

Synthesis and Electrochemical Performance Evaluation of a Thermally Reduced ZnO@V2O5 Binary Nanocomposite for Supercapacitor Applications

Naveen Jyoti Jyoti

Guru Gobind Singh Indraprastha University

Arpita Kajal

Guru Gobind Singh Indraprastha University

Kajal Kajal

Guru Gobind Singh Indraprastha University

Aniket Bharti

Guru Gobind Singh Indraprastha University

Raju Tiwari Tiwari

Boudhik Sampada Bhawan

Anurag Gaur Gaur

Netaji Subhas University of Technology

Rajesh Kumar Kumar

rajeshkumar@ipu.ac.in

Guru Gobind Singh Indraprastha University

Research Article

Keywords: Nanocomposite, Vanadium pentoxide, Zinc oxide, Specific capacitance, Supercapacitor

Posted Date: August 8th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10337695/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Journal of Materials Science: Materials in Electronics on October 6th, 2026. See the published version at <https://doi.org/10.1007/s10854-026-18544-7>.

Synthesis and Electrochemical Performance Evaluation of a Thermally Reduced ZnO@V₂O₅ Binary Nanocomposite for Supercapacitor Applications

Naveen Jyoti¹, Arpita sharma¹, Kajal¹, Aniket Bharti¹, Raju Tiwari³, Anurag Gaur⁴, Rajesh Kumar^{1, 2*}

¹University School of Basic and Applied Sciences,

Guru Gobind Singh Indraprastha University, New Delhi 110078, India

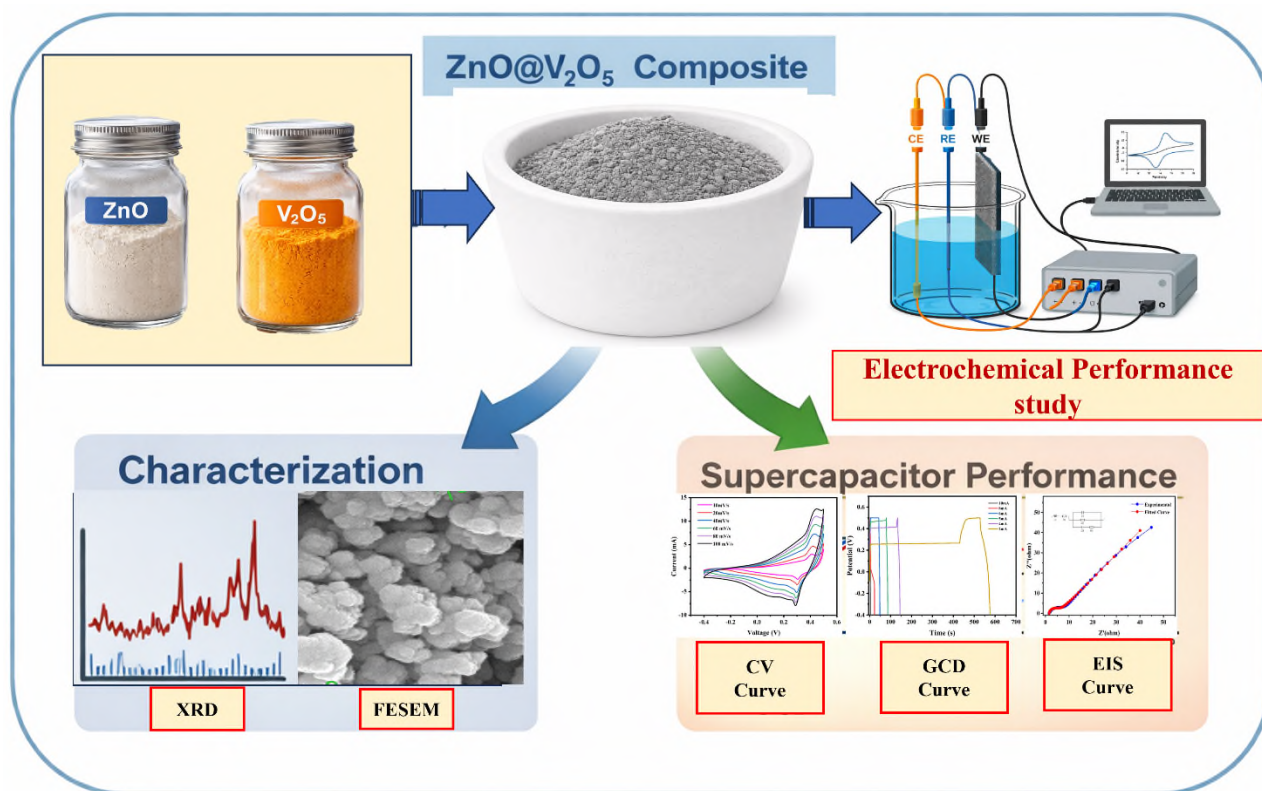
²Delhi Skill and Entrepreneurship University, New Delhi-110077, India

³Boudhik Sampada Bhawan, New Delhi-110078, India

⁴Department of Physics, Netaji Subhas University of Technology, New Delhi, 110078, India.

Abstract

Developing electrode materials that simultaneously exhibit good electrical conductivity and high electrochemical activity remains a primary concern for high-performance supercapacitors. To address this, we have synthesised a ZnO@V₂O₅ based binary nanocomposite. The composite was synthesised through a simple solid-state method by thermally reducing the oxides, which enables effective integration of ZnO and V₂O₅ at the nanoscale level. The morphological study showed a well-built composite structure that helps ions move through short pathways for faster transport, while the structural and phase examination verified the development of crystalline ZnO and V₂O₅ within the composite. Galvanostatic charge–discharge measurements and cyclic voltammetry were employed to evaluate the electrochemical performance of the synthesised electrode in 2 M KOH electrolyte. The ZnO@V₂O₅ electrode was found to exhibit stable charge–discharge characteristics with good rate capabilities at a varying current of 2–10 mA. Also, the Cyclic voltammetry measurements revealed an overall specific capacitance of 80 F g^{−1} at a scan rate of 10 mV s^{−1}, demonstrating effective charge-storage behaviour. The current contributions were analysed and found to be predominantly diffusion-controlled, suggesting that Faradaic ion intercalation is the principal and dominating charge-storage mechanism in the nanocomposite. Overall, the ZnO@V₂O₅ nanocomposite is considered a promising electrode material for supercapacitor applications.



Keywords Nanocomposite, Vanadium pentoxide, Zinc oxide, Specific capacitance, Supercapacitor.

*Corresponding author: rajeshkumar@ipu.ac.in

1. Introduction

Rising greenhouse gases, global warming, and dwindling fossil fuels are pushing the world to find renewable energy sources and better ways to store the power. Energy production and consumption, which rely on burning fossil fuels, may have a significant effect on the environment and world economy. As a result, there was an increased demand for low-cost, high-performing, and ecologically friendly storage systems for renewable energy. Supercapacitors stand out as the top choice as they deliver high power density, charge and discharge in a flash, and last far longer than batteries, while packing more energy than a standard capacitor. Supercapacitors deliver far greater power density than batteries, making them appealing for portable gadgets, humming electric buses [1],[2] and sleek electric trains. Supercapacitors are mainly grouped into three types, each defined by how they store charge. They include electric double-layer, pseudocapacitive, and faradic materials. In carbon materials

