

Research Article

Chemical Vapor Deposition-Grown Hierarchical SnS₂ Nanostructures for High-Performance Supercapacitor Electrodes

Indu Sharma ¹, Guru Prakash Nunna ^{2,3}, Tae Jo Ko ², Rosaiah Pitcheri ^{3,4} and Jungwook Choi ¹

¹School of Mechanical Engineering, Chung-Ang University, Seoul 06974, Republic of Korea

²School of General Education, Yeungnam University, Gyeongsan, Gyeongbuk 38541, Republic of Korea

³School of Mechanical Engineering, Yeungnam University, Gyeongsan, Gyeongbuk 38541, Republic of Korea

⁴Department of Physics, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai 602105, India

Correspondence should be addressed to Guru Prakash Nunna; drguruprakashn@gmail.com and Jungwook Choi; choij@cau.ac.kr

Received 4 June 2025; Revised 21 August 2025; Accepted 9 October 2025

Academic Editor: Samarjeet Singh Siwal

Copyright © 2025 Indu Sharma et al. International Journal of Energy Research published by John Wiley & Sons Ltd. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Transition metal sulfides and their composite materials have received considerable attention as electrode materials for electrochemical devices. In particular, tin(IV) disulfide (SnS₂) nanoflowers have attracted significant interest because of their unique nanoscale architectures and layered crystalline structures. Herein, this study investigates the controlled synthesis of hierarchical SnS₂ nanostructures via chemical vapor deposition (CVD) and their potential as advanced electrode materials for high-performance supercapacitors. X-ray diffraction (XRD) analysis confirmed the hexagonal crystalline phase of SnS₂, while X-ray photoelectron spectroscopy (XPS) verified the chemical states and elemental composition of the synthesized material. Morphological analysis using scanning electron microscopy (SEM) revealed a consistent flower-like nanostructure, whereas stoichiometry of Sn and S elements was confirmed through energy-dispersive X-ray analysis. Cyclic voltammetry (CV) indicated pseudocapacitive behavior, with chronopotentiometry yielding a specific capacitance of 187 F/g at 0.5 A/g. Electrochemical impedance spectroscopy (EIS) analysis revealed a low charge-transfer resistance (R_{ct}) of approximately 1.2 Ω . Additionally, long-duration stability assessments at a current density over 5000 cycles demonstrated outstanding cycling stability, retaining approximately 88% of the original capacitance. This improved electrochemical performance was primarily due to the SnS₂ nanostructures featuring a flower-mimetic shape, which substantially increased the effective surface area and enhanced the accessibility of the electroactive sites, thus, significantly increasing the specific capacitance.

1. Introduction

Energy storage devices are vital to modern energy systems and play a key role in enhancing their efficiency, reliability, and sustainability. Energy storage systems absorb excess energy when production exceeds demand and release it when production drops, ensuring consistent energy availability and supporting the seamless adoption of renewables into power grids [1]. Electric vehicles (EVs) primarily rely on batteries as their main method of storing energy. Improvements in energy storage have increased EV range, reduced charging times, and made electric transportation more

practical, thereby supporting the transition to cleaner mobility options. Energy storage devices are crucial for achieving a resilient, cost-effective, and sustainable energy future. They play a key role in expanding the use of renewable energy, enhancing grid reliability, cutting down emissions, and promoting emerging technologies like EVs—critical steps toward a more sustainable and efficient energy system [2]. Supercapacitors offer several benefits compared to traditional batteries, making them well-suited for uses that demand rapid charging, strong endurance, and high power delivery. Although supercapacitors store less energy than batteries, their high power output, extended lifespan, quick

charging and discharging capabilities, and ability to function across a broad temperature range make them highly effective for a wide range of demanding applications [3]. As technology advances, supercapacitors are increasingly complementing or replacing batteries in applications in which their unique advantages offer significant benefits.

