Peak} / \text{Total Area under the curve} \times 100\%$$

The average crystallite size of the CdCrO₃/GO/PANI nanocomposite was found to be approximately 38.42 nm, as listed in Table 1 [53].

Table 1: XRD analysis of Ternary Nano-composite over the Binary and Pristine CdCrO₃

Name of Sample	Crystallinity %	crystallite size	microstrain
CdCrO₃/GO/PANI	95.0495	38.42 nm	4.35×10^{-3}
CdCrO₃/GO	96.88	29.13 nm	4.12×10^{-3}
CdCrO₃	97.21	35.43 nm	3.84×10^{-3}

3.4. Fourier Transform Infrared Spectroscopy

Fourier transform infrared (FTIR) spectroscopy is utilized to probe the bonding environment and identify functional groups in the CdCrO₃/GO/PANI nano-composite. Owing to the inorganic perovskite nature of CdCrO₃, direct identification of its vibrational features is inherently challenging; however, the incorporation of GO and PANI gives rise to several well-defined spectral signatures, as illustrated in Fig. 4. The absorption bands located at 491.81 and 650.1 cm⁻¹ are assigned to metal–oxygen (M–O) stretching modes, specifically associated with Cd–O [2] and Cr–O linkages. Meanwhile, the bands observed at 1489.1 cm⁻¹ and 860.3 correspond to symmetric bending and stretching vibrations of oxygen within the CrO₆ octahedral framework, confirming the structural integrity of the perovskite lattice.

Absorption at 2852 cm⁻¹ is associated with C–H stretching vibrations [54], and the peak at 1016.51 cm⁻¹ appears from stretching vibrations of C–N bond, while the broadened feature near 3367 cm⁻¹ can be ascribed to –NH₂⁺ stretching within the –C₆H₄NH₂⁺–C₆H₄– segments, originating from protonated PANI [55], [56]. A band around 557.0 cm⁻¹ is attributed to (C–O–C) epoxy groups. Minor features observed in the spectrum are likely associated with residual species from the synthesis process, including nitriles, CO₂, ethanol, and adsorbed water [57].

Additionally, absorption bands at 1802 cm⁻¹ and 1747 cm⁻¹ are attributed to carbonate (CO₃²⁻) and O–H hydroxyl groups, respectively [58]. The spectral contributions from GO and PANI are further evidenced by a band at 779.3 cm⁻¹ [59], corresponding to out-of-plane C–H bending vibrations, and a feature at 939.36 cm⁻¹ associated with the carbon skeletal framework [60]. A broad band centered at 3367.8 cm⁻¹ is assigned to stretching modes of N–H bond. While at 1629.90 cm⁻¹ corresponds to a band of C=C stretching within aromatic rings, indicative of sp²-hybridized carbon domains in GO [61].

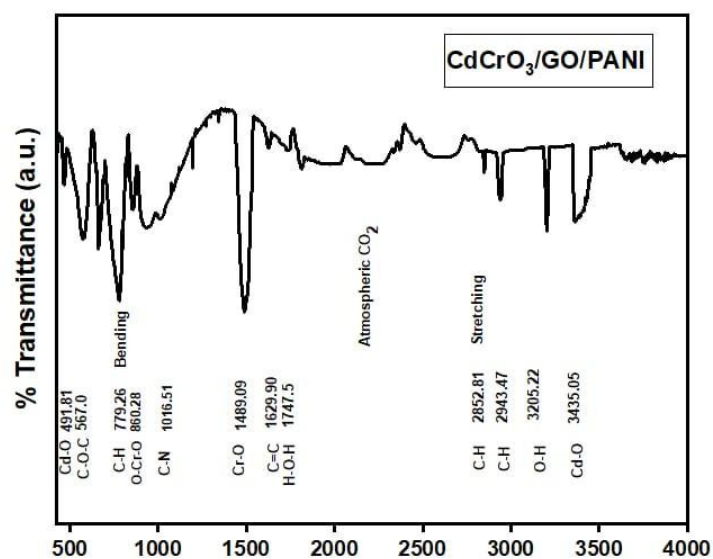


Figure 4: FTIR profile of Ternary PANI/GO/CdCrO₃.

3.3. Scanning electron microscopy (SEM)

The microstructural features and surface morphology of the synthesized nanocomposites were investigated by using scanning electron microscopy, as illustrated in Figure 3. The pristine CdCrO₃ (Fig. 3 (a)) reveals a micrograph with a largely amorphous structure composed of fine, agglomerated particles. In contrast, the GO/CdCrO₃ sample (Fig. 3 (b)) exhibits irregularly shaped particles with an interconnected network.

The PANI/GO/CdCrO₃ composite (Fig. 3 (c)) displays a heterogeneous morphology, where CdCrO₃/GO nanoparticles are effectively embedded within the PANI matrix. Moreover, the polymeric framework appears to develop as discrete, interwoven domains with non-uniform features. In the ternary PANI/GO/CdCrO₃ system (Fig. 3 (c)), the layered structure of GO is clearly discernible, serving as a supporting platform onto which both PANI and CdCrO₃ nanoparticles are uniformly anchored, indicating strong interfacial integration among the constituents [62].