like nanotubes, graphene, and activated carbon, energy stores through a mechanism based on the electric double layer, where charge builds quietly along each tiny surface [3]. Pseudo capacitors with metal oxide or conducting polymer electrodes and high electrochemical pseudo capacitance material are another kind of supercapacitor. Similar to oxidation-reduction reactions, the Faradaic mechanism involves the transfer of charge between the electrode and electrolyte. The third type consists of asymmetric electrode hybrid capacitors, of which one is mostly electro-static and the other is electro-chemical [4],[5]. Nowadays, binary metal oxides (BMOs) have gained significant attention for supercapacitor applications owing to the synergistic interaction between two metal cations, which enhances electrical conductivity, redox activity, and charge-transfer kinetics [6]. To boost how much charge the material can hold, researchers have turned to binary metal oxides mixes of two transition metals that fuse into one powerful composite structure [7]. Various combinations of metal oxide and transition metal oxide nanocomposites, commonly known as binary transition metal oxide (BTMOs) are widely considered due to their unique physical, chemical, electrical, magnetic and optical properties [8]. Additionally, BTMOs have a low cost, a wealth of mineral resources, and an excellent theoretical capacitance. Ternary and even quaternary metal oxides have more redoxactive centres and a composition that can be adjusted in comparison to BTMOs. It is considered that there are more active sites and a more predictable capacity and capacitance when there are more redox-active centres [9]. Explored binary metal oxides like NiCo_2O_4 , MnCo_2O_4 , ZnV_2O_5 , CoMoO_4 , or $\text{Fe}_2\text{V}_2\text{O}_7$ were found to deliver stronger redox activity, better conductivity, and plenty of accessible electroactive sites compared to oxides made from a single metal.[10] Because two metal ions are present, several oxidation states can take part in charging and discharging, boosting pseudocapitance and speeding up the reactions. Their mix of strengths clear electronic pathways, extra oxygen gaps, and a tough, stable framework makes them a standout choice for next-generation supercapacitors [1],[11]. Various studies have also shown that pairing oxides such as Ni–Co, Mn–Co forms uneven interfaces that speed up ion flow and pack in more electroactive sites than single oxides [12],[13]. Additionally, the blend of oxidation states and the defect-packed lattices that often form in binary oxides speed up faradaic reactions, leading to greater energy density and faster rate performance. These materials show stronger cycling stability because their volume hardly shifts during redox reactions, which makes them especially appealing for next-generation supercapacitors. Among various other transition-metal oxides, vanadium pentoxide (V_2O_5) is as an exceptional pseudocapacitive material due to its flexible oxidation states (V^{5+} , V^{4+} , V^{3+}) driving fast, reversible Faradaic redox reactions electrons [14],[15]. In addition to its mixed valence states

and layered crystalline structure, V_2O_5 has a large theoretical specific capacity (2120 F g^{-1} at 1 V). It is also a very promising candidate for supercapacitor applications due to its easy synthesis, earth-abundant nature, and non-toxic properties. However, V_2O_5 has a relatively low structural stability and electrical conductivity, which causes the insertion/extraction of ions to proceed slowly. Moreover, its layered design lets ions glide in and out with ease, building remarkable theoretical capacitance [16]. Even so, pure V_2O_5 often loses conductivity and its structure starts to crumble after many cycles, so researchers mix it with conductive supports such as rGO or polymer meshes to keep charges flowing and the material strong [17]. By contrast, zinc oxide (ZnO) shines for its wide band gap, stable chemistry, and eco-friendly character traits that make it a favourable in hybrid electrode systems [18]. Pure ZnO delivers only modest capacitance because its redox activity's limited, but its structure allows rapid electron movement, enhance surface contact and let ions slip through with ease. When paired with V_2O_5 , ZnO teams up to raise conductivity and stabilize the electroactive framework, giving the system more capacitance, quicker charge–discharge cycles, and a longer lifespan. Nevertheless, V_2O_5 has a slow rate of ion insertion and extraction due to its comparatively low structural stability and electronic conductivity. Significant work has been done in this study to increase ZnO's electron diffusion rate and improve its capacitive capabilities when combined with V_2O_5 .

In this study we have synthesised a binary transition metal oxide (BTMO) comprised of ZnO and V_2O_5 . Objective of this work is to examine how composition affects ZnO's electrochemical performance in combination with V_2O_5 . Capacitance and charge-discharge properties of the synthesised composite were assessed using 2M KOH as the electrolyte in a conventional three-electrode configuration.

2. Experimental section

2.1 Chemicals

Vanadium (III) acetylacetonate, polyvinylidene difluoride (PVDF) and graphite fine powder was purchased from Sigma Aldrich at 98% purity. Polyvinylpyrrolidone and Ethylene glycol were purchased from SRL chemicals with 99% purity. Zinc Oxide were purchased from Thomas baker with 98% purity. Carbon black, acetylene (100% compressed) and N-methyl 2 pyrrolidone NMP, was purchased from Thermo Scientific Chemicals with 99.99% purity.

2.2 Synthesis

Synthesis of $\text{ZnO}@V_2O_5$ binary metal oxide nanocomposite

The $V_2O_5@ZnO$ binary metal oxide nanocomposite was synthesised by merely heating the mixture through thermal decomposition, as shown in Fig.1[19]. until it became a fine, grey powder. Using an agate mortar and pestle, we ground the powders of zinc oxide and vanadium pentoxide in the proper ratio until the mixture was smooth and pale grey, resembling fine dust. V_2O_5 and ZnO were fused by constant heat in a glowing muffle furnace after the fine, uniform powder was poured into an alumina crucible. The metal was slightly warm to the touch as the composite gradually cooled on its own to room temperature after the heating was turned off. After that, it was ground again into a fine grey powder and kept for electrochemical testing and subsequent characterisation.

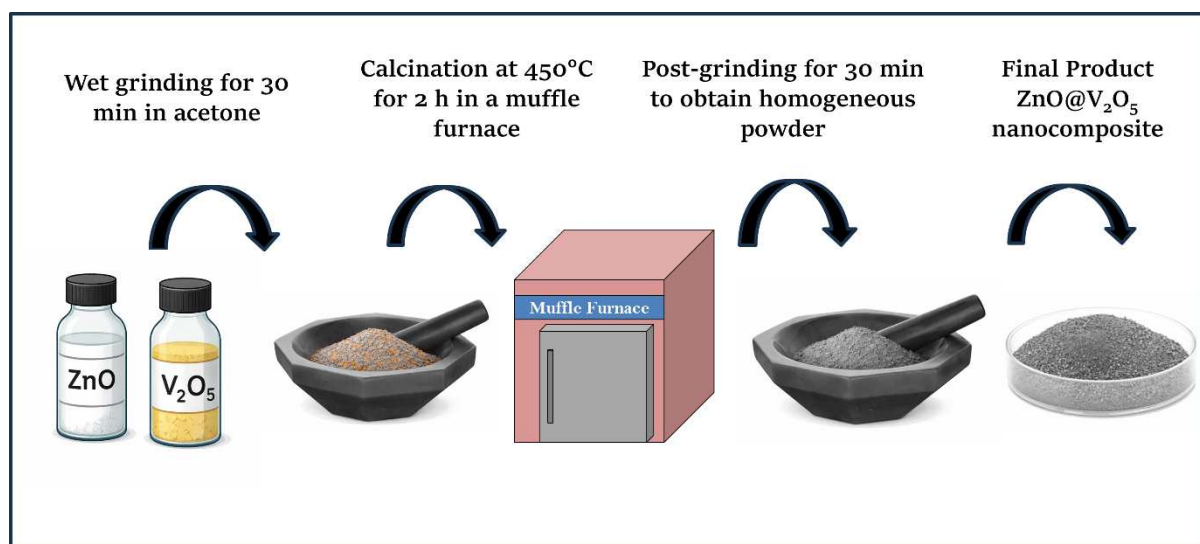


Fig. 1 Schematic representation of the synthesis route of the $\text{ZnO}@V_2O_5$ nanocomposite.

2.3 Electrode Fabrication:

The working electrode was made by combining carbon black, PVDF (polyvinylidene difluoride), and the active material ($\text{ZnO}@V_2O_5$ nanocomposite) in 16:2:2 ratio. PVDF is a chemically stable polymer that serves as a binder, keeping active material and conductive additives together. A mortar and pestle were used to thoroughly mix all three compounds. The mixture was continuously mixed for several hours before three to four drops of N-methyl-2-pyrrolidone (NMP) solvent were added dropwise. After adhering this uniform slurry to 1×1

cm² of nickel foam, it was dried for a few hours at 80°C in an oven [20,21]. The stepwise electrode fabrication process is shown in Fig.2.

