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Facile Synthesis of Tin Oxide (SnO_2)/Reduced Graphene Oxide (rGO) Nanocomposite For Energy Storage Application

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This study presents the synthesis and in-depth evaluation of a novel Tin(IV) oxide/reduced graphene oxide (SnO_2/rGO) nanocomposite developed as an electrode material for advanced electrochemical supercapacitors. Utilizing a scalable synthesis method with optimized parameters, the resulting nanocomposite was characterized by X-ray diffraction (XRD), transmission electron microscopy (TEM), and scanning electron microscopy (SEM), revealing its well-defined morphology, crystal structure, and composition. Comprehensive electrochemical assessments, including galvanostatic charge-discharge (GCD), electrochemical impedance spectroscopy (EIS), and cyclic voltammetry (CV), demonstrated that SnO_2/rGO exhibits superior performance metrics compared to pure SnO_2. Notably, at a current density of 1 A g^{-1}, the SnO_2/rGO nanocomposite achieved a specific capacitance of 140 F g^{-1}, surpassing the 133 F g^{-1} of pure SnO_2. These findings highlight the SnO_2/rGO nanocomposite's potential to significantly enhance energy storage capabilities, making it a promising candidate for applications in electric vehicles, portable electronics, and sustainable energy systems.

Keywords: *SnO_2/rGO, Nanocomposite, Supercapacitors, Energy storage, Galvano static charge-discharge.*

1. Introduction

The ongoing efforts to address the rising demand for energy storage that is both ecologically benign and highly efficient technologies for a range of uses, such as electric automobiles and the integration of green energy sources and portable electronics, have yielded significant results. In response to the surging demand for high-performance, eco-friendly energy storage solutions across various sectors, extensive research has yielded notable breakthroughs. Researchers have meticulously scrutinized a range of energy storage technologies, both electrochemical and non-electrochemical, assessing their techniques, environmental impact, operational efficiency, costs, and applicable domains[1]. Furthermore, they have engaged in detailed discussions on diverse energy storage options, facilitating a direct comparison based on power, energy, and efficiency requisites[2]. The assimilation of green energy into power grids has dramatically enhanced their dependability, effectiveness, and stability, with power storage systems serving as a linchpin in this transformation[3]. The paper underscores the necessity for innovative energy storage solutions in confronting the ever-evolving challenges posed to power networks, emphasizing the importance of sustaining reliability and power quality[4]. In a noteworthy stride, the research spotlights the promise of composite energy storage technologies, exemplified by aqueous and ionic liquid Al-ion batteries, heralding cost-effectiveness and feasibility for electric vehicle propulsion[5]. These findings collectively advance sustainable energy storage solutions for diverse applications.

Supercapacitors, lauded for their extended life cycle, quick charge/discharge characteristics, and high power density, bridge the gap that exists between batteries and conventional capacitors[6,7]. Oxides of transition metals are being investigated as components of supercapacitor electrodes for enhanced energy density and electrochemical performance[8]. The research also highlights the potential of polyoxometalates as electrode materials, delivering high specific capacitance and stability to supercapacitors[9]. Advancements in energy-holding multilayer Ceramic Capacitors (MLCCs) show possibilities for stability at high temperatures and elevated energy densities. The objective of the proactive study is to hasten the creation of effective and high-performing methods for storing energy. Reduced graphene oxide (rGO) with tin oxide (SnO_2) emerge as captivating candidates for supercapacitor enhancement. SnO_2, with its exceptional electrochemical properties, for supercapacitor applications, rGO's strong stability during cycling and specific capacitance increase its versatility and use[10,11]. Combining these materials in a Nanocomposite structure exhibits the potential to elevate specific capacitance and electrical conductivity, further enhancing supercapacitor performance[12,13]. Diverse methodologies, encompassing hydrothermal/solvothermal synthesis, chemical vapour deposition, electro-deposition, and physical mixing techniques, afford unique advantages in terms of property control, underscoring their influence on

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Nanocomposite electrochemical behaviour[14]. The selection of a fabrication method plays a pivotal role in shaping Nanocomposite properties and performance across diverse applications.

The introduction of TiO_2/rGO, enriched with other metal oxides like Fe_3O_4, as a powerful catalyst that accelerates the breakdown of organic contaminants ushers in a significant breakthrough, backed by solid electrochemical properties, positioning it as a potential Li+ battery anode material[15]. This composite material displays vast potential in a spectrum of applications, including photocatalysis and energy storage. The amalgamation of rGO with the SnO_2 matrix showcases a potent synergy, enhancing electrical conductivity, structural stability, and active surface area, ultimately boosting supercapacitor performance[16,17]. This synthesis underscores the forefront of energy storage research. The research demonstrates the viability of SnO_2-rGO composites for energy storage, as they present high specific capacitance, cyclic stability, ozone sensing capabilities, and lithium-ion battery potential[18-20]. The amalgamation of SnO_2 Nanoparticles with reduced graphene oxide sheets within the composite structure drives this superior performance[21].

In conclusion, by examining the synergistic potential of nanocomposite materials, particularly SnO_2-rGO composites, in diverse energy storage applications, the research presented here increases our understanding and use of energy storage solutions. Despite the absence of the pristine rGO CV curves in this investigation, previous research indicates that rGO demonstrates distinctive capacitive characteristics. Our attention was drawn to the way that SnO_2 nanoparticles and rGO interact to improve the composite material's overall electrochemical performance. These material's special qualities present an appealing option for meeting the urgent demand for energy storage in contemporary technological fields. In order to contribute significantly to the body of knowledge currently available on energy storage and to the development of more efficient and environmentally friendly energy storage devices for a range of applications, this study aims to shed light on the untapped potential of these materials and their use.