Supercapacitors can be grouped into three main categories depending on their electrode composition and the way they store energy: electrical double-layer capacitors (EDLCs), pseudocapacitors, and hybrid variants that merge the properties of the first two types. To improve supercapacitor efficiency, researchers commonly aim to increase energy retention by tailoring and advancing electrode material properties [4]. Material selection for electrode depends on key criteria including cost-effectiveness, high electrical conductivity, substantial specific surface area, and environmental friendliness. While some characteristics may be preferred—for instance, the outstanding capacity of RuO_2 relative to carbon-based options—its expensive nature has driven the search for more economical substitutes [5]. Numerous investigations reveal that metal sulfides possess impressive optoelectronic features, such as strong photon capture and efficient energy conversion. In particular, tin(IV) disulfide (SnS_2), a layered transition metal dichalcogenide, stands out due to its wide bandgap, affordability, nontoxicity, excellent stability, and plentiful availability in the Earth's crust [6]. SnS_2 has a high theoretical capacitance because of its ability to store energy through electrostatic charge separation and faradaic redox reactions. The unique characteristics of SnS_2 enable it to exhibit the combined behavior of both EDLCs and pseudocapacitors, resulting in enhanced energy storage capabilities compared to conventional carbon-based materials [7]. Its two-dimensional layered structure facilitates easy ion intercalation and deintercalation, promoting efficient ion transport during charge–discharge cycles. This structural advantage significantly improves the rate capability and overall electrochemical performance of supercapacitors. In addition, the layered geometric configuration of SnS_2 offers an extensive surface area, which is critical for maximizing energy storage. An increased surface area offers a greater number of reactive sites for ion adsorption and redox reactions, thereby enhancing both capacitance and energy density [8]. SnS_2 undergoes fast and reversible redox reactions that enhance its pseudocapacitive behavior. This enables it to store more charge in smaller volumes than other materials that rely solely on electrostatic charge storage. This pseudocapacitive characteristic results in a higher energy density, making it suitable for use in high-performance supercapacitors [9]. Tin (Sn) and sulfur (S) are comparatively abundant, environmentally benign, and economically viable, making them attractive alternatives to more expensive and potentially toxic materials such as transition metal oxides, which are commonly used in supercapacitors. This makes SnS_2 an environmentally friendly option for sustainable energy storage and reduces the overall cost of supercapacitor production [10].

SnS_2 , which shares structural similarities with graphene, displays distinctive shapes, and has recently gained

significant attention as a promising electrode material for improving the efficiency of electrochemical capacitors. Its intrinsic layered structure makes it well-suited for the intercalation of foreign ions, especially alkali metal ions [11]. Furthermore, SnS_2 demonstrates a variety of outstanding attributes that make it suitable for integration into multiple advanced technologies such as energy storage devices, catalytic systems, and both lithium- and sodium-based battery platforms [12]. Although it holds significant promise, the use of nanostructured SnS_2 in energy storage systems remains relatively underinvestigated. Its substantial predicted capacitance, layered crystal structure, faradaic charge storage capability, and ability to form conductive hybrids highlight its potential in this field [13]. In addition, its cost-effectiveness, environmental compatibility, and tunable physicochemical properties render it a viable material for advanced supercapacitor architectures. Therefore, this study investigates the charge storage behavior of SnS_2 and examines its contribution to enhancing pseudocapacitor performance.

2. Materials and Methods

2.1. Materials. Tin chloride pentahydrate ($\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$), sulfur, a Si/ SiO_2 substrate, and isopropyl alcohol (IPA) were used in this study. All chemicals and solvents were obtained from Sigma–Aldrich and utilized as received, without further purification.