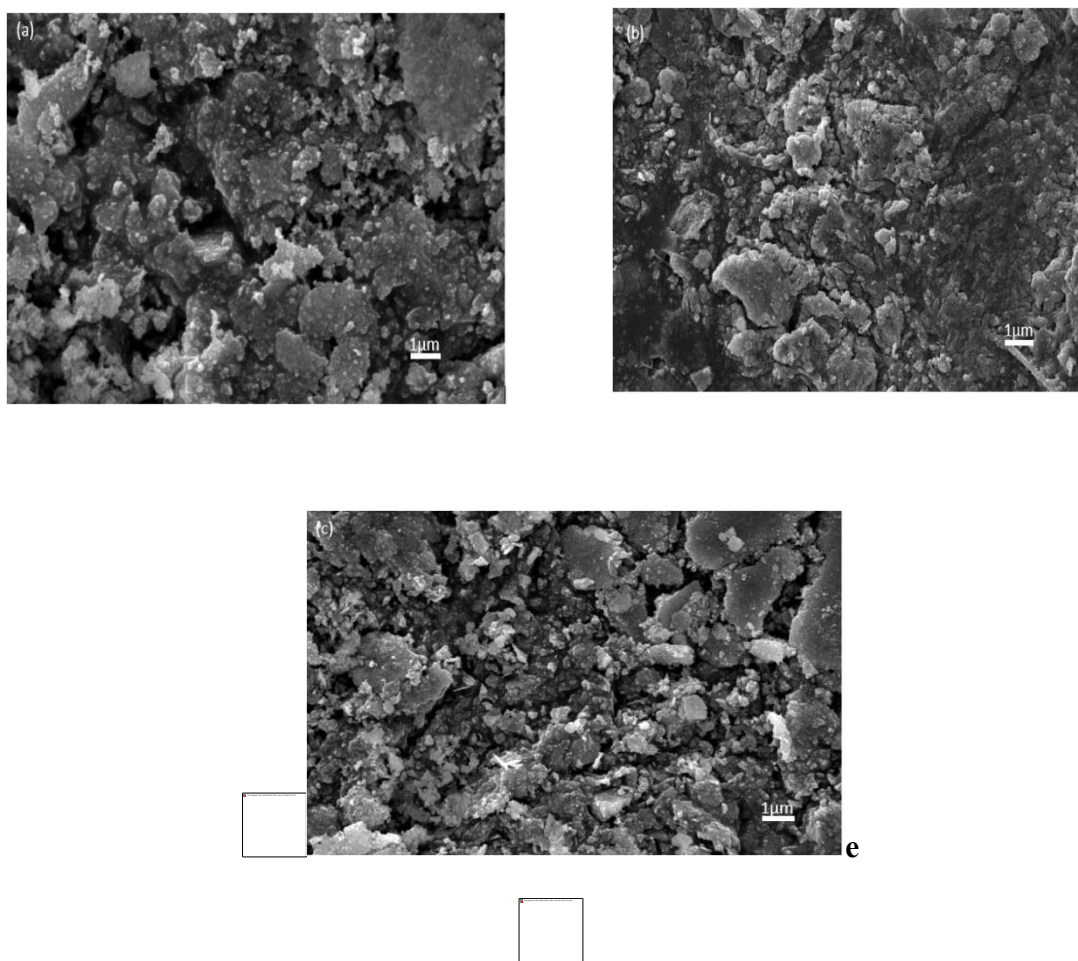


Figure 4: SEM images of Pure (a) CdCrO₃ Perovskite s(b) GO/CdCrO₃, and (c) Ternary PANI/SCdCrO₃/GO.

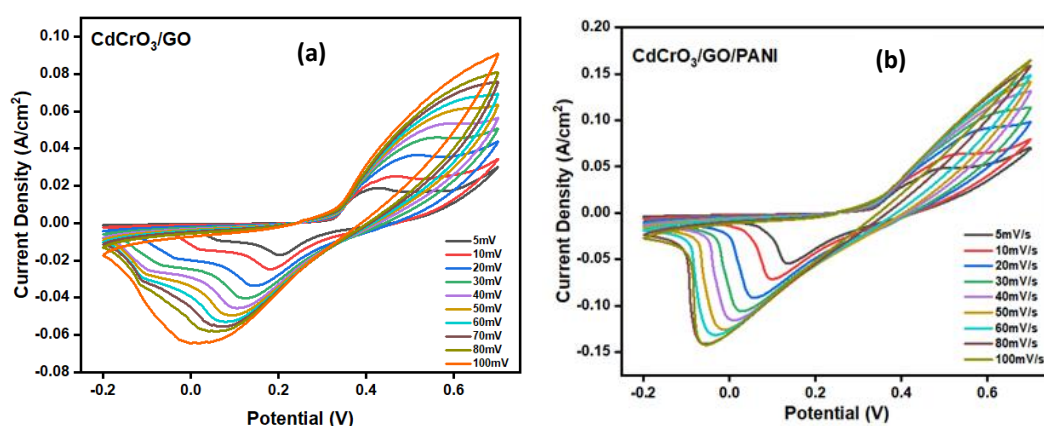
3.4. Electrochemical Measurements

The pseudocapacitive response of the GO/CdCrO₃ binary and PANI/GO/CdCrO₃ ternary nanocomposites was systematically examined using Cyclic Voltammetry (CV). The obtained voltametric profiles reveal the presence of distinct redox features, indicative of faradaic charge to PANI/GO/CdCrO₃ rage processes in both systems [63-65]. The CV curves for the binary GO/CdCrO₃ and ternary PANI/GO/CdCrO₃ composites are both presented in Fig. 5. (a, b), with their scan-rate-dependent behavior (5–100 mV s⁻¹) in 2 M KOH electrolyte.