2. Preparation and Characterization of SnO_2-rGO Nanocomposite and Electrochemical Analysis

2.1. Preparation of SnO_2-rGO nanocomposite by hydrothermal method

Graphene oxide (GO) was synthesized using various methods, including electrochemical exfoliation, changing the graphite/oxidizing reagents mass ratios, a one-pot hydrothermal method[22], and modifying Hummers' method[23]. 50 ml of distilled water was combined with 50 mg of graphene oxide, and the mixture was ultrasonically processed for roughly an hour. Later, 0.95 g of pure SnO_2 Nanoparticles (from Alfa Aeser) were added to the GO suspension and then swirled for about two hours in order to obtain a uniform mixture. After the homogeneous solution was created, the mixture was transported into the autoclave and heated to 120° C for 6 hours before being left undisturbed and allowed to reach room temperature. Lastly, the product with a deep black hue obtained from the autoclave demonstrated the conversion of GO to graphene[24]. The resulting composite was further strained, rinsed with de-ionized water and ethanol, then dried for approximately 12 hours in the vacuum oven set at 60°C to create the Tin (IV) oxide / Reduced Graphene Oxide electrode's Nanocomposite[24-26].

2.2. Electrode preparation and electrochemical analysis

The electrochemical studies of pristine SnO_2 and SnO_2/rGO composites were investigated using a Biologic VMP3 electrochemical workstation[24,27]. Measurements using cyclic voltammetry (CV), chromatopotentiometry (CP), and electrochemical impedance spectroscopy (EIS) were used to examine the materials' electrochemical behaviour. The studies revealed that when compared to whole SnO_2, the SnO_2/rGO combination performed better electrochemically. The SnO_2/rGO composite showed higher initial discharge capacity and better capacity retention after multiple cycles, indicating its improved stability and cycling performance[28,29]. Additionally, the SnO_2/rGO composite demonstrated greater surface area, enhanced electrical conductivity, and reduced charge transfer resistance, which contributed to its enhanced electrochemical performance. According to these results, the SnO_2/rGO combination shows potential as an electrode material for future battery technology[30].

The electrochemical properties of Tin (IV) oxide and Tin (IV) oxide / Reduced Graphene Oxide electrode's composite electrodes in a 1M KOH electrolyte were analyzed using a three-terminal system[24].

To further assess the storage properties claimed in this study, we constructed a super-capacitor device. This device configuration is crucial for evaluating practical performance metrics such as energy density and cycle stability. Figure 1 provides a schematic illustration of the super-capacitor device used. The assembly includes:

- A SnO_2/rGO composite material as the working electrode.
- A platinum counter electrode.
- A separator soaked in 1M KOH electrolyte.

Because of this elaborate arrangement, we were able to analyze the composite material's capacitance, energy density, and cycle stability with accuracy, which validates our claims about its electrochemical performance. The SnO_2/rGO composite exhibits improved CV profiles, improved charge-discharge properties, and superior specific capacitance, all of which highlight its potential for use in supercapacitors.

The electrodes used for analysis included Ag/AgCl, glassy carbon electrode, and platinum electrodes. The electrochemical behaviour of the electrodes was studied using methods including electrochemical impedance spectroscopy, cyclic voltammetry (CV), linear sweep voltammetry (LSV), chronoamperometry, and chronopotentiometry. The findings indicated that when compared to whole SnO_2, the SnO_2/rGO composite electrodes revealed enhanced electrochemical performance. The composite electrodes demonstrated increased specific capacitance and cyclic stability, indicating their potential for energy storage applications. Additionally, the SnO_2/rGO composite electrodes showed improved electro-catalytic

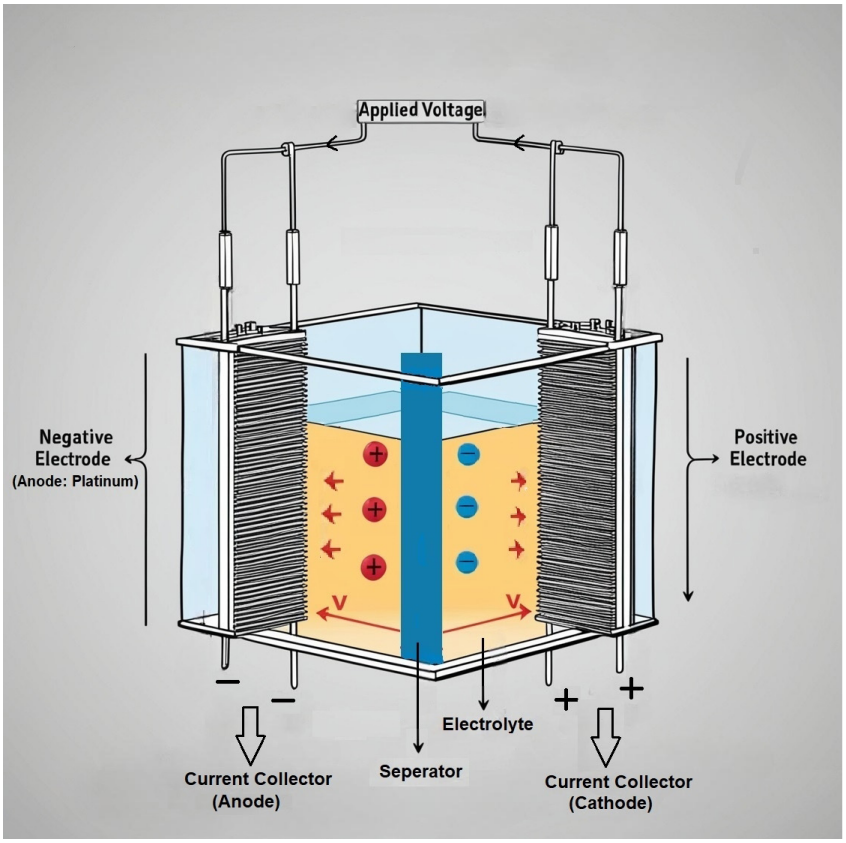

Figure 1. Schematic of the supercapacitor device configuration used for evaluating the storage properties of the SnO_2/rGO composite material.

oxidation activity, making them suitable for applications such as the removal of organic pollutants from water[31].