3. Characterisation Techniques

The prepared composite underwent a comprehensive characterisation procedure to evaluate its structural, morphological, and electrochemical properties. X-ray diffraction (XRD) patterns were recorded using an XRD BRUKER D8 ADVANCE instrument operating at 40 kV and 25 mA with a Cu K α X-ray source ($\lambda = 1.5418 \text{ \AA}$), ranging 2 θ from 8° to 60°. Apreo Lovac field emission scanning electron microscopy (FESEM) was used to obtain high-resolution

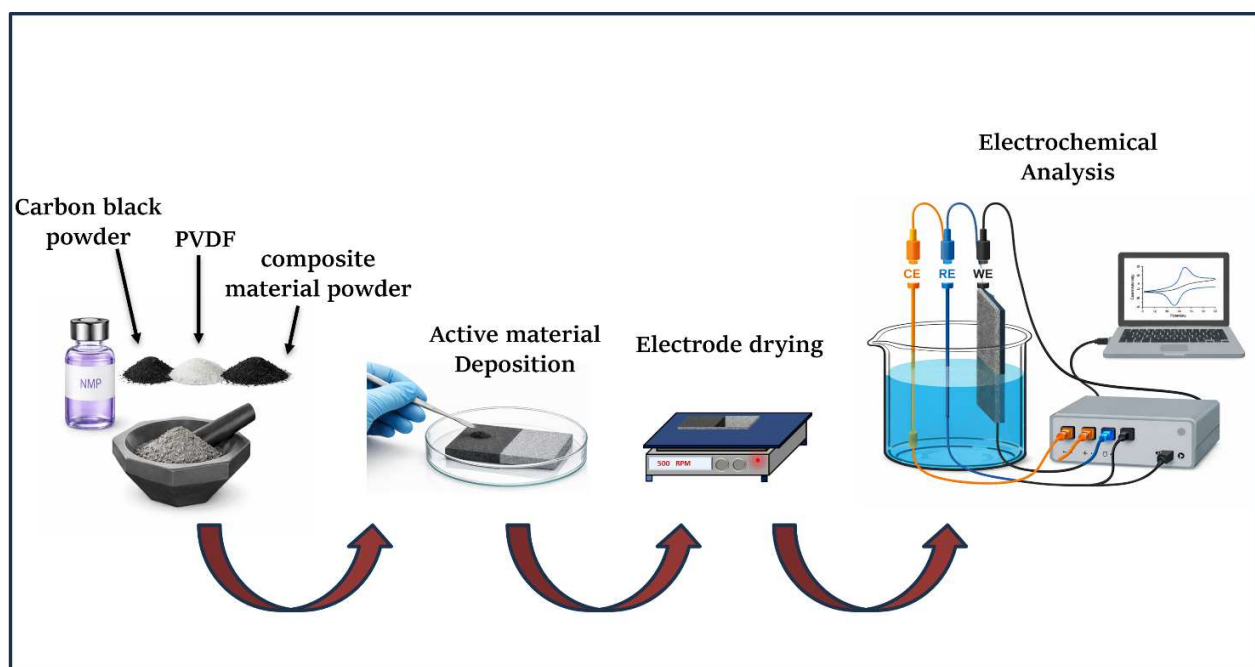


Fig. 2 Schematic diagram showing stepwise electrode fabrication process, including active material slurry preparation, coating onto current collectors, drying, and assembly for electrochemical testing.

surface images in order to determine the texture and surface morphology of the samples. To check the surface area and porosity of the synthesised composite, a BET (Brunauer Emmett Teller) surface area analyzer Quantachrome Nova 2200e was used. In order to obtain cyclic voltammograms and perform galvanostatic charge-discharge tests, electrochemical properties were characterised using a three-electrode CV setup Biologic SP-240. The charge-transfer resistance and ion-diffusion properties were also examined using electrochemical impedance spectroscopy (EIS).

4. Results and Discussions

4.1 X-Ray Diffraction Analysis

The XRD spectra of the prepared V₂O₅, pristine ZnO and synthesised ZnO@V₂O₅ composite are displayed in Fig.3(a), (b), and (c), respectively. All the diffraction peaks observed in Fig.3(a) corresponds to orthorhombic phases of V₂O₅ and are well matched with the JCPDS-89-0612 [22]. The diffraction peaks observed in Fig. 3(b) correspond to the hexagonal wurtzite phases. Fig.3(c) depicts the diffraction peaks of the synthesised ZnO@V₂O₅ nanocomposite. As observed in the XRD patterns, the composite was found to retain characteristic ZnO reflections at ~31.7°, 34.4°, and 36.2°, corresponding to the (100), (002), and (101) planes [23] [24], also known as the characteristic triplet for ZnO, but Changes in crystallite orientation, partial peak overlap with V₂O₅ reflections, and interfacial interactions between ZnO and V₂O₅ inside the composite matrix are the causes of this intensity variation. Moreover, the V₂O₅ phase is also preserved in the ZnO@V₂O₅ composite at lower 2θ (around ~15°, ~20°, and ~25°) regions with slight intensity variations, indicating successful incorporation of V₂O₅ and strong interfacial interaction with the ZnO lattice. Thus, the diffraction peaks from both ZnO and V₂O₅ are clearly present, confirming the coexistence of both phases and successful composite formation. Additionally, the average crystallite size of the synthesised composite was analysed using the Debye–Scherrer equation as shown in equation (1).

$$D = \frac{k\lambda}{\beta \cos \theta} \quad - (1)$$

Where β is the full width at half maximum (FWHM) and is the shape factor (0.9), λ is the wavelength of Cu Kα radiation [25] . Also, dislocation density was calculated, which gives insight into the defect density of the composite. Table 1 shows the various parameters calculated using the Debye-Scherrer equation.

Table 1. Effective particle size, crystallite size, strain and dislocation density of all three sample

Sample	2 θ (°)	FWHM (°)	Average crystallite size using Scherrer's formula D (nm)	Dislocation density δ (1/ nm ²) ($\times 10^{-4}$)
V ₂ O ₅	25.90	0.004	35.42	0.0007
ZnO	36.5	0.021	6.72	0.022
ZnO@V ₂ O ₅	30.6	0.022	6.46	0.239

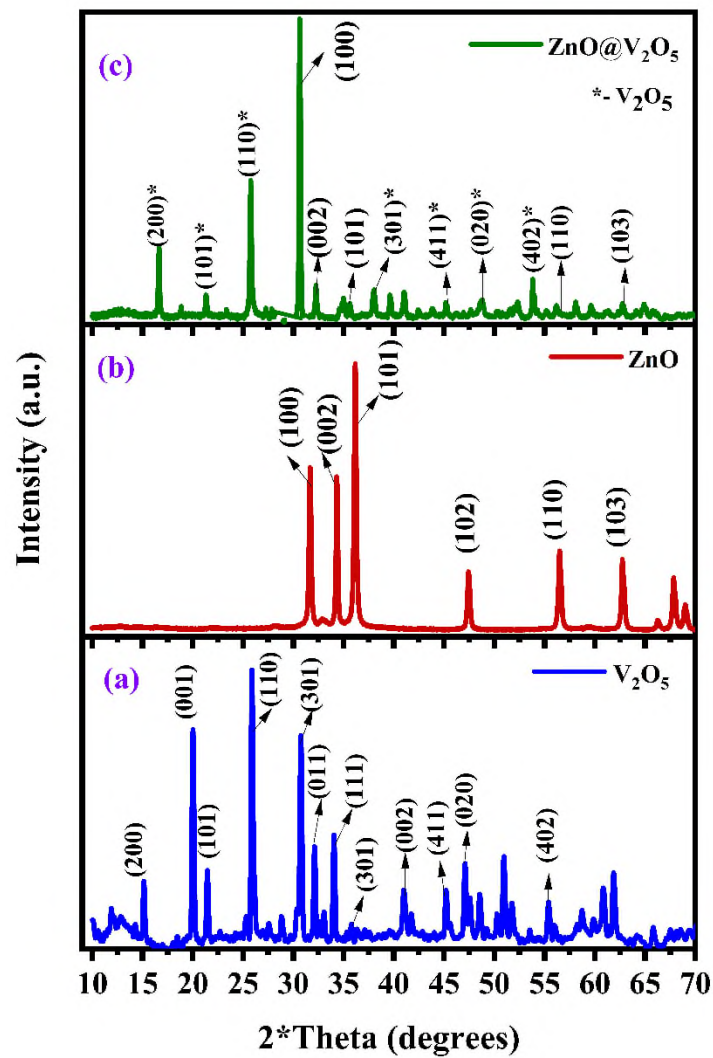


Fig. 3. shows the XRD patterns of (a) pristine V₂O₅, (b) pristine ZnO, and (c) ZnO@V₂O₅ composite.