A progressive increase in scan rates 5, 10, 20, 30, 40, 50, 60, 80, and 100 mVs^{-1} , leads to a corresponding expansion in the enclosed CV area, reflecting enhanced current response and an extended potential window. This behavior is directly associated with improved specific capacity and overall electrochemical performance, highlighting the suitability of the materials used in supercapacitor applications [31]. The high ionic conductivity of the electrolyte facilitates a stable operating potential window of 0V to 0.88 V [66]. Notably, the electrodes exhibit their maximum specific capacity at the lowest scan rate (5 mV s^{-1}), while higher scan rates result in a systematic enlargement of the CV loop area.

The presence of sharply defined and reproducible redox peaks further confirms the excellent capacitive characteristics of the synthesized electrodes. At a scan rate of 5 mV s^{-1} , the binary composite exhibits anodic and cathodic [67] peaks at 0.018 and -0.017 A cm^{-1} , respectively, whereas the ternary system shows enhanced peak currents at 0.048 and -0.054 A cm^{-1} . With increasing scan rates, both oxidation and reduction peaks shift toward their respective higher and lower potentials. This behavior arises from increased electrode polarization effects and ohmic resistance, which impose kinetic constraints on ion and electron transport within the electrode matrix [55].

Such peak shifts reflect the combined influence of internal resistance and polarization, ultimately affecting the redox kinetics of the system. The overall CV profiles suggest a quasi-reversible charge storage mechanism, indicating that although the redox reactions are not fully reversible, they maintain relatively fast and efficient charge transfer dynamics.



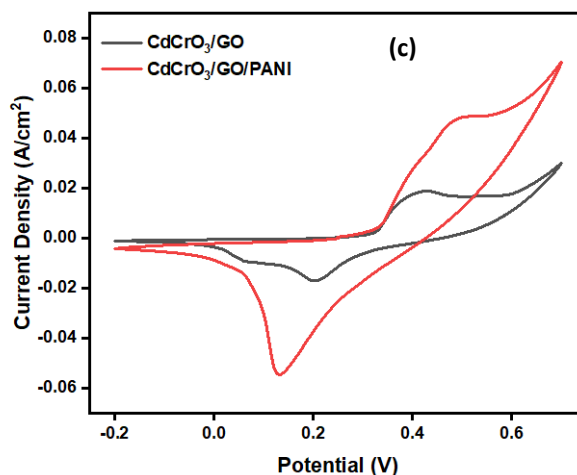


Figure 5: The Cyclic Voltammogram of (a) GO/CdCrO₃, (b) PANI/GO/CdCrO₃ nanocomposite, at various scan rates, and (c) assessment between the GO/CdCrO₃ and PANI/GO/CdCrO₃ nanocomposites at scan rate of 5mVs⁻¹.

The cooperative interaction between CdCrO₃ and GO thus offers a dual benefit: the formation of conductive networks that enhance charge transport, and the generation of abundant electrochemically active sites [68], [69]. Together, these effects account for the marked improvement in energy storage capability, highlighting the effectiveness of combining perovskite with GO, which is a conductive carbon material for high-performance electrode design. The integration of graphene oxide (GO) into the CdCrO₃ framework leads to a pronounced enhancement in electrochemical performance. The presence of GO nanosheets improves the inherent electrical conductivity of CdCrO₃ while simultaneously providing interconnected pathways for efficient electron transport, thereby reducing internal resistance. As a result, the GO/CdCrO₃ composite exhibits a highly significant specific capacitance as compared to the pristine CdCrO₃ electrode.

In addition, interfacial interactions among functional groups of the oxygen in GO i.e., graphene oxide, and the CdCrO₃ perovskite lattice contribute to an increase in the effective surface area. This structural integration promotes improved electrolyte accessibility, facilitating faster ion diffusion and more efficient charge storage processes.

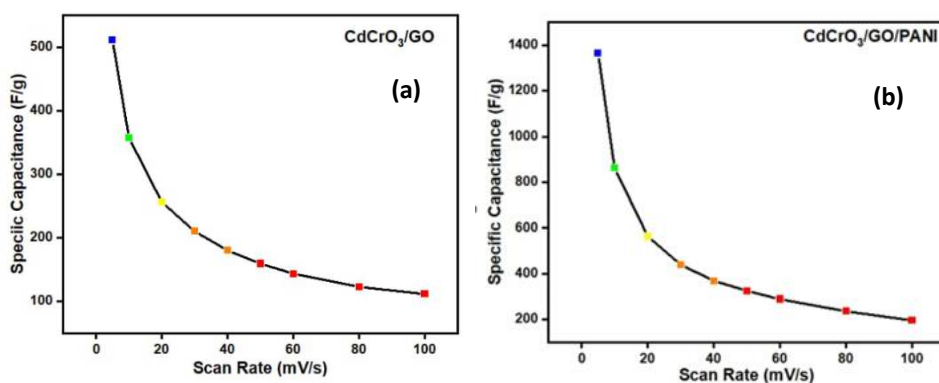
As indicated in Fig. 4.15(b), the PANI/GO/CdCrO₃ ternary composite exhibits substantially higher current density and an expanded electroactive surface area

relative to the individual components, indicating improved charge storage efficiency. This enhancement can be attributed to the synergistic interplay between redox-active CdCrO_3 , conductive PANI, and the high-surface-area GO matrix, underscoring the nanocomposite's promise as advancement in electrode material with superior energy density specific capacitance [70]. The specific capacitance (C_s) variations with scan rate is summarized in Table 2.