After dispersing 5 milligrams of the sample in 0.5 millilitres of ethanol and adding 20 microliters of Nafion as a binding agent, the electrode material was placed onto the glassy carbon electrode. For ten minutes, the mixture was sonicated. Ultimately, the solution was placed onto the electrode, which is active in 20 µl increments and allowed to dry at ambient temperature[32].

2.3. Characterization techniques for electrode materials

X-ray powder diffraction (XRD) analysis using CuKα (0.1514nm) radiation (Rigaku, MiniFlex II-C) was employed for analysing the composition and crystalline purity of the electrode material. The examination of the morphology of the composite material was conducted using SEM (TESCAN, VEGA 3) and HR-TEM (FEI-TECNAI G2-20 TWIN) techniques[24].

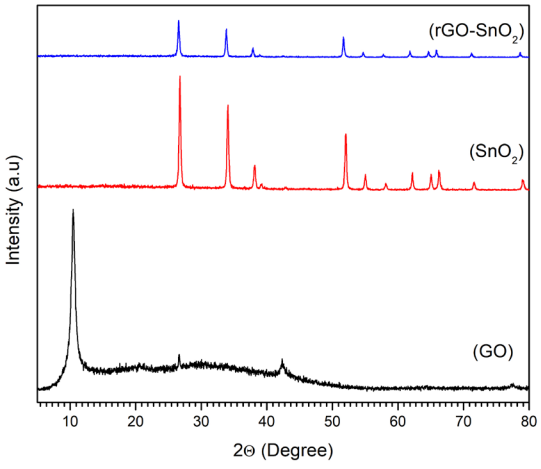

Figure 2. X-ray diffraction pattern of (a) Graphene oxide, (b) Tin, (IV) oxide, and (c) SnO_2/rGO nanocomposite.

3. Results and Discussions

3.1. X-ray diffraction analysis

The X-ray Diffraction peaks of GO, SnO_2 and Tin (IV) oxide / Reduced Graphene Oxide electrode's composite have been displayed in Figure 2a, b, and c, respectively[25]. Graphene oxide shows the dominant peak at the (001) plane.

The distinctive peaks were identified based on JCPDS cards, occurring at 2θ°= 26.72, 34.02, 38.15, 52.05, 55.03, 62.18 and 65.04o having (h k l) values of (110), (101), (200), (211), (220), (310) and (301), respectively. In both instances, the tetragonal rutile- type SnO_2 phase is observed, and the peak positions align well with JCPD data card 41-1445[33,34] as

shown in Figure 2b. All diffraction patterns of SnO_2 particles appeared in the Tin (IV) oxide / Reduced Graphene Oxide electrode's Nanocomposite, and the sharp peaks of the composite showed high crystalline properties, as shown in Figure 2c[35]. The SnO_2/rGO Nanocomposite showed an additional diffraction peak (002) at a 2θ of 26.55°, which could be attributed to the disorganized nature of the layered graphene sheets[36,37]. The results indicate that the process by which graphene oxide is reduced to graphene, as the joining of SnO2 particles with it to form a composite, was successfully achieved.

3.2. Scanning electron microscopy analysis

The surface morphology of graphene oxide (GO), Tin (IV) oxide, and Tin (IV) oxide / Reduced Graphene Oxide electrode composites has been examined by Scanning Electron Microscopy (SEM)[26,38,39]. The aim of the Scanning Electron Microscopy examination was to examine the surface morphology (as shown in Figure 3) of the composite of SnO_2 Nanoparticles mixed with graphene. The SEM images confirmed the presence of a stacked sheet-like arrangement, indicating surface morphology of graphene oxide[24].

By oxidizing natural graphite powder, Nanosheets were created, and XRD, SEM, and TEM were used to describe them. The analysis confirmed the developed graphene oxide Nanosheets confirm the existence of oxygen-containing groups, which exhibited a thin, wrinkled, and crumpled structure[40]. The electrical conductivity of the material composite was enhanced by the close distribution of SnO_2 Nanoparticles across the graphene layers. Figure 3(d-e)'s scanning electron microscopy (SEM) images unambiguously illustrate the random distribution of SnO_2 Nanoparticles along with the graphene layers throughout the composite.

3.3. High-resolution transmission electron microscopy studies

Figure 4a-e shows that the HR-TEM images of SnO_2 and Tin (IV) oxide / Reduced Graphene Oxide electrode's Nanocomposite at varying magnifications show a layered structure with many wrinkles throughout the surface, confirming that the interlayer's are loosened[24].