2.2. Chemical Vapor Deposition (CVD) of SnS_2 . First, the Si/ SiO_2 substrate was cleaned via ultrasonication in acetone and IPA to remove organic impurities. $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ and sulfur powder (S) were placed in separate alumina boats, maintaining a molar ratio of Sn to S of 1:2. Specifically, 0.7 g of $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ and 1.4 g of S were used to achieve this ratio. A quartz tube was centrally aligned within a single-zone furnace, and the alumina boat containing $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ was positioned at the midpoint of the quartz tube. The sulfur-containing boat was positioned upstream, 15 mm from the $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ boat. Two Si/ SiO_2 substrates were used: one inverted to cover the top of the $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ boat and the other placed 10 mm downstream. Prior to heating, the system was purged with 100 sccm high-purity argon gas for 15 min to remove residual air. During the process, a constant argon flow of 50 sccm was maintained as the carrier gas. The furnace temperature was ramped from room temperature to 450°C at a rate of 15°C/min and held at this temperature for 30 min. Under these conditions, the substrate temperature was estimated to be in the range of 200–250°C due to its downstream placement, providing optimal conditions for SnS_2 nanostructure growth. The growth of Si/ SiO_2 was carried out at 450°C for 30 min under a continuous Ar gas flow of 50 sccm. Following the growth process, the furnace was rapidly cooled while maintaining the same Ar gas flow rate, that is, 50 sccm (Figure 1). Consequently, a Si/ SiO_2 substrate coated with yellow-colored SnS_2 was obtained, and approximately 20 mg of the active material was collected using the scribing method—mechanically scratching or scraping the surface with a clean blade or spatula—to facilitate further analysis and supercapacitor studies.

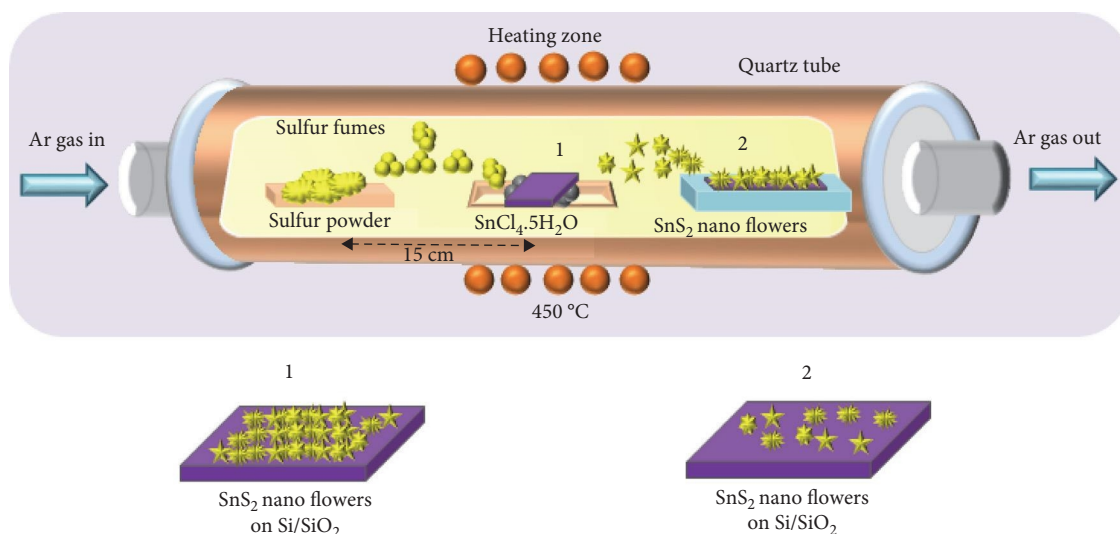


FIGURE 1: Illustration of the CVD system utilized for the synthesis of SnS_2 nanostructures on Si/SiO_2 substrates.