Table 2. “ C_s ” Calculations from Cyclic Voltammetry

Sample Name	5mV s ⁻¹ (F/g)	10mV s ⁻¹ (F/g)	20 mV s ⁻¹ (F/g)	30mV s ⁻¹ (F/g)	40mV s ⁻¹ (F/g)	50m s ⁻¹ V (F/g)	60mV/s (F/g)	80m V s ⁻¹ (F/g)	100mV s ⁻¹ (F/g)
GO/ CdCrO_3 (C_{sp})	511	357	256	210	180	159	144	123	111
PANI/GO/ CdCrO_3 (C_{sp})	1363	861	563	439	369	325	288	236	195

The C_s values, calculated from the CV curves presented in Fig. 5(a, b) using Equation (1), demonstrate that the PANI/GO/ CdCrO_3 electrode significantly outperforms the CdCrO_3 /GO system, delivering 1363 F/g at 5 mV s⁻¹ compared to 511 F/g for the binary composite. This improvement is primarily associated with the hybrid architecture, in which GO enhances electrical conductivity and provides additional electron transport channels, thereby promoting efficient charge storage.



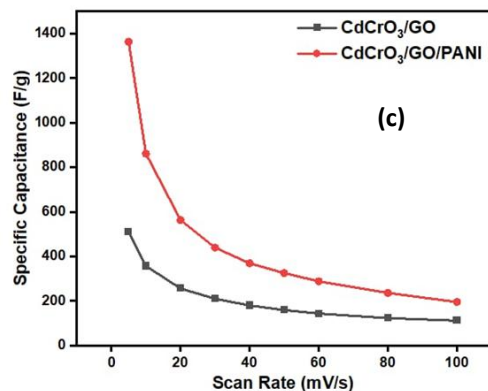


Figure 6: (a) Specific capacitance profile for both (a) GO/CdCrO₃ & (b) PANI/GO/CdCrO₃ nanocomposite (c) Comparison of both Nanocomposites.

As illustrated in Fig. 6 (a & b), at higher scan rates (100 mV s^{-1}), although the current response increases, the redox peaks shift toward more positive and negative potentials, respectively, due to increased internal resistance within the electrode. The specific capacitance decreases progressively with increasing scan rate, reflecting the typical inverse relationship between C_s and scan rate. The decline in capacitance at elevated scan rates is mainly attributed to ohmic drop and limited ion diffusion, which restrict sufficient charge transfer within the available time scale.

Despite this behavior, the porous structure and large accessible surface area of the composite continue to support efficient electrochemical activity, maintaining its overall performance advantage.

The PANI/GO/CdCrO₃ nanostructure, characterized by a high surface area and an open porous framework, promotes efficient electrolyte penetration [31] and offers numerous electroactive sites, thereby delivering superior electrochemical performance compared to the GO/CdCrO₃ composite. These attributes highlight its potential as an electrode material for achieving enhanced energy density and charge storage capacity [71].

To further evaluate the charge storage characteristics, Galvanostatic Charge–Discharge measurements were conducted on both GO/CdCrO₃ and PANI/GO/CdCrO₃ electrodes in 2.00 M KOH electrolyte at a potential window in range of -0.20 to 0.80 V at different current densities $j_d = 2, 3, 4, 5, 7, 10 \text{ Ag}^{-1}$, as shown in Fig. 7 (a, b & c). This technique provides critical insight into the overall

charge–discharge behavior of the electrodes and the influence of current density on specific capacitance.