4.2 FESEM Analysis

We examined the surface of the synthesized $\text{V}_2\text{O}_5/\text{ZnO}$ nanocomposite using FESEM at two magnifications, as shown in Fig.4. The composite exhibits a noticeable, grainy texture at low magnification, with tiny particles dispersed throughout its surface. The precursor materials nucleate and form tiny crystallites. These crystallites then cluster together to reduce surface energy, forming the grain-shaped structure [26], [27]. The Gaussian distribution verifies a restricted size distribution, indicating good uniformity of the nanostructures, and the FESEM analysis shows a uniform morphology with an average grain size of about 110 nm. At higher magnification, the grains look packed, their edges pressing together to form a smooth network that boosts ion mobility and reveals more sites for electrochemical reactions [28]. This step makes sure the composite comes together perfectly. Pure V_2O_5 typically shows up as thin, brittle flakes, while ZnO tends to grow into round grains. In the blend, each distinct trait fades away, merging into one smooth surface [29]. This shows how V_2O_5 and ZnO bond tightly as heat breaks them down, pulling their atoms closer until the structure feels denser and more unified. This shape boosts the supercapacitor's performance by increasing surface area, letting the electrolyte slip easily through narrow gaps, and giving electrons a smoother path.

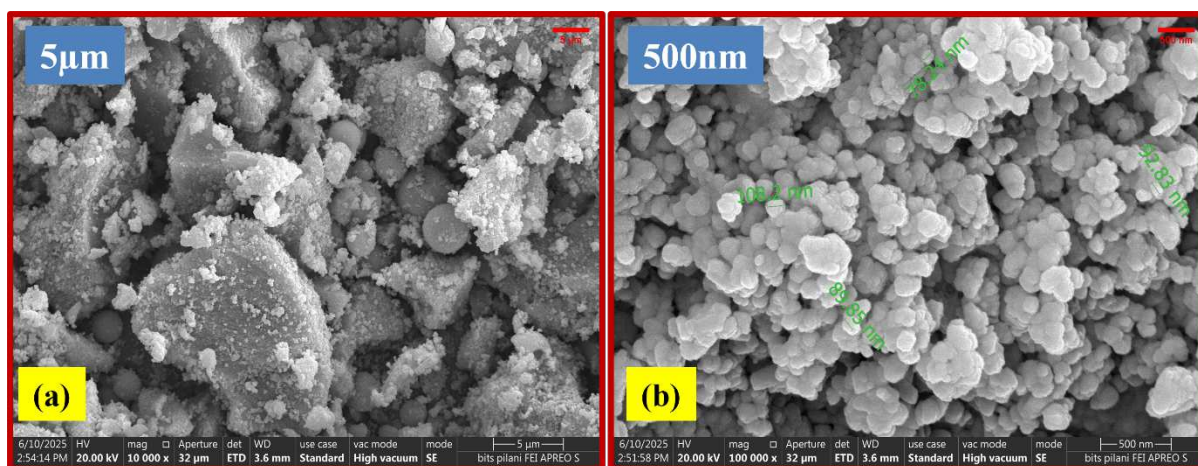


Fig.4 FESEM images of $\text{ZnO}@\text{V}_2\text{O}_5$ composite sample at two different magnifications.

The left column shows low-magnification images (1 μm), and the right column shows higher magnification (500nm) revealing finer morphological details.

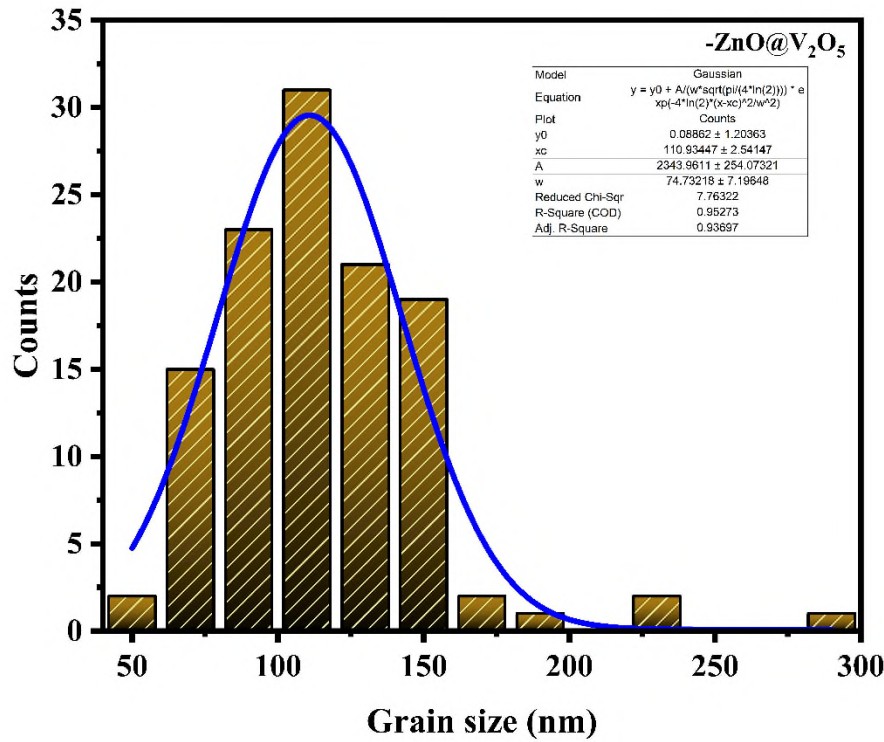


Fig. 5 Histogram of particle sizes measured from FESEM micrographs of the ZnO@V₂O₅ composite.

4.3 BET Analysis

Various textural properties of the synthesised material were investigated by N₂ adsorption–desorption measurements conducted at 77 K. Fig.6 clearly depicts the obtained isotherm, which exhibits type-IV behaviour with a hysteresis loop showing mesoporous structure. The material was found to exhibit the specific surface area of 31.167m²/g evaluated using Braunaauer-Emmett-Teller method relative pressure (P/P₀) range of 0.1–1.0.

Previous studies show that ZnO nanoparticles made by the sol–gel process have an extremely small BET surface area, around 0.23 m²/g [30]. since particles clumps or agglomerate together and grows thick. Whereas, after composite formation tight contact between ZnO and V₂O₅ that keeps the particles from clumping and helps a fine, sponge-like porous structure emerge. V₂O₅ nanostructures open up tiny gaps between particles and reveal more active sites, making it easier for the electrolyte to reach them and for ions to flow smoothly through. The larger surface area helps boost the composite electrode's pseudocapacitive behaviour and overall electrochemical performance [31].

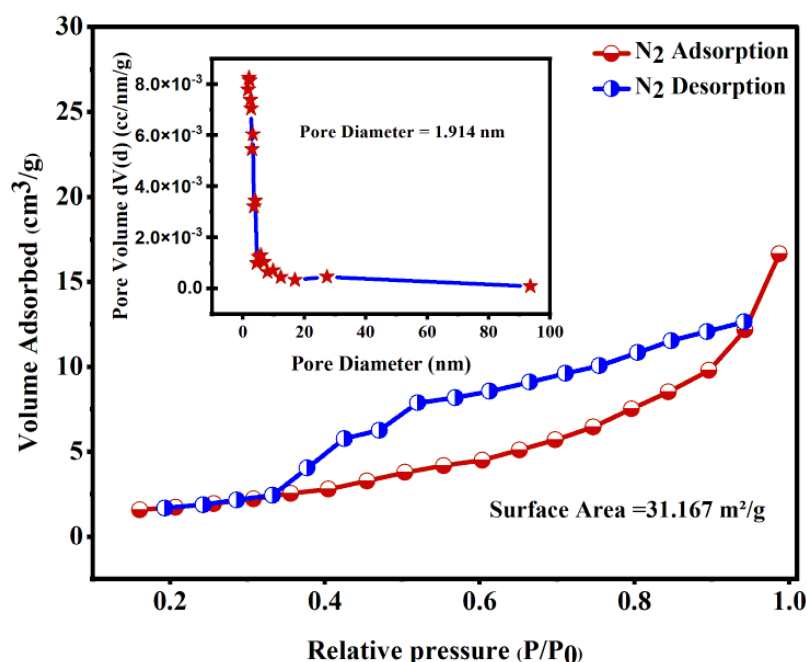


Fig. 6 Nitrogen adsorption–desorption isotherms and BET surface area analysis of the ZnO@V₂O₅ composite.