2.3. Material Characterization Techniques. Nanostructures of SnS_2 produced through CVD were analyzed to assess their structural, compositional, optical, and electrochemical characteristics. The crystallographic phase and structural purity were identified using powder X-ray diffraction (XRD) analysis with $\text{Cu-K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$). Surface morphology was investigated with field emission scanning electron microscopy (FESEM; HITACHI S-4800) operating at an accelerating voltage of 10 kV. Elemental composition analysis was conducted using energy-dispersive X-ray spectroscopy (EDX). The optical bandgap of SnS_2 was estimated using a UV–visible spectrophotometer (NEOGEN NEO–D3117). The Brunauer–Emmett–Teller (BET) method was employed to measure the specific surface area and analyze the pore size distribution. X-ray photoelectron spectroscopy (XPS) utilizing $\text{Al-K}\alpha$ radiation (1486.6 eV) was employed for surface chemical analysis. Micro-Raman spectroscopy (NOST RAON), equipped with a 532 nm excitation laser, 50x objective lens, and 1200 g/mm grating (providing a resolution of $\sim 1 \text{ cm}^{-1}$), was employed to probe the vibrational modes. The electrochemical properties were assessed using an SP200 Bio-Logic workstation with a three-electrode configuration. In this setup, Hg/HgO electrode was used as the reference, platinum acted as the counter electrode, and SnS_2 functioned as the working electrode within a 1 M KOH electrolyte solution. An electrode slurry was prepared by combining SnS_2 (as an active material), polyvinylidene fluoride, and carbon black in a mass ratio of 8.5:0.75:0.75. This mixture was drop-cast on a Ni foam substrate and dried at 90°C for 6 h with the active material loading estimated at around 0.0035 g.

3. Results and Discussion

3.1. Microstructural Analysis. Detailed microstructure investigation of the SnS_2 nanostructure was conducted using XRD for phase identification and crystallographic orientation,

SEM for surface morphology, and XPS for chemical bonding state analyses. The XRD patterns presented in Figure 2 provide comprehensive information regarding the crystal structure, preferred orientation, and degree of crystallization of the SnS_2 thin films. The diffraction pattern in Figure 2a reveals peaks at 2θ values of 14.87° , 26.55° , 28.49° , 33.73° , 37.85° , 50.17° , 51.61° , 54.67° , 61.67° , 64.69° , 65.71° , 71.17° , and 78.53° , corresponding to the (001), (100), (002), (101), (102), (110), (111), (103), (201), (004), (202), (113), and (203) planes, respectively. These peaks match well with JCPDS card Number 00-023-0677, confirming that the synthesized SnS_2 nanostructures possessed a hexagonal crystalline structure. The lack of secondary peaks indicates the high phase purity of the material. To assess the directional growth behavior, the texture coefficient (TC) for each (hkl) plane was calculated from the XRD data shown in Figure 2b using Equation (1): [14, 15]

$$\text{TC}_{hkl} = \frac{I_{(hkl)}}{I_{0(hkl)}} / \left(\frac{1}{N} \sum \frac{I_{(hkl)}}{I_{0(hkl)}} \right), \quad (1)$$

where N is the total number of considered diffraction peaks, $I(hkl)$ is the experimentally recorded intensity of the (hkl) plane, and $I_0(hkl)$ represents the standard intensity obtained from the JCPDS reference card for hexagonal SnS_2 (Number 00-023-0677).

Figure 2b shows that the (111) plane exhibited the highest TC (~ 2.0), indicating strong preferential growth along this direction. This aligns with the highest intensity peak observed in the XRD pattern. Other planes such as (110), (202), and (204) also showed TC values greater than 1, suggesting secondary preferred orientations. The TC value serves as an indicator of the preferred orientation, where $\text{TC} = 1$ implies random orientation, $\text{TC} > 1$ suggests a preferred orientation, and $\text{TC} < 1$ indicates a less favored alignment. Preferred crystallographic orientations often enhance