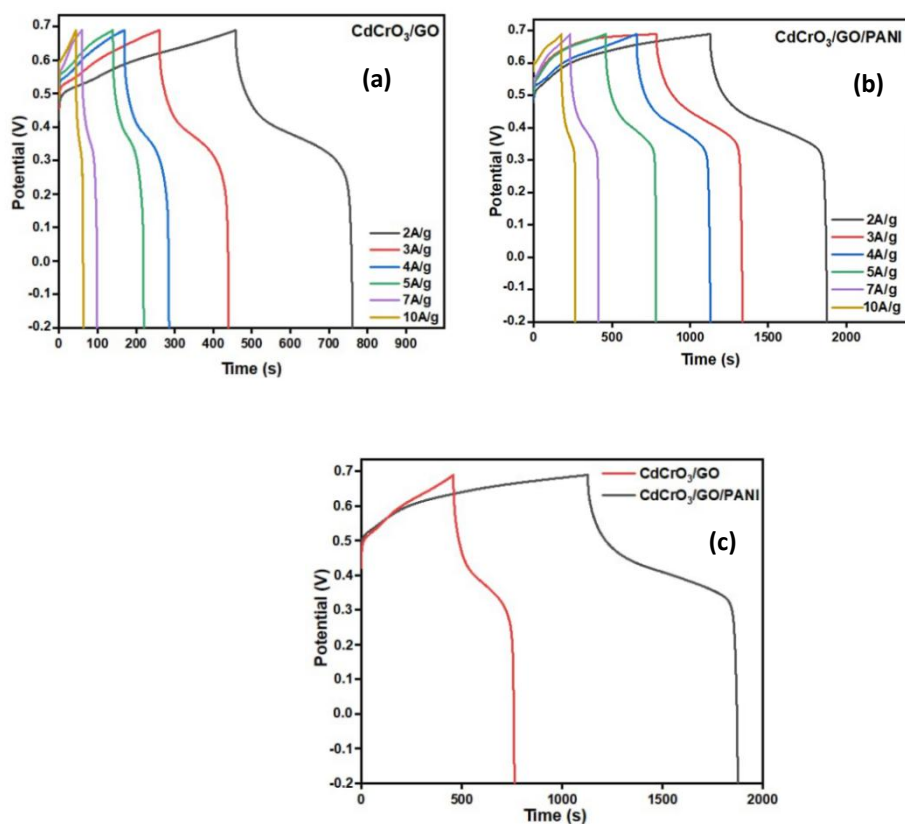


Figure 7: (a) GCD curves of GO/CdCrO₃ nanocomposite, (b) PANI/GO/CdCrO₃ nanocomposite, and (c) Comparison of PANI/GO/CdCrO₃ and GO/CdCrO₃ nanocomposite.

The discharge profiles of both binary and ternary systems exhibit nonlinear characteristics with distinct redox features, confirming their pseudocapacitive nature. At a 2 A g⁻¹ of current density, the GO/CdCrO₃ and PANI/GO/CdCrO₃ electrodes deliver maximum specific capacitances of 802 F/g and 1715 F/g, respectively, as computed using Equation no. 2. The elevated capacitance values reflect the contribution of graphene oxide sheets to enhanced charge storage [72].

The significant improvement observed for the ternary composite over the binary counterpart is attributed to the synergistic interaction among CdCrO₃, GO, and PANI. In this architecture, GO and PANI function as conductive frameworks that anchor CdCrO₃ nanoparticles, thereby facilitating rapid electron and ion transport across the

electrode–electrolyte interface. This cooperative effect ultimately leads to improved capability rate and higher specific capacitance [31] .

Gravimetric capacitance (F/g) reflects the charge storage capability per unit mass; however, for practical device applications, volumetric performance is often more critical. Materials exhibiting high gravimetric capacitance but low packing density may deliver limited volumetric efficiency. In this context, the PANI/GO/CdCrO₃ ternary composite demonstrates a high specific capacitance (C_s) of 1715 F/g, while corresponding ‘ C_v ’ volumetric capacitance’s value for the ternary nanocomposite is 1372 F cm⁻³, as determined from Eq. (5), primarily due to the relatively lower packing density associated with GO and PANI components.

The charge–discharge profiles exhibit a relatively small IR drop at low current densities, which becomes increasingly pronounced at higher current densities. This initial voltage decline during the discharge process reflects the internal resistance of the electrode system. Such behavior indicates strong interfacial interaction between CdCrO₃ and the nanostructured GO surface, facilitating improved electrical conductivity within the electrode. Moreover, the incorporation of GO significantly enhances both the surface area and electronic transport properties of the composite, resulting in a markedly improved electrochemical response in comparison with perovskite CdCrO₃. Notably, the CdCrO₃/GO Binary electrode exhibits an extended discharge duration with similar current densities, highlighting the beneficial role of graphene oxide in facilitating charge transfer kinetics as well as improving the nanocomposite’s stability for electrode.

The galvanostatic charge–discharge (GCD) profiles illustrated in Fig. 7 (a,b,c) show that increasing current density causes a progressive decline in S_c , consistent with typical super-capacitive behavior. This reduction at higher current densities can be attributed to limited time for electrolyte ions to effectively intercalate and deintercalate at the available electroactive sites. Fast charge storage is a critical requirement for practical supercapacitor applications. Notably, the near symmetry between charging and discharging durations across all applied current densities indicates high coulombic efficiency and minimal energy loss during cycling.