The mesoporous nature and increased surface area facilitate enhanced electrolyte accessibility and charge storage performance.

5. Electrochemical Investigation

We tested the synthesized active materials in a standard three-electrode cell filled with 2M KOH, noting their electrochemical response. A platinum wire served as the counter electrode, and an Ag/AgCl electrode acted as the reference, while the active material was coated onto nickel foam, the working electrode. We evaluated the capacitive performance using electrochemical tests such as impedance spectroscopy (EIS), galvanostatic charge–discharge (GCD), and cyclic voltammetry (CV), watching the current trace rise and fall with each cycle.

5.1 Cyclic Voltammetry

Cyclic voltammograms (CVs) of the synthesized ZnO@V₂O₅ nanocomposite are cycled under the potential range of -0.4 to 0.5 V at a varying scan rate of 10,20,40,60,80,100mV/s which is displayed in Fig.4 below. The CV curves measured at various scan rates show sharp redox peaks, revealing that the capacitance mainly comes from pseudocapacitive Faradaic reactions,

not just simple electrostatic charge buildup on the electrode's surface. These redox traits stem from the reversible V^{5+}/V^{4+} oxidation–reduction reactions working in tandem with Zn^{2+} -driven surface changes, a pattern often seen in vanadium- and zinc-based oxide systems where even a thin oxide film can shift colour slightly as electrons move [32]. The cyclic voltammetry curves of the $ZnO@V_2O_5$ composite electrode show a strong current surge along with sharp redox peaks, confirming that pseudocapacitive charge storage is the main mechanism at play. As the scan rate climbs, the anodic and cathodic peak currents rise noticeably, showing faster charge transfer and quicker ion movement through the electrode matrix. The spacious enclosed region forms through the combined action of ZnO and V_2O_5 , creating plenty of electroactive sites and letting the electrolyte seep through easily. Zinc oxide alone is found to have very low intrinsic capacitance, e.g., $\sim 15 \text{ F g}^{-1}$ at 3 A g^{-1} [33]. All the specific capacitance values obtained at a particular scan rate is listed in Table.3. Pure ZnO electrodes typically exhibit low specific capacitance values (often $< 40 \text{ F g}^{-1}$). whereas the synthesised composite was found to deliver a specific capacitance of $\sim 80 \text{ F g}^{-1}$ at 10 mV/s , which is nearly double that of bare ZnO . On the other hand, at a higher scan rate, like 100 mV/s , a specific capacitance was observed to be 37.67 F/g which is because at low scan rates, electrolyte ions are provided sufficient time to go deep into all the available porous electrode structure so that they can fully access the available electroactive sites. Whereas, at higher scan rates, ion diffusion becomes partially limited to some extent, restricting charge storage mainly to the surface regions of the electrode only [34].

Table 2: Electrochemical performance comparison of $ZnO@V_2O_5$ nanocomposite from the literature.

Composite Material	Method	Specific Capacitance	Electrolyte	Scan Rate /Current Density	References
$ZnO@V_2O_5$	Hydrothermal	37.5 mF cm^{-2}	Aqueous	1 mA cm^{-2}	[35]
V_2O_5/ZnO film	magnetron sputtering	83.59 mF/cm^2	-	-	[36]
$ZnO@V_2O_5$	Solid-state Method	80 F g^{-1}	2M KOH	10 mV/s	This work

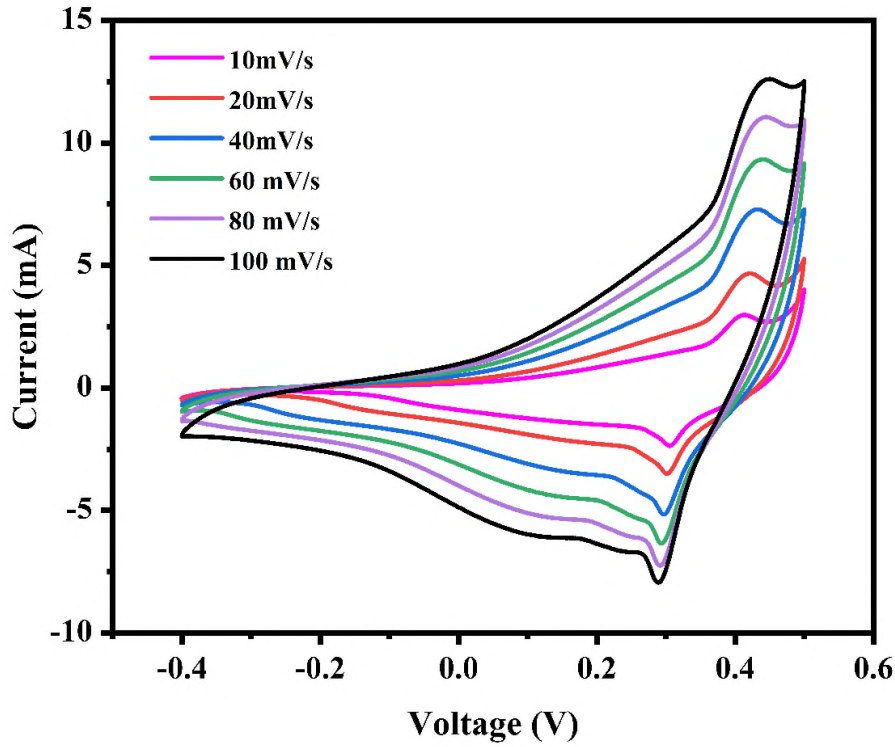


Fig. 7 Cyclic voltammetry (CV) curves of the ZnO@V₂O₅ composite electrode recorded at different scan rates. The increase in current response and enlarged enclosed area with scan rate indicate combined capacitive and diffusion-controlled charge storage behaviour.

The charge storage kinetics of the ZnO@V₂O₅ composite electrode were further analysed using the power-law relationship between peak current (i) and scan rate (v), expressed as $i = av^b$ [37][38]. The linear fit of $\log i$ versus $\log v$ yields a b -value of 0.61, as shown in fig 8(a), indicating that the charge storage mechanism is governed by a combination of diffusion-controlled Faradaic processes and surface capacitive effects. Using the relation $i(V) = k_1v + k_2v^{1/2}$, the charge storage mechanism was quantified by separating it into capacitive and diffusion-controlled contributions as shown in Fig. 8(b). From the obtained values of $k_1 = 0.04$ and $k_2 = 0.86$, it was confirmed that the charge storage process is predominantly governed by diffusion-controlled Faradaic reactions along with some small contributions from surface-controlled capacitive effects. Fig.8(c) shows how the capacitive and diffusion-controlled current contributions vary in the synthesised nanocomposite as the scan rate changes. When the scan rate slows, diffusion takes the lead, indicating better ion movement and at high scan rates, the composite still shows a strong diffusion-driven response [39]. Fig.8(d) illustrates the current contribution behaviour of the ZnO@V₂O₅ composite electrode at a single scan rate of

100 mV s^{-1} , highlighting the relative dominance of diffusion-controlled and capacitive charge storage processes. The shaded region represents the diffusion-controlled contribution, while the remaining portion corresponds to surface-controlled capacitive processes. At 100 mV s^{-1} , the diffusion-controlled current contributes dominantly to the total current response, indicating that Faradaic redox reactions play a major role in the charge storage mechanism of the composite.