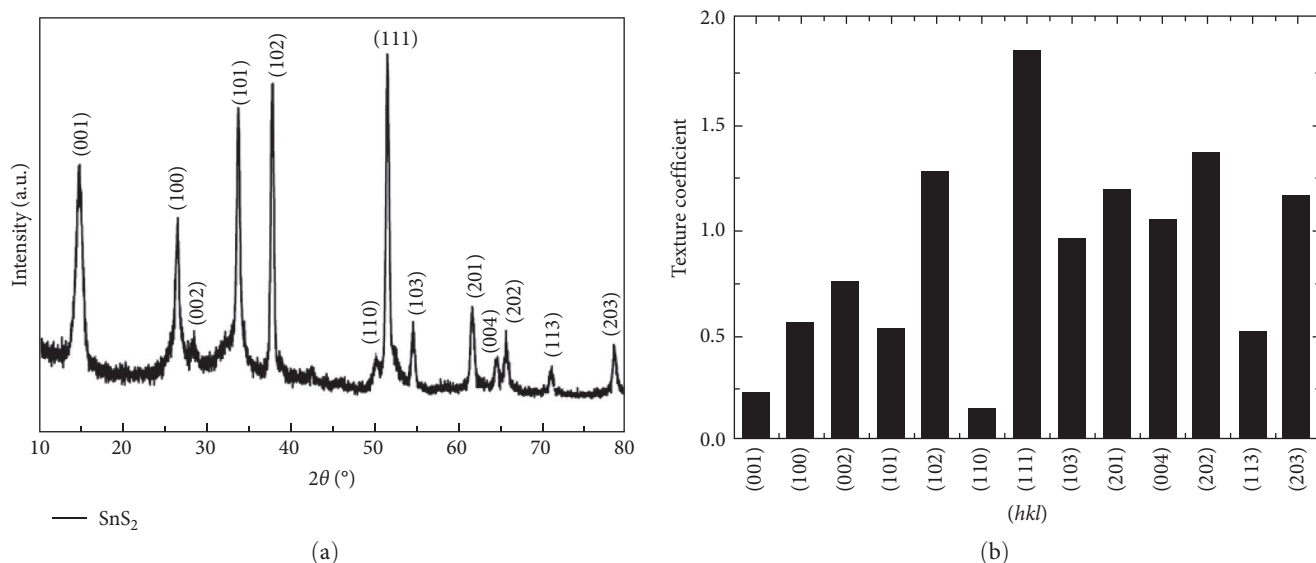


FIGURE 2: (a) XRD pattern of SnS_2 nanostructures and (b) texture coefficient (TC) for each (hkl) plane analyzed from the XRD pattern in Subpart (a).

film quality, grain alignment, and device performance by improving the electronic, optical, and catalytic properties.

Furthermore, broadening of the Bragg diffraction peaks indicates the presence of a nanostructured morphology. The conventional Debye–Scherrer formula was applied to estimate the average crystallite size (D) [16].

$$D = \frac{0.9\lambda}{\beta \cos \theta}, \quad (2)$$

where D is the crystallite size in nanometers, $\lambda = 1.5406 \text{ \AA}$ is the wavelength of the $\text{Cu-K}\alpha$ X-rays used in the measurement, β is the full width at half maximum (FWHM) of the diffraction peak in radians, and θ is the Bragg angle. Based on this analysis, The approximate average size of the crystallites was calculated as 15.8 nm, assuming spherical, strain-free crystallites with peak broadening primarily attributed to size effects.

To explore the growth and deposition behavior of SnS_2 on the substrate, the surface characteristics of the samples were studied through FESEM. Figure 3 shows high-resolution FESEM images that reveal the formation of hierarchical nanostructures. These structures comprise distinct large spherical aggregates of SnS_2 accompanied by scattered nuclei, forming flower-like spherical clusters. The uniform size and shape of the structures indicated a well-regulated deposition process. The spheres exhibited a characteristic rose-like morphology in which the nanosheets were arranged hierarchically (Figure 3a,b). At higher magnification (Figure 3b), the nanosheets or platelets exhibited a well-ordered arrangement within the rose-like structure.