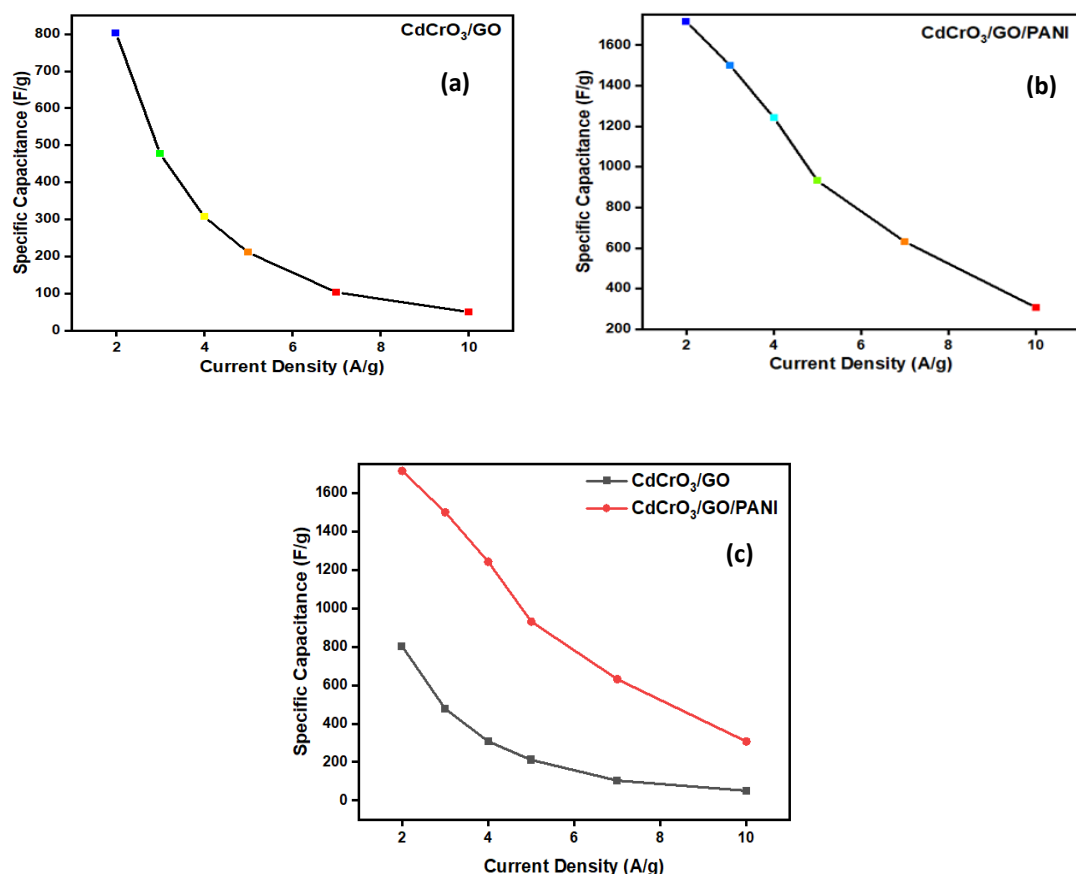


Figure 8: Specific capacitance (Fg⁻¹) verses Jd (Ag⁻¹) for (a) GO/CdCrO₃ and (b) PANI/GO/CdCrO₃, and (c) Comparison of both Nanocomposites s

Furthermore, both electrodes exhibit characteristic pseudocapacitive features, with discharge times of 303.55 s for the binary system and 765 s for the ternary composite under identical conditions, as illustrated in Fig. 8 (c). This substantial difference reflects the distinct and more efficient charge storage mechanism in the ternary configuration [73, 74]. The corresponding specific capacitance Cs values derived from the GCD measurements are summarized in Table 3.

Table 3: GCD data for Specific Capacitance calculations

Sample Name	2 Ag ⁻¹ (Fg ⁻¹)	3 Ag ⁻¹ (Fg ⁻¹)	4 Ag ⁻¹ (Fg ⁻¹)	5Ag ⁻¹ (Fg ⁻¹)	7 Ag ⁻¹ (Fg ⁻¹)	10 Ag ⁻¹ (Fg ⁻¹)
GO/CdCrO ₃	802	477	307	211	103	50

(C _{sp})						
PANI/GO/CdCrO ₃	1715	1500	1242	930	631	307
(C _{sp})						

The GCD responses of the GO/CdCrO₃ binary and PANI/GO/CdCrO₃ ternary electrodes reveal a combined electric double-layer capacitance (EDLC) and pseudocapacitive mechanism. In this hybrid behavior, GO contributes to capacitive plateaus, while the presence of faradaic redox features confirms additional pseudocapacitive contributions (see Table 3). The involvement of GO significantly improves electrical conductivity and increases the accessible surface area, resulting in extended discharge durations and enhanced capacitance values [44].

Table.4 A Comparative study of Cs values of present research with relevant Literature works

Sr. No.	Specific Capacitance (Fg ⁻¹)	Specimens	Electrolyte	Current density (Ag ⁻¹)	References
1.	1580	GO/BiCrO ₃	2.0 M KOH	2	[62]
2.	1980	GO/BiCrO ₃ /PANI	2.0 M KOH	2	[62]
3.	802	rG/LaMnO ₃ /PANI (Sc)	PVA-KOH-Gel	1	[31]
4.	262.5	MnSiO ₃ /GO	1M Na ₂ SO ₄	0.5	[19]
5.	812	BiFeO ₃ /NC	H ₂ SO ₄	0.5	[75]
6.	1264	BaSnO ₃ /rGO	KOH	1	[16]
7.	722	LaAlO ₃ /rGO	KOH	2	[76]
8.	367	rGO/LaFeO ₃	KOH	1	[77]
9.	802	CdCrO ₃ /GO	2 M KOH	2	This work
10.	1715	GO/CdCrO ₃ /PANI	2 M KOH	2	This work