HR-TEM imaging confirms the composite's Tin (IV) oxide Nanoparticles are crystalline, consistent with the

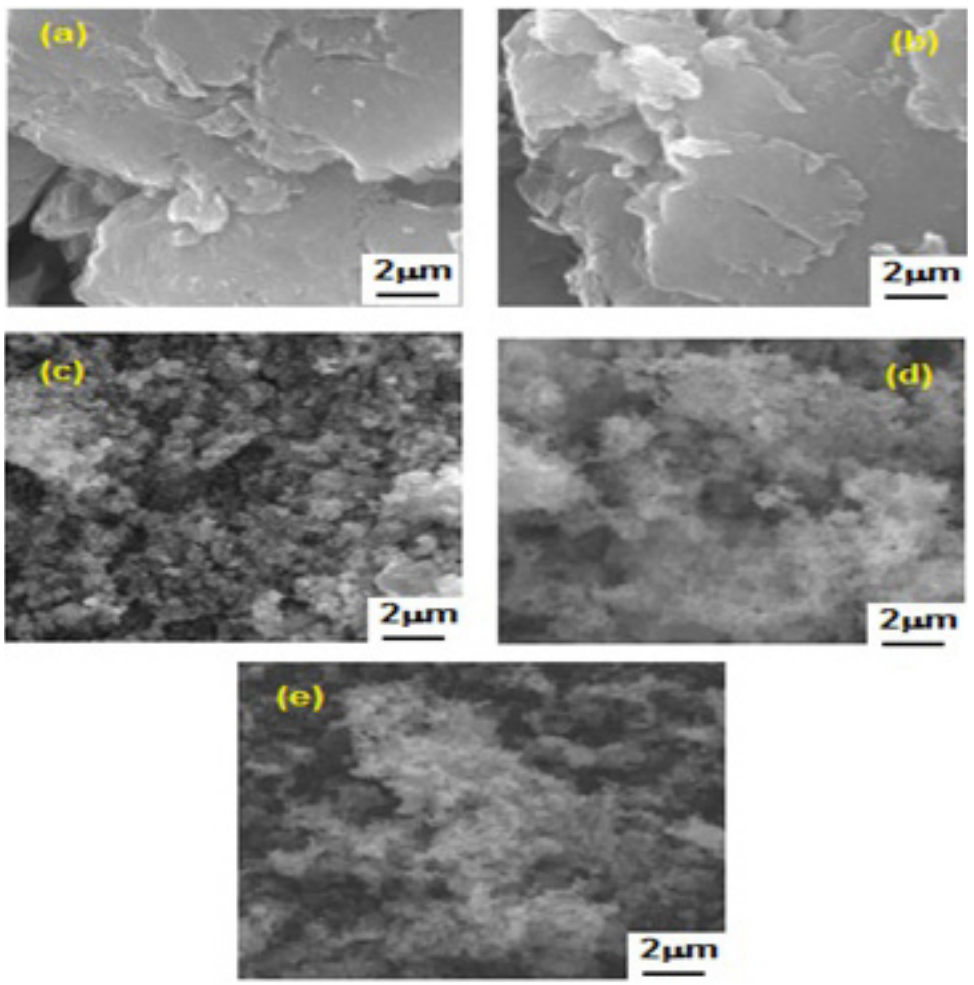

Figure 3. SEM imaging of (a-b) Graphene oxide (c) Tin (IV) oxide nanoparticles and (d-e) Tin (IV) oxide / Reduced graphene oxide electrode's Nanocomposite.