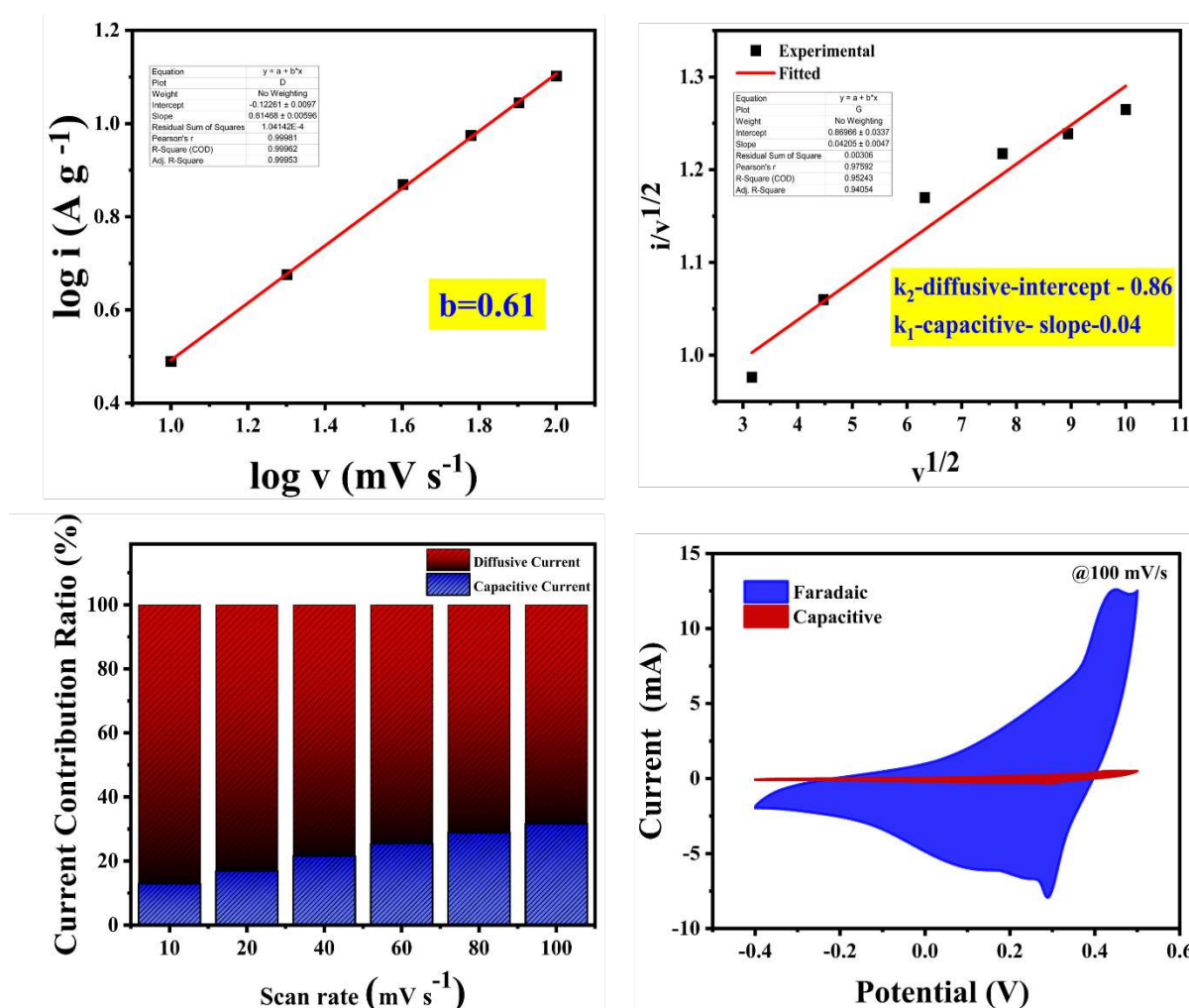


Fig. 8 (a) shows the cyclic voltammetry (CV) curves of the ZnO@V₂O₅ composite electrode recorded at different scan rates. (b) shows the $\log(i)$ versus $\log(v)$ plots obtained from CV data, (c) shows the variation of capacitive and diffusion-controlled current contribution ratios as a function of scan rate. (d) shows the separation of capacitive and diffusion-controlled current contributions at a fixed scan rate of 100 mV/s.

Similarly, Fig. 5 shows how the specific capacitance shifts with changing scan rate, drawn from cyclic voltammetry tests, with each curve rising and dipping. As the scan rate rises, the specific capacitance gradually falls. This drop occurs because, at slower scan speeds, electrolyte ions have more time to slip into the electrode's tiny inner active sites. Whereas, when the scan speed climbs, ions can't move as easily, most of the charge ends up stored on the electrode's outer surface [40].

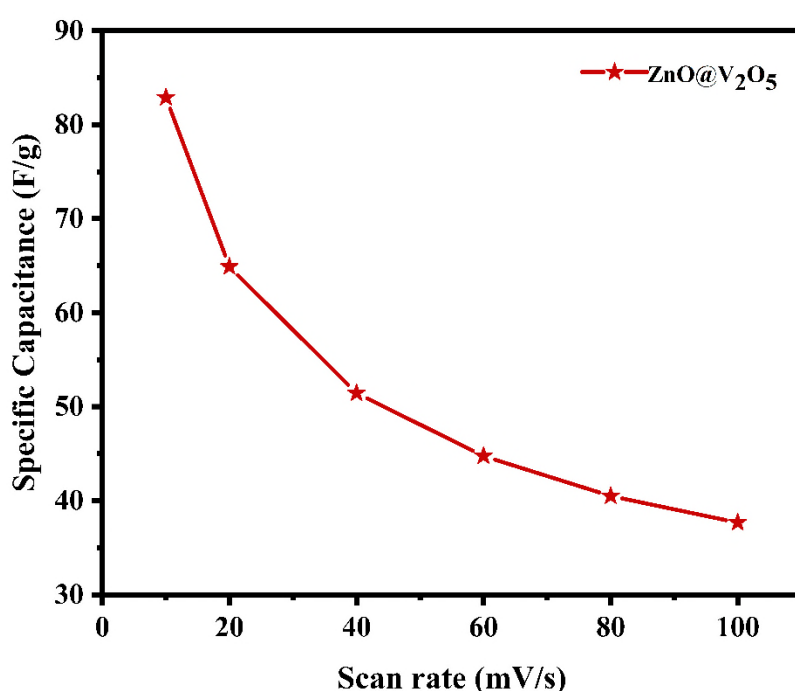


Fig. 9. Variation of specific capacitance as a function of scan rate for the electrode measured from cyclic voltammetry.

Table. 3 lists the energy density values calculated from the specific capacitance from CV. At a scan rate of 10 mV s⁻¹, the electrode hit its peak energy density of 9.32 Wh kg⁻¹. As the scan rate rose to 100 mV s⁻¹, the energy density gradually fell to 4.24 Wh kg⁻¹. When the scan is faster, the ions don't have enough time to travel through the electrolyte, so fewer charge-storing sites are used and the drop occurs. thus, the electrode stores energy well at every scan rate, proving it could charge and discharge fast and perform reliably.

Table 3. Specific capacitance and corresponding energy density of the synthesised electrode calculated from cyclic voltammetry (CV) measurements at different scan rates.

Scan rate (mV/s)	Specific Capacitance (F/g)	Energy Density (Wh Kg ⁻¹)
10	82.88	9.32
20	64.86	7.29
40	51.43	5.79
60	44.75	5.03
80	40.49	4.55
100	37.67	4.24

5.2 Galvanostatic charge discharge study

We ran galvanostatic charge–discharge tests in a three-electrode setup, using the prepared electrode as the working one, an Ag/AgCl electrode for reference, and a thin Pt wire as the counter electrode, all immersed in a 2 M KOH solution. GCD measurements were taken at various current densities, such as 2mA, 4mA, 5mA, 6mA, 8mA, 10mA, within a selected potential window ranging from -0.4V to 0.5V. GCD curves of the synthesised composite were found to exhibit plateau-like regions, which show that faradaic behaviour is predominant here as compared to ideal electric double-layer behaviour. At low currents, like 5mA, ions from the electrolyte get enough time to migrate and participate in reversible redox reactions, which results in higher charge storage and longer plateau-like discharge time regions [41],[42]. On the other hand, at low currents like 10mA, rapid electron extraction results in shorter discharge times. Also, shapes show identical and remained consistent at various currents, confirming the stable charge–discharge characteristics of the electrode [43].