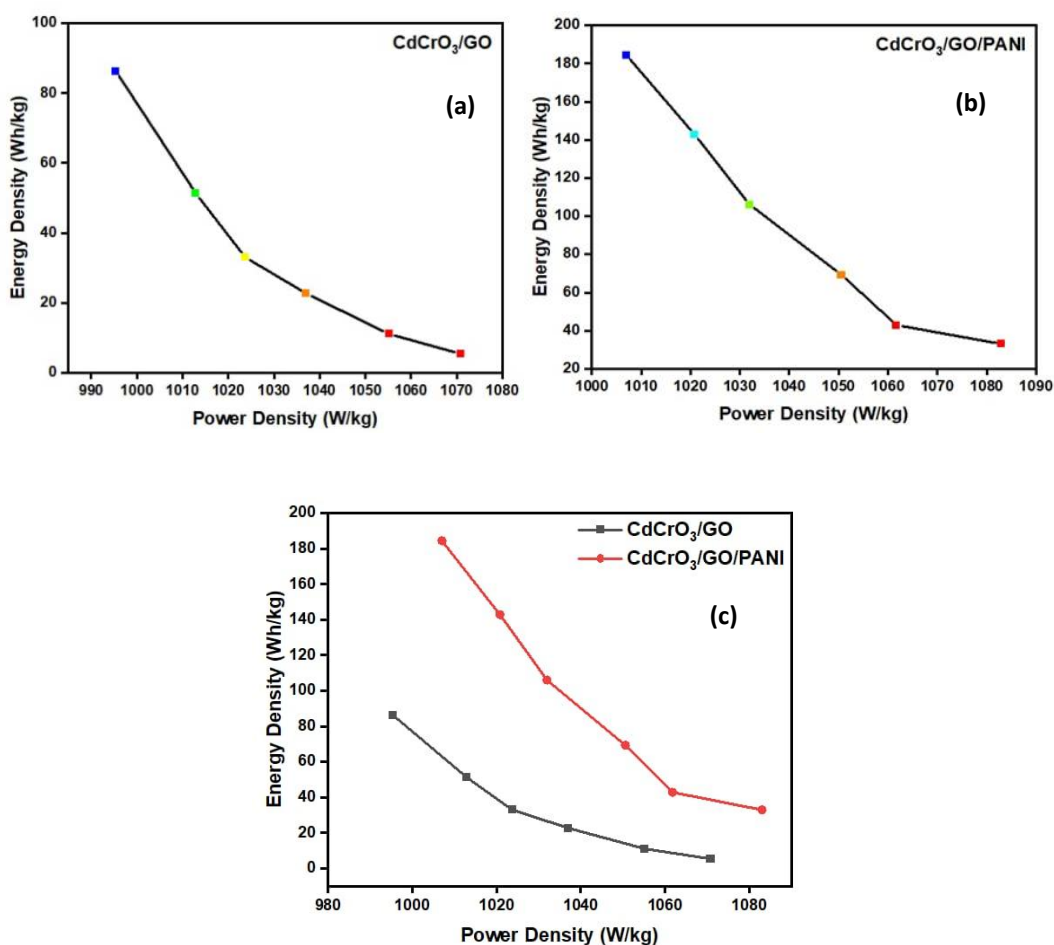


Figure 9: The Ragone plot of (a) GO/CdCrO₃ (b) PANI/GO/CdCrO₃, and (c) comparative plots for both nanocomposites.

The energy (E_d) and power (P_d) densities were determined using Equations (3) and (4). For the GO/CdCrO₃ binary electrode, the calculated values are 86.2 Wh kg⁻¹ and 995.4 W kg⁻¹, respectively. In contrast, the PANI/GO/CdCrO₃ ternary nanocomposite demonstrates superior electrochemical performance, achieving an energy density E_d of 184.4 Wh kg⁻¹ along with a power density P_d of 1007 W kg⁻¹, as illustrated in Fig. 9 (a–c).

Electrochemical impedance spectroscopy (EIS) is the very impactful technique for the investigation of electrochemical diffusion processes and dynamics of ion diffusion as compared to other electrochemical techniques [78]. It was employed to elucidate the charge transport behavior and electrical conductivity of the electrodes over a frequency range of 0.1 Hz to 100 kHz, using a sinusoidal AC perturbation of 5 mV [79]. The corresponding Nyquist plots for CdCrO₃/GO and PANI/GO/CdCrO₃, as

shown in Fig. 10, exhibit three distinct regions, each reflecting different electrochemical processes.

In the high-frequency domain, the real axis intercept represents the equivalent series resistance (ESR), which arises from contributions of the electrolyte, intrinsic material resistance, and electrode–current collector contact. All electrodes display low ESR values of less than 1 ohm, representing efficient charge transport characteristics.

The intermediate-frequency region features a semicircular arc associated with the charge-transfer resistance (R_{ct}) at the electrode–electrolyte interface, where the diameter of the semicircle corresponds directly to R_{ct} [80]. A progressive reduction in this diameter is observed from pristine CdCrO_3 to CdCrO_3 with GO and further to the PANI/GO/ CdCrO_3 ternary system, signifying enhanced interfacial conductivity due to the synergistic contributions of GO and PANI. This trend is in accordance with the electrochemical behavior observed in CV and GCD analyses [77] .

The Nyquist plots, at low frequencies, exhibit an approximately vertical line, attributed to Warburg diffusion impedance (Z_p), which reflects ion diffusion within the electrode material. Hydroxyl ions disperse in the low frequency array as a direct line in the electrode material [69]. In an ideal capacitive system, this line approaches a vertical orientation (approximately 90° to the real axis), indicating efficient ion transport kinetics [31] .