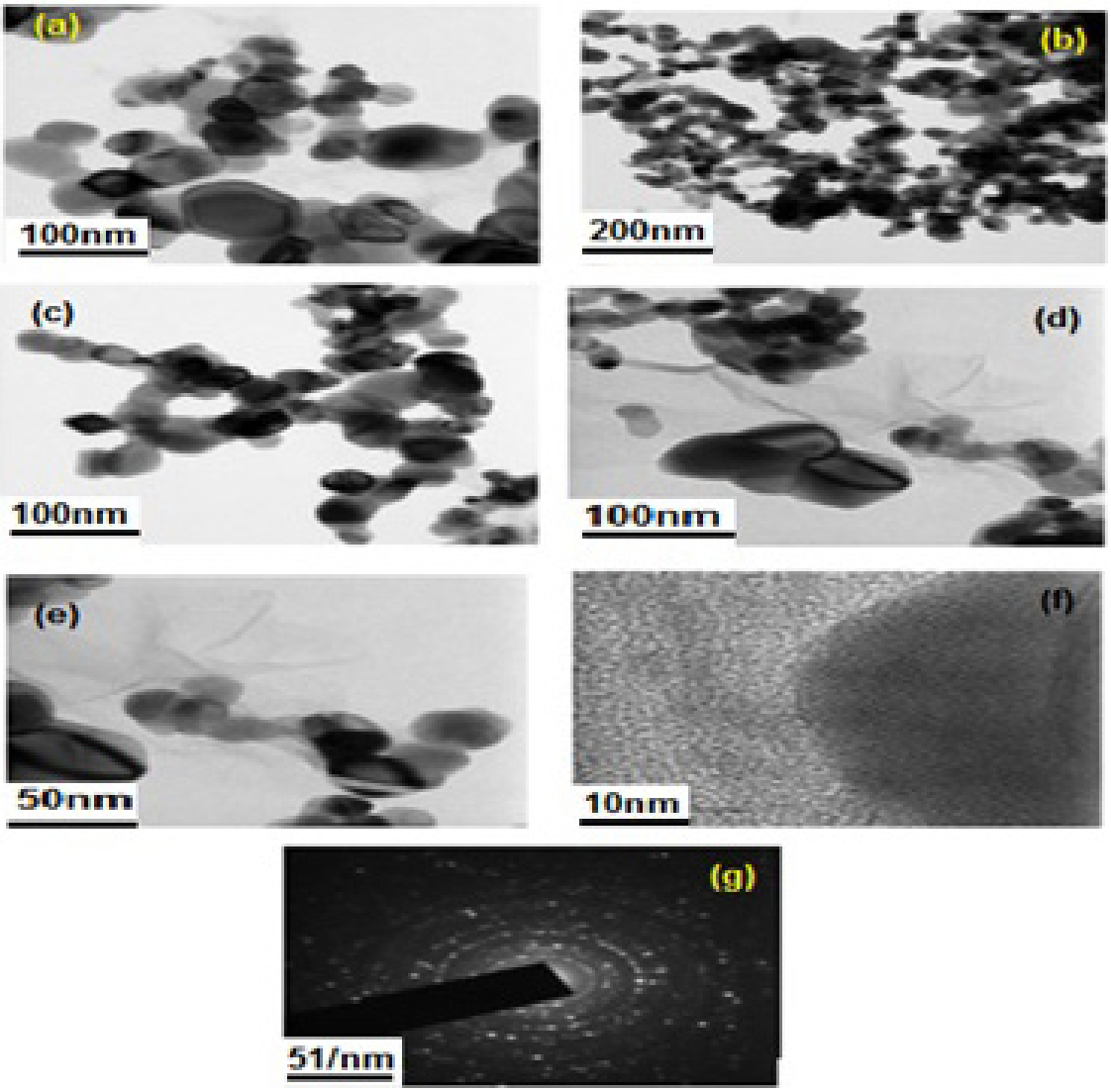

Figure 4. HR-TEM imaging of (a-c) SnO_2 electrode material, (d-e) Tin (IV) oxide / Reduced graphene oxide electrode material, (f) lattice structure pattern and (g) FFT imaging of SnO_2/rGO electrode component.

XRD results. The SnO_2 Nanoparticles persistently secured to the graphene layer surface with a high density, even following prolonged sonication before the preparation of the TEM specimen, indicating a robust bond between the graphene layers and the SnO_2 Nanoparticles[27]. The addition of Nanoparticles to graphene sheets acts as a blockade, impeding the nearby re-stacking of the sheets and preserving their high active surface area[37,41]. This prevents the loss of the graphene sheets' electrochemical performance and enhances their specific capacitance[42]. The Nanoparticles serve as spacers between the graphene sheets, preventing agglomeration and maintaining the porous structure of the composite material. This layered structure allows for easy access to both surfaces of the graphene sheets, facilitating the transfer of gas or liquid species[43]. The use of Nanoparticles as spacers in graphene-based Nanocomposite has been shown to substantially raise the material's specific capacitance, making it a potential candidate for supercapacitor electrodes.

The graphene sheets exhibit a wrinkled morphology, while the SnO_2 Nanoparticles are uniformly dispersed across the surface of the graphene sheets. The volume of synthesized SnO_2 Nanoparticles ranges from 5 to 10 nm, and there are some larger secondary particles and smaller particles due to agglomeration. The lattice fringe image (Figure 4f) of the SnO_2/rGO Nanocomposite shows a lattice pitch of approximately 0.46nm, corresponding to the lattice plane[44].

High-Resolution Transmission Electron Microscopy (HRTEM) tests demonstrate the high crystallinity of Tin (IV) oxide Nanoparticles, as evident in the FFT image (Figure 4g). XRD analysis of SnO_2 Nanoparticles in this study reveals a single rutile crystal phase, confirming their high crystallinity[45]. The highly crystalline nature of SnO_2 Nanoparticles is further confirmed by HR-TEM images. Additionally, morphology and microstructure characterization of SnO_2 Nanosheets from another study indicate that the Tin (IV) oxide Nanoparticles consist of oriented particles with a diameter of 6–12 nm.

The electrochemical performance of graphene is enhanced by both the direct deposition of SnO_2 Nanoparticles on its surface and the doping of Sb into SnO_2 Nanoparticles. This results in high reversible capacity, excellent durability, and remarkable rate performance. π-π interactions in-between the orderly stacked graphene and SnO_2 Nanoparticles enhance the discharge performance and stability of SnO_2 are observed in a hybrid structure integrating SnO_2 onto orderly stacked graphene sheets (SnO_2@OS-rGO) formed[46]. Furthermore, the synthesis of SnO_2 Nanoparticles attached to chlorinated graphene as electrodes without the need for binder's electrodes demonstrates a prolonged cycling life and stable discharge capacity, attributed to the improved electrical conductivity of graphene and increased adsorption energies between graphene and SnO_2 Nanoparticles[47]. Outstanding rate capability is also demonstrated by the hierarchical hybrid of SnO_2 Nanoparticles enclosed in Graphene Oxide Nanoribbons (GONRs)[48].

3.4. SnO_2/rGO nanocomposite electrochemical characterization for supercapacitor applications

In the context of electrochemical characterization, with an emphasis on supercapacitor applications, a thorough investigation of the Nanocomposite SnO_2/rGO was carried out[35]. This section delves into the performance assessment of these Nanocomposites, primarily utilizing cyclic voltammetry (CV) analysis.

3.4.1. Cyclic voltammetry analysis

Using cyclic voltammetry (CV)[49], we evaluated the electrochemical nature of SnO_2 and SnO2/rGO Nanocomposite. Existing literature indicates that pristine rGO exhibits well-characterized capacitive behaviour with notable scan rate dependence due to its high surface area and excellent electrical conductivity. Studies by[50] and[51] report specific capacitances in the range of 130-200 F g^{-1}, depending on synthesis methods and scan rates. Given this extensive documentation, our study focused on the SnO_2/rGO composite to explore the synergistic effects on electrochemical performance rather than reproducing known data on pristine rGO[52-54].

By combining the high surface area and conductive routes offered by rGO with the pseudocapacitive contributions of SnO_2, the interaction between SnO_2 nanoparticles and rGO in the composite improves overall electrochemical performance. The observed performance increases can be attributed mostly to the enhanced specific capacitance and electrochemical stability that arise from this synergy[55-57]. The CV curves for the SnO_2/rGO composite electrodes and pure SnO_2 electrodes at different scan speeds are shown in Figure 5, which also shows how the structure of the composite significantly improves its electrochemical capabilities.