The images contribute deeper insight into the particle sizes of the SnS_2 nanostructures. In Figure 3a, the spherical clusters are primarily within the sub-micron scale ($\sim 1 \mu\text{m}$ or slightly smaller), whereas the individual nanosheets observed in Figure 3b have dimensions on the order of hundreds of

nanometers. This hierarchical configuration results in a highly porous structure that enhances the specific surface area, which is an important attribute for applications such as supercapacitors.

The elemental profile of the sample was established by means of EDX, and a spectrum was generated to illustrate the correlation between the X-ray counts and energy (keV). The EDX results confirmed the occurrence of Sn and S, as evidenced by the characteristic peaks of the energy emissions, validating the successful formation of SnS_2 nanostructures (Figure 3c). The elemental composition of the SnS_2 nanostructures, exhibiting a stoichiometric ratio of $\text{Sn}:\text{S} = 1:2$ as determined by EDX analysis, is summarized in Table 1. Additionally, the EDX spectrum contained minor peaks associated with trace impurities, likely originating from the crucible used during the deposition process or from contaminants introduced during sample preparation for characterization.

XPS analysis was conducted to probe the chemical states of the SnS_2 nanostructures, as depicted in Figure 4. The survey spectra confirmed the presence of Sn, S, and O elements in the sample. In the high-resolution Sn 3d spectrum (Figure 4a), two prominent peaks at binding energies of 494.7 and 486.3 eV correspond to Sn 3d_{3/2} and Sn 3d_{5/2}, respectively, indicating tin in the Sn^{4+} oxidation state [17]. The S 2p spectrum (Figure 4b) exhibited two distinct peaks at 162.5 and 161.3 eV, assigned to S 2p_{1/2} and S 2p_{3/2}, respectively [18]. Along with that, the O 1s spectrum, shown in Figure 4c after background correction, exhibited an asymmetric peak. Upon deconvolution using Gaussian fitting (with an FWHM of 1.1 eV), this peak split into two components corresponding to lattice oxygen and surface-adsorbed oxygen species. The dominant peak at 529.6 eV aligned closely with the signature binding energy of oxygen in SnO_2 [19, 20], while a secondary peak at 530.8 eV, accounting for 11% of the O 1s signal, corresponded to oxygen-containing surface adsorbates such as hydroxyl groups or