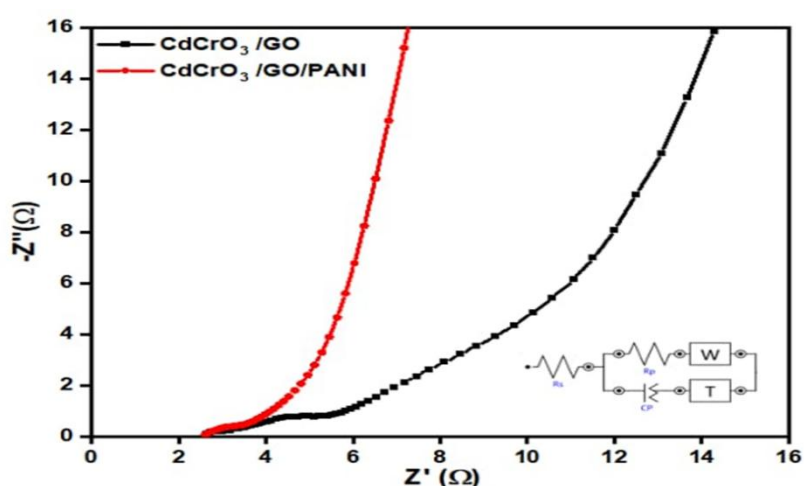


Figure 10: EIS plot PANI/GO/ CdCrO_3 nanocomposite.

Particularly, the PANI/GO/CdCrO₃ ternary electrode displays a reduced charge-transfer resistance value of $R_{ct} = 1.30 \, \Omega$ for the ternary composite as compared to $R_{ct} = 2.50 \, \Omega$ for the GO/CdCrO₃/GO binary system, indicating improved electrical conductivity. The R_s is usually due to ionic resistance and intrinsic resistance of the substrate, and R_{ct} is mainly related to interface contact resistance between the electrode material and current collector [81]. Whereas the series resistance (R_s) of the PANI/GO/CdCrO₃ ternary composite is also relatively low ($2.3 \, \Omega$), further supporting efficient charge transport. The presence of Warburg impedance features is associated with diffusion-controlled processes and suggests effective charge migration inside the electrode, which contributes to enhanced energy storage performance [76].

Furthermore, the Nyquist profile of the ternary electrode approaches an ideal vertical line ($\sim 90^\circ$) in the low-frequency region, reflecting superior capacitive behavior relative to the binary counterpart. All impedance spectra were analyzed using an appropriate equivalent circuit model in the above Figure 10.

Overall, the EIS results reveal low solution resistance and charge-transfer resistance, indicative of strong electrode–electrolyte interactions and excellent electrical conductivity. These findings confirm that the synergistic incorporation of CdCrO₃, Graphene oxide, and PANI significantly improves the kinetics of charge transport and capacitive characteristics, establishing the PANI/GO/CdCrO₃ ternary nanocomposite as a promising high-performance electrode material for supercapacitor applications.

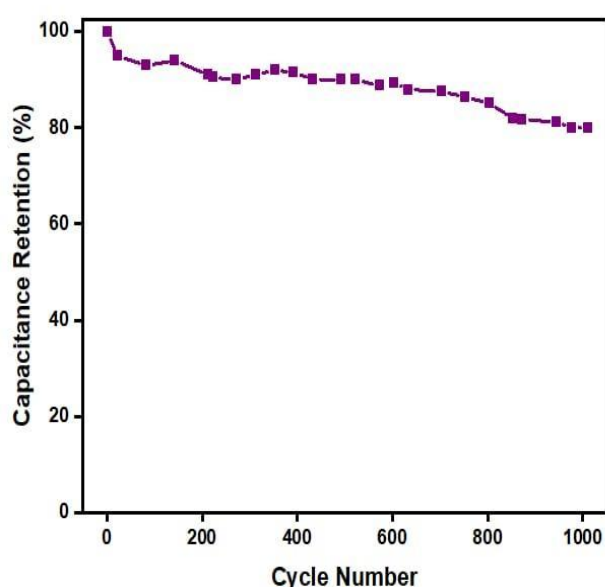


Figure 11: Cyclic stability of GO/CdCrO₃/PANI nanocomposite.

Figure 11. presents the long-term GCD performance of the GO/CdCrO₃/PANI electrode evaluated over 1000 cycles at a 1 A g⁻¹ current density. The electrode retains 80 % of its initial specific capacitance after prolonged cycling, highlighting the excellent electrochemical durability and stability of the ternary nanocomposite system. In this investigation, by using a hybrid of PANI, CdCrO₃ and GO we present a novel symmetric electrode configuration for supercapacitors.

Conclusion

The assembled device demonstrated outstanding electrochemical performance, delivering a Cs of 1715 F g⁻¹, achieving an Ed of 184.4 Wh kg⁻¹, with a Pd of 1007 W kg⁻¹. When tested at 1 Ag⁻¹, the composite maintained 80% of its initial capacitance over 1000 cycles and attained a coulombic efficiency. Furthermore, the PANI/CdCrO₃/GO composite exhibits a solution resistance of 2.3 Ω and charge-transfer resistance R_{ct} values of 1.30 Ω for the ternary composite, when compared GO/CdCrO₃ binary system with 2.50 Ω, reflecting improved electrical and interfacial charge-transfer characteristics. Structural analysis revealed improved crystallinity of the Orthorhombic phase, while FTIR confirmed the characteristic organic ligands and surface functional groups of the synthesized materials. The enhanced capacitance, conductivity, and long-term cycling behavior demonstrate the effectiveness of GO incorporation and establish PANI/CdCrO₃/GO as a promising electrode material for next-generation supercapacitors. Moreover, the adopted in-situ chemical oxidative polymerization strategy provides a straightforward and economical pathway for designing PANI/CdCrO₃/GO based materials with desirable electrochemical properties.

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