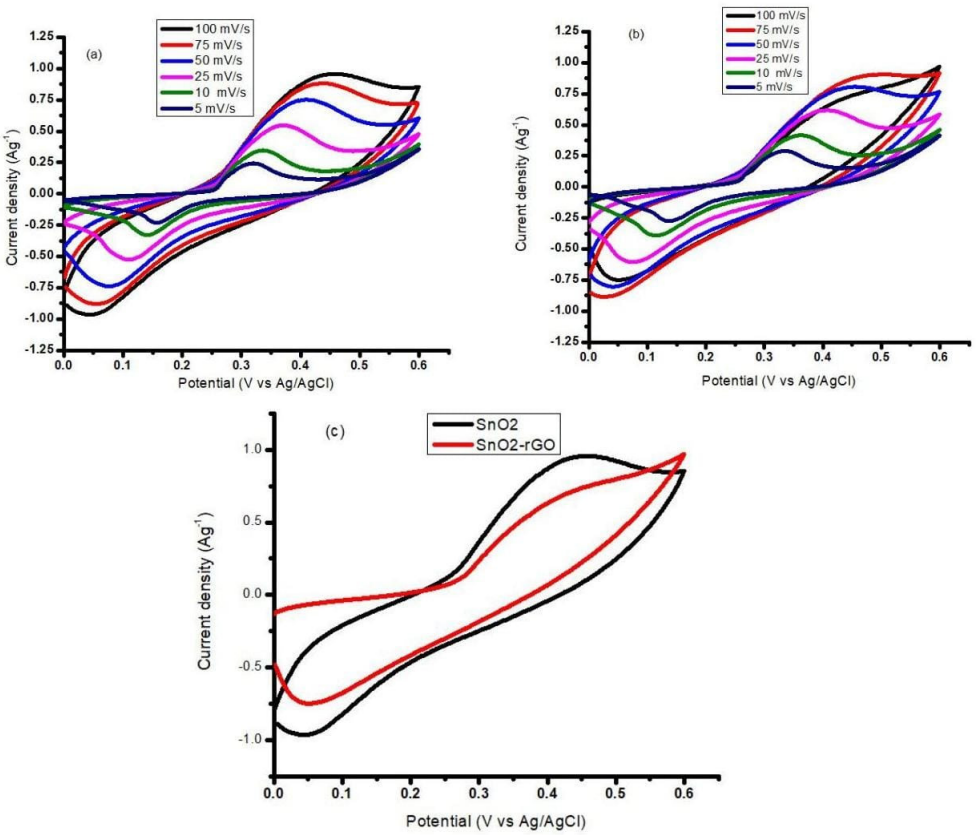

Figure 5. presents CV curves for (a) pristine SnO_2, (b) SnO_2/rGO composite scan at various rates, and (c) a differentiation of the electrode CV profiles at 100 mVs^{-1} for both types of SnO_2.

Significant oxidation and reduction peaks were seen in the CV curves (Figure 5a) for SnO2 electrodes in 1 M KOH aqueous electrolyte, suggesting non-faradaic behaviour[24,58].

Cyclic voltammetry (CV) examined SnO_2 electrode electrical behaviour across different scan speeds[24]. The electrode's current response was proportional to the scan rate, indicating distortion without a scan rate, peaking at 100 mVs^{-1}. SnO_2 Nanoparticles CV profile (Figure 5a) depicted a 0.1 V to 0.6 V window across a variety of scan rates. The electrochemical double-layer capacitance behaviour and its mechanism of charge storage were confirmed to exhibit nonlinearity. While the curves held onto their original shape, it was discovered that scan rates between 5 and 100 mVs^{-1} increased the absolute area covered[59].

The Cyclic voltammetry curves in Figure 5b of SnO_2/rGO Nanocomposite at various repetition rates, including higher scan rates of 100 mVs^{-1}, exhibited nonlinear shapes without any distortion, indicating a capacitance behaviour[60]. The SnO_2/rGO electrode exhibits capacitive behaviour and low contact resistance. The SnO_2/rGO composites have properties that provide a high surface area at the interface between SnO_2 Nanoparticles and its electrolytes[61]. The SnO_2/rGO Nanocomposite electrode exhibited a higher current compared to pure SnO_2 in the CV curve at a repetition rate of 100 mVs^{-1} in Figure 5c. The Cyclic voltammetry curves showed that SnO_2/rGO had a larger integrated area and higher specific capacitance compared to pure SnO_2 and graphene sheets. This is explained by the composite material's enhanced electron conductivity and capacitance behavior, as well as the creation of new channels for electron transmission. These channels were made possible by the SnO_2 Nanoparticles that were present on the graphene sheets, which increased capacitance. The composite material demonstrated much greater capacitance when the states of the SnO_2 Nanoparticles and graphene sheets were strong[43,62].