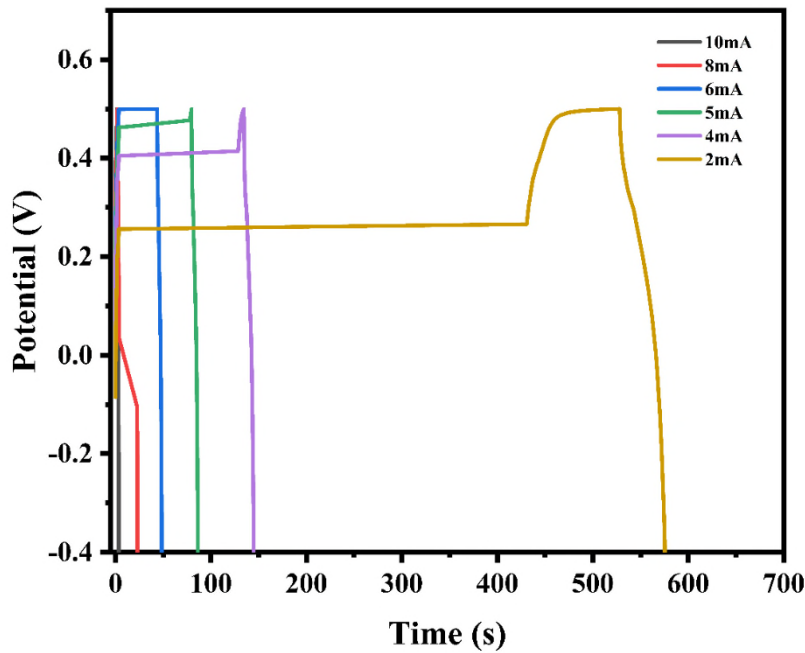


Fig. 10 Galvanostatic charge–discharge (GCD) curves of the ZnO@V₂O₅ composite electrode recorded at different current densities. The quasi-linear and symmetric profiles indicate good capacitive behaviour, reversible charge storage, and low internal resistance.

5.3 Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy was employed to study how charges moved and ions travelled through the ZnO@V₂O₅ composite electrode. On the Nyquist plot, a tight semicircle appears at high frequencies, then stretches into a slanted line at lower ones, showing both charge-transfer resistance and diffusion-driven behaviour at work [44]. The tiny intercept on the real axis marks the solution resistance (R_1), showing the electrolyte conducts ions easily and the electrode sits in close, solid contact with its current collector. The relatively low charge-transfer resistance (R_3) shows that charge moves more easily across the interface, due to the strong synergy between ZnO and V₂O₅, an effect often seen in transition-metal-oxide composites where electrons slip smoothly from one oxide layer to the next. In the low-frequency range, the system's imperfect capacitive behaviour appears as a constant-phase element (CPE), where the exponent ($\alpha < 1$) reflects uneven surface sites and the mixed, pseudocapacitive way charge builds up [45], [46]. The steep low-frequency tail clearly shows efficient ion diffusion and a dominant capacitive effect, matching earlier findings for ZnO and V₂O₅-based composite electrodes. Overall, the EIS outcomes reveal that forming the composite

lowers interfacial resistance and speeds up electron and ion movement, boosting the ZnO@V₂O₅ electrode's electrochemical performance. The complete EIS table, including all fitting parameters, is listed below in Table 4.

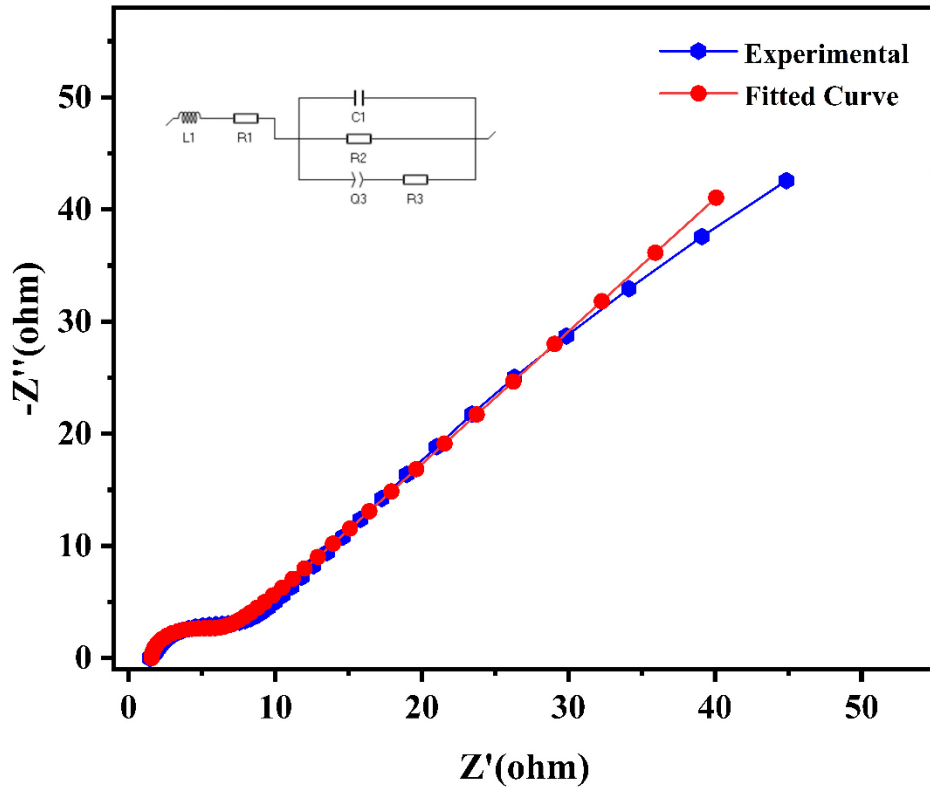


Fig. 11 Nyquist plot of the electrode obtained from electrochemical impedance spectroscopy (EIS), measured in the selected electrolyte. The inset shows the corresponding equivalent electrical circuit used to fit the impedance data.

Table 4: EIS Fitting Parameters for Composite

Parameter	Value	Unit	Standard Error
L ₁	6.89×10^{-97}	H	3.07×10^{-80}
R ₁	1.57	Ω	0.020
C ₁	1.49×10^{-3}	F	5.99×10^{-5}
R ₂	4.99×10^{31}	Ω	8.89×10^{40}
Q ₃	0.0668	F·s ^(a-1)	9.46×10^{-4}
a ₃	0.554	-	0.00569
R ₃	4.32	Ω	0.122

Conclusion

In this report, we have synthesized ZnO@V₂O₅ nanocomposite comprising equal ratios and investigated it for supercapacitor applications. A well-distributed nanostructure was confirmed by the Structural and morphological analyses. A specific surface area of 31.16 m²g⁻¹ was observed, which provides more electroactive sites for ion adsorption and charge storage. The electrochemical analysis revealed stronger capacitive performance, indicating that the electrode material can hold more charge. At a scan rate of 10 mV/s, the synthesised composite showed a specific capacitance of roughly 80 F g⁻¹, nearly double that of bare ZnO. Moreover, Electrochemical studies also demonstrated dominant redox-based pseudocapacitive characteristics mainly contributed by the V₂O₅ component, which indicates efficient faradaic reactions during the charge–discharge process. Therefore, the composite electrode's synergy between ZnO and V₂O₅ is responsible for the improved electrochemical performance, and hence it appears to be very promising for electrochemical energy storage in the future.

Acknowledgments

One of the authors Ms. Naveen Jyoti is thankful to Guru Gobind Singh Indraprastha University, New Delhi, India, for providing the Indraprastha University Ph.D. Fellowship (IUPF). The characterization facilities provided by the Material Analysis & Research Centre (MARC), Bengaluru, Netaji Subhas University of Technology (NSUT), New Delhi, Babasaheb Bhimrao University (BBAU), Lucknow, Malaviya National Institute of Technology (MNIT), Jaipur, Birla Institute of Technology and Science (BITS), Pilani India are gratefully acknowledged.