3.4.2. Chronopotentiometry analysis

Within a voltage range of 0.1 V to 0.6 V, an analysis of charge and discharge was conducted to determine the specific capacitance value[63]. The charge-discharge process of SnO_2 at current densities ranging from 1 to 6 Ag^{-1} is depicted in Figure 6a. Symmetrical and triangular CP curves characterize SnO_2 electrodes, indicative of non-Faradic behaviour. Additionally, the cyclic voltammetry (CV) results demonstrate satisfactory performance. Challenges encountered during sample preparation included an IR drop at the discharge potential within the SnO_2 electrode and poor charge efficiency. Contributing factors to these issues include the internal resistance of the electrode as well as electrical resistance. Furthermore, factors such as solution resistance

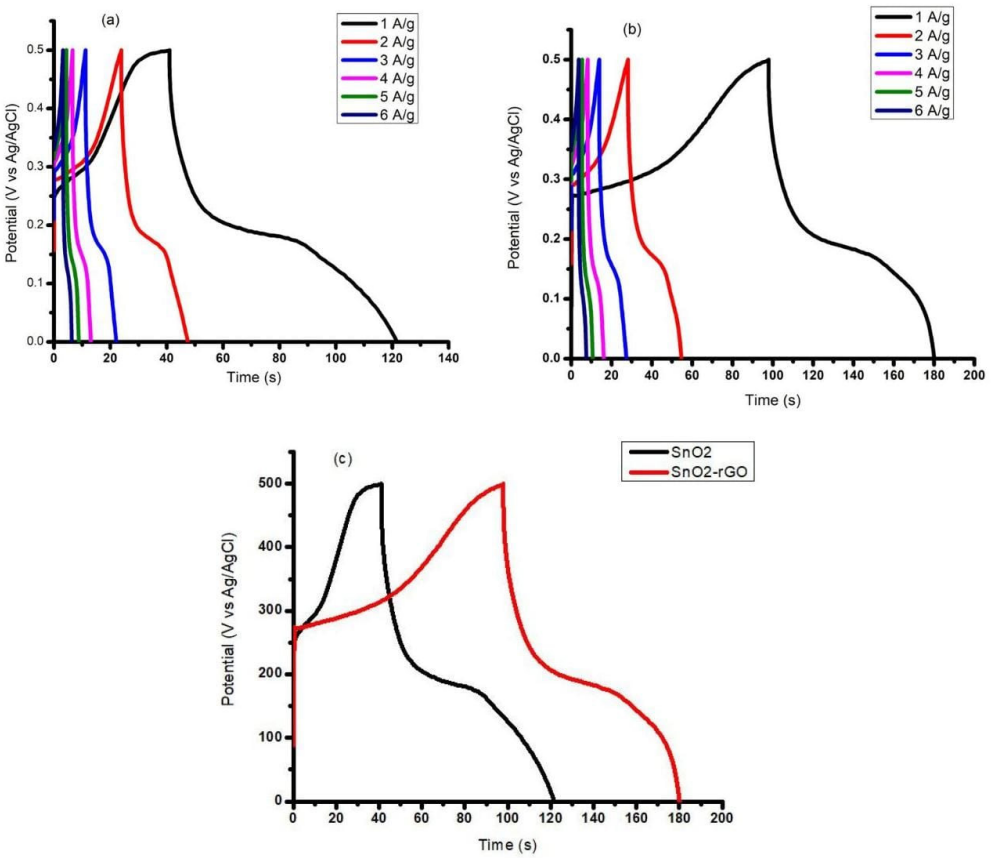

Figure 6. Curves representing the charge-discharge for the following: (a) SnO_2 nanoparticles (b) SnO_2 and its composite with reduced graphene oxide (rGO) at varying current densities; and (c) a comparison of the cyclic voltammetry curves for the two materials at a current density of one Ag^{-1}.

in bulk form and ion migration resistance within electrode materials also contributed to the overall IR drop[64]. SnO_2/rGO composite electrodes exhibited superior capacitance with good rate capability, as depicted in Figure 6b. The reduced internal resistance observed in SnO_2/rGO composites, indicated by small IR drops, can be attributed to the enhanced electrical connection between SnO_2 Nanoparticles and graphene in a conductive network[65]. The application of SnO_2 onto the graphene electrode surface via spraying further enhanced the composite material's capacitance value. Comparison of the capacitive behaviour of pure SnO_2 and SnO_2/rGO composite electrodes, conducted at a density of 1 Ag^{-1} as illustrated in Figure 6c, revealed extended discharge durations for SnO_2/rGO electrodes[24]. This improvement can be attributed to the synergistic effects between SnO_2 and graphene, which increased the interconnected liquid-solid interfacial area and facilitated hydrogen transport within the composite materials. The formation of the composite material resulted in improved discharge time due to the enhanced properties of the 2D porous graphene and the increased interaction between SnO_2 and graphene[66]. The specific capacitance of charge-discharge curves can be calculated using the relation[24]

$$Cs = I \times t / m \times V \quad (3.1)$$

The electronically conducting graphene sheets with SnO_2 Nanoparticles provide efficient electron pathways, allowing for rapid charge transport. This enables the electrolyte to have evenly distributed access to the SnO_2 Nanoparticles on the graphene surfaces[67]. The combination of SnO_2 Nanoparticles and graphene layers creates a three-dimensional conductive framework, facilitating the effective transport of electric charge. The graphene layers also improve the electrodes' capacitance and responsiveness at high frequencies, while reducing both resistance to charge transfer and diffusional contributions. The composite comprising $NiCo_2S_4$ Nanoparticles supported on graphene layers demonstrates an elevated specific capacitance and enhanced durability for asymmetrical capacitors[68]. The reduction process of graphene oxide (GO) films initiates at specific oxygen-functional groups, with conductive regions expanding throughout the reduction phase[69,70]. The incorporation of graphene sheets functionalized with aryl groups can mitigate undesired reactions at the interface between the electrode and electrolyte, leading to a reduced voltammetric response. Consequently, the specific capacitance of the SnO_2/rGO Nanocomposite (140 Fg^{-1}) exceeded that of pure SnO_2 (133 Fg^{-1}) at a current density of 1 Ag^{-1}. Furthermore, the operational potential range of the SnO_2/rGO composite material was greater than that of pure SnO_2. The SnO_2/rGO nanocomposite exhibited a specific capacitance of 140 F g^{-1} at 1 A g^{-1}, outperforming pure SnO2 (133 F g^{-1}) and comparable to the specific capacitance values reported for pristine rGO in the literature (130-200 F g^{-1}).