Author contributions

Naveen Jyoti: conceptualization, methodology, formal analysis, investigation, writing original draft, writing - review & editing. **Arpita Sharma:** formal analysis, review and editing. **Kajal:** review & editing, **Aniket Bharti:** review and editing. **Raju Tiwari:** Review & editing, **Anurag Gaur:** Review & editing. **Rajesh Kumar:** Supervision, conceptualization, review & editing.

Statements & Declarations

Funding

None.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. M. Dinesh, Y. Haldorai, and R. T. Rajendra Kumar, *Ceram. Int.* **46**, 28006 (2020).
2. N. A. Wadodkar, R. S. Salunke, S. K. Pawar, A. Umar, A. A. Ibrahim, S. Akbar, S. A. Ansari, S. Baskoutas, and D. J. Shirale, *Adv. Sustain. Syst.* **10**, (2026).
3. D. Iannuzzi and P. Tricoli, in *SPEEDAM 2010* (IEEE, 2010), pp. 750–756.
4. M. I. A. Abdel Maksoud, R. A. Fahim, A. E. Shalan, M. Abd Elkodous, S. O. Olojede, A. I. Osman, C. Farrell, A. H. Al-Muhtaseb, A. S. Awed, A. H. Ashour, and D. W. Rooney, *Environ. Chem. Lett.* **19**, 375 (2021).
5. M. Czagany, S. Hompoth, A. K. Keshri, N. Pandit, I. Galambos, Z. Gacsi, and P. Baumli, *Materials (Basel)*. **17**, 702 (2024).
6. D. P. Dubal, N. R. Chodankar, P. Gomez-Romero, and D.-H. Kim, in *Met. Oxides Supercapacitors* (Elsevier, 2017), pp. 79–98.
7. J. H. Zheng, R. M. Zhang, P. F. Yu, and X. G. Wang, *J. Alloys Compd.* **772**, 359 (2019).
8. N. Shaheen, M. Aadil, S. Zulfiqar, H. Sabeeh, P. O. Agboola, M. F. Warsi, M. F. Aly Aboud, and I. Shakir, *Ceram. Int.* **47**, 5273 (2021).
9. S. Li, W. Wu, and X. Yan, *Renewables* **1**, 142 (2023).
10. M. Iqbal, N. G. Saykar, S. K. Mahapatra, V. Kumar, and A. Arya, *Mater. Res. Bull.* **194**,

113724 (2026).

11. P. Sivakumar, C. J. Raj, J. Park, and H. Jung, *Ceram. Int.* **48**, 9459 (2022).

12. R. Wang and X. Yan, *Sci. Rep.* **4**, 3712 (2014).

13. S. L. Kadam, S. M. Mane, P. M. Tirmali, and S. B. Kulkarni, *Curr. Appl. Phys.* **18**, 397 (2018).

14. M. D. Patil, S. D. Dhas, A. A. Mane, and A. V. Moholkar, *Mater. Sci. Semicond. Process.* **133**, 105978 (2021).

15. S. Beke, *Thin Solid Films* **519**, 1761 (2011).

16. A. . Mansour, P. . Smith, W. . Baker, M. Balasubramanian, and J. McBreen, *Electrochim. Acta* **47**, 3151 (2002).

17. S. Sutrave, S. Konda, D. Velpula, S. A. Volety, S. R. Ravula, S. C. Chidurala, and B. N. Tumma, *Appl. Surf. Sci. Adv.* **12**, 100331 (2022).

18. Q. Luo, P. Xu, Y. Qiu, Z. Cheng, X. Chang, and H. Fan, *Mater. Lett.* **198**, 192 (2017).

19. R. Saravanan, V. K. Gupta, E. Mosquera, and F. Gracia, *J. Mol. Liq.* **198**, 409 (2014).

20. (n.d.).

21. K. Shen, S. Zhai, S. Wang, Q. Ru, X. Hou, K. San Hui, K. Nam Hui, and F. Chen, *Batter. Supercaps* **4**, 860 (2021).

22. P. Jing, W. Wei, W. Luo, X. Li, F. Xu, H. Li, M. Wei, D. Yu, Q. Zhu, and G. Liu, *Inorg. Chem. Commun.* **117**, 107953 (2020).

23. P. Singh, A. Kumar, A. Kaushal, D. Kaur, A. Pandey, and R. N. Goyal, *Bull. Mater. Sci.* **31**, 573 (2008).

24. A. C. Mohan and B. Renjanadevi, *Procedia Technol.* **24**, 761 (2016).

25. S. Mustapha, M. M. Ndamitso, A. S. Abdulkareem, J. O. Tijani, D. T. Shuaib, A. K. Mohammed, and A. Sumaila, *Adv. Nat. Sci. Nanosci. Nanotechnol.* **10**, 045013 (2019).

26. M. Saber, C. C. Koch, and R. O. Scattergood, *Mater. Res. Lett.* **3**, 65 (2015).

27. R. Marder, W. C. Carter, and W. D. Kaplan, *MRS Bull.* **51**, 181 (2026).

28. J. Naumann, M. Müller, N. Bohn, J. R. Binder, M. Kamlah, and Y. Gan, *ACS Appl.*

Energy Mater. **7**, 4786 (2024).

29. Z. Zhang, W. Xu, T. Guo, Y. Jiang, and M. Yan, J. Alloys Compd. **594**, 153 (2014).

30. M. S. Alnarabiji, N. Yahya, S. B. A. Hamid, K. A. Azizli, M. Kashif, S. Qureshi, and B. Alqasem, Defect Diffus. Forum **354**, 201 (2014).

31. P. Simon and Y. Gogotsi, Nat. Mater. **7**, 845 (2008).

32. M. Alpha, U. E. Uno, K. U. Isah, and U. Ahmadu, Niger. J. Technol. **38**, 997 (2019).

33. X. Xiao, B. Han, G. Chen, L. Wang, and Y. Wang, Sci. Rep. **7**, 40167 (2017).

34. M. H. Aleinawi, R. Tutar, E. Saritas, D. Senturk, F. Bakan-Misirlioglu, E. Erdem, and A. M. Rostas, Sci. Rep. **16**, 362 (2025).

35. S. Sathiya, S. Durairaj, S. Seenivasan, and M. Sasikumar, Ionics (Kiel). **31**, 11643 (2025).

36. M. Karuppaiah, J. K. Lee, and G. Ravi, ACS Appl. Electron. Mater. **6**, 1504 (2024).

37. H. Wang, K. J. Aoki, J. Chen, T. Nishiumi, X. Zeng, and X. Ma, J. Electroanal. Chem. **741**, 114 (2015).

38. S. Harish and P. U. Sathyakam, J. Electron. Mater. **54**, 10858 (2025).

39. Ş. Karabiberoğlu and Z. Dursun, Fullerenes, Nanotub. Carbon Nanostructures **33**, 1139 (2025).

40. S. Tanwar, N. Singh, and A. L. Sharma, J. Energy Storage **45**, 103797 (2022).

41. Z. Lu and X. Ren, Batteries **11**, 63 (2025).

42. M. Yaseen, M. A. K. Khattak, M. Humayun, M. Usman, S. S. Shah, S. Bibi, B. S. U. Hasnain, S. M. Ahmad, A. Khan, N. Shah, A. A. Tahir, and H. Ullah, Energies **14**, 7779 (2021).

43. Y. Zhou, P. Jin, Y. Zhou, and Y. Zhu, Sci. Rep. **8**, 9005 (2018).

44. M. E. Orazem and B. Tribollet, *Electrochemical Impedance Spectroscopy* (Wiley, 2008).

45. Y. Yang, F. Yang, S. Lee, X. Li, H. Zhao, Y. Wang, S. Hao, and X. Zhang, Electrochim. Acta **191**, 1018 (2016).

46. M. A. Anderson, A. L. Cudero, and J. Palma, Electrochim. Acta **55**, 3845 (2010).