The range of current density extends from 1 to 6 Ag^{-1} with an incremental step rate of 1 Ag^{-1} in a water-based electrolyte solution, resulting in a plotted graph depicting the relationship between specific capacitance and the density of current[71], depicted in Figure 7. The capacitance exhibited by the Tin (IV) oxide / Reduced Graphene Oxide electrode surpasses that of the pure Tin (IV) oxide electrode, showcasing higher specific capacitance values. The utilization of an aqueous electrolyte characterized by elevated ion conductivity, coupled with the synergistic interplay between graphene and SnO_2 Nanoparticles, significantly enhances the effectiveness of the Tin (IV) oxide / Reduced Graphene Oxide electrode[72]. The composite electrode facilitates efficient charge transfer across the double-layer interface, while the limited diffusion distance of SnO_2 Nanoparticles within the electrolyte promotes reversible Faradic reaction and increased electrochemical activity, leading to a faster reaction[73].

3.4.3. EIS characterization of Tin (IV) oxide (SnO_2) and Tin (IV) oxide / reduced graphene oxide (rGO) electrode

Figure 8, the Nyquist plot, offers insights into the electrical transport behaviour and charge conductivity characteristics of both SnO_2 and also in combination with reduced graphene oxide (rGO)[24]. The impedance response is shown in this plot across a broad frequency scale, from 100 kHz down to 0.1 Hz.

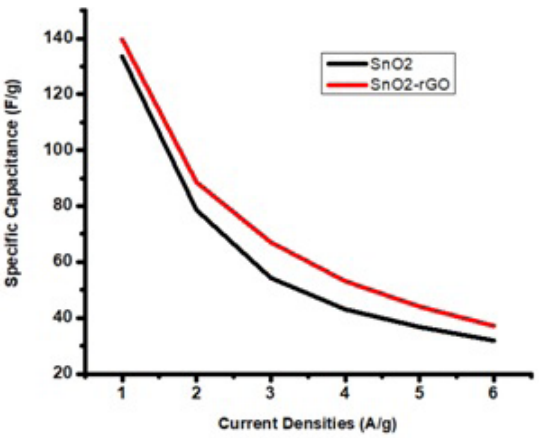

Figure 7. Comparing the specific capacitance of SnO_2 and with reduced graphene oxide (rGO) electrodes at various current density values.

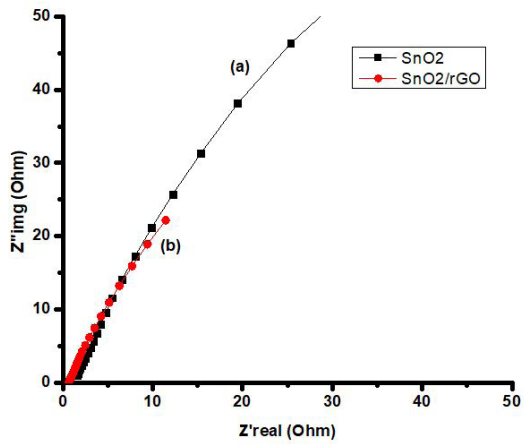

Figure 8. Nyquist plots of Tin (IV) oxide (SnO_2) and Tin (IV) oxide / Reduced Graphene Oxide (rGO) electrode.

The observed impedance variation across frequencies provides valuable information regarding the electrical properties of the materials. The Nyquist plot can reveal the presence of different charge transport mechanisms, such as hopping or diffusion, and can also indicate the presence of different types of charge carriers. The plot can be used to analyze the electrical behaviour of the materials and to understand their performance in various applications[74].

The behaviour of the supercapacitor can be characterized by the combination of the capacitive parameter and the real component Z', which represents the Ohmic behaviour. The supercapacitor functions like a pure resistor at elevated frequencies. However, at low frequencies, there is a sharp increase in the imaginary component Z'', indicating the behaviour of the purest capacitance. It is also noticed that the resistance and capacitance in electric double layers at polarized interfaces vary in frequency. In contrast to the parallel resistance, which is inverted in relation to frequency, the capacitance falls linearly with the frequency's logarithm[75,76]. The accurate modelling of the frequency-dependent impedance of supercapacitors requires direct impedance measurement using electrochemical impedance spectroscopy[77]. A non-impedance method using a measurement circuit consisting of an operational amplifier with negative feedback can also be used to extract the parameters of a supercapacitor.

4. Conclusions

The hydrothermal method was employed to produce the SnO_2/rGO Nanocomposite electrode material without the need for surfactants. SnO_2/rGO Nanocomposite with improved electrochemical characteristics was successfully created using the hydrothermal synthesis process. Although pristine rGO was not examined in-depth in this study, previous research on its capacitive properties indicates that it plays a major role in the composite's overall performance. To clarify its function in the composite material, pristine rGO will be further analyzed in subsequent research. This synthesis method successfully reduced graphene oxide (GO) with SnO_2 Nanoparticles, and the adhesion of SnO_2 Nanoparticles with the graphene sheet was validated by XRD analysis. When the current density was $1Ag^{-1}$, the SnO_2/rGO Nanocomposite electrode's inherent capacitance for supercapacitors was robust, measuring 140 Fg^{-1}, surpassing that of pure SnO_2. This result implies that by offering a higher specific capacitance, the nanocomposite can greatly increase the supercapacitors' efficiency. Similar specific capacitance values (130-200 F g^{-1}) have been reported for pristine rGO in the literature. This suggests that combining SnO_2 and rGO can have synergistic effects, which are essential for developing high-performance energy storage applications.

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