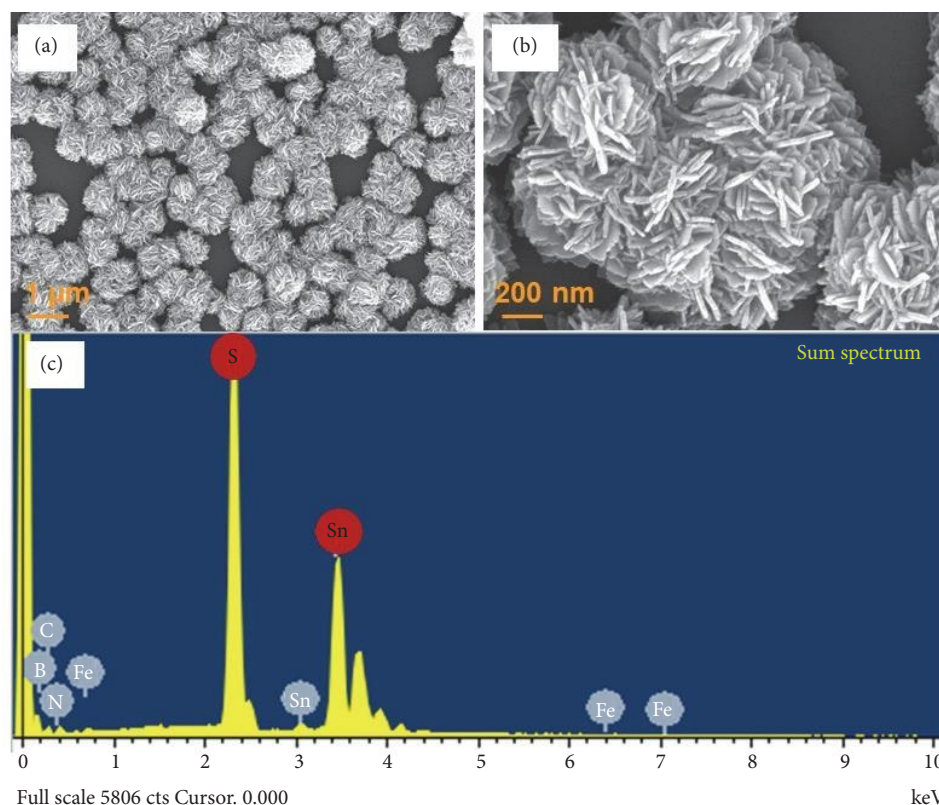


FIGURE 3: FESEM micrographs of SnS_2 nanostructures at magnifications of (a) 10x and (b) 50x, and (c) EDX spectra of SnS_2 nanostructures.

TABLE 1: EDX elemental composition of the SnS_2 nanostructures.

Element	Weight %	Atomic %
B K ^a	16.52 ^a	44.71 ^a
C K ^a	8.03 ^a	19.55 ^a
S K	25.76	23.50
Sn	49.69	12.25
	100	100

^aImpurities.

water molecules [21]. Generally, surface-adsorbed oxygen significantly influences the chemical adsorption and ionized oxygen states on material surfaces, potentially enhancing the supercapacitive performance of SnS_2 [8].

The supercapacitor application is mainly dependent on surface contact, and hence, the surface area of the materials is an essential factor. We have determined the surface area by the nitrogen adsorption–desorption isotherm for SnS_2 . The textural properties of SnS_2 FLNSs were examined using N_2 adsorption–desorption isotherms, and pore size distribution was estimated via the Barrett–Joyner–Halenda (BJH) method (Figure 4d). N_2 adsorption–desorption analysis revealed a Type-IV isotherm with a pronounced hysteresis loop, confirming the mesoporous nature of SnS_2 FLNSs. The BET surface area was measured as $4.59 \text{ m}^2/\text{g}$, which is nearly five to eight times higher than that of bulk SnS_2 ($<1 \text{ m}^2/\text{g}$). The BJH analysis reveals a cumulative pore volume of

$0.029 \text{ cm}^3/\text{g}$ and an average pore diameter of approximately 25–30 nm (mesoporous regime), corresponding to an overall porosity of approximately 11%–12%. This hierarchical mesoporosity, originating from intrananostructural voids and interparticle spaces, provides efficient ion diffusion channels and maximizes electrolyte-accessible surface area. Consequently, it directly enhances the electrochemical performance by increasing the number of active sites and enabling faster ion transport, which explains the observed improvement in capacitance and rate capability compared to bulk SnS_2 .

3.2. Electrochemical Properties. To further understand the electrochemical behavior of SnS_2 nanoflowers as a working electrode in a three-electrode configuration, cyclic voltammetry (CV) was performed over a potential range of 0.0–0.6 V. As illustrated in Figure 5a, the CV profiles obtained at various scan rates (5–100 mV/s) exhibited distinct redox peaks, corresponding to the reversible redox transition between Sn^{2+} and Sn^{4+} oxidation states. This behavior is a hallmark of pseudocapacitive materials. Additionally, the nonlinear pattern observed in the CV profiles confirms the pseudocapacitive behavior demonstrated by the SnS_2 electrode [22]. To quantify the capacitive performance, the total current density (i) was plotted against the square root of the scan rate (Figure 5b). The observed linear relationship indicates that the redox reactions were mainly governed by diffusion-controlled processes. The enhanced diffusion can be attributed to the large surface area offered by the flower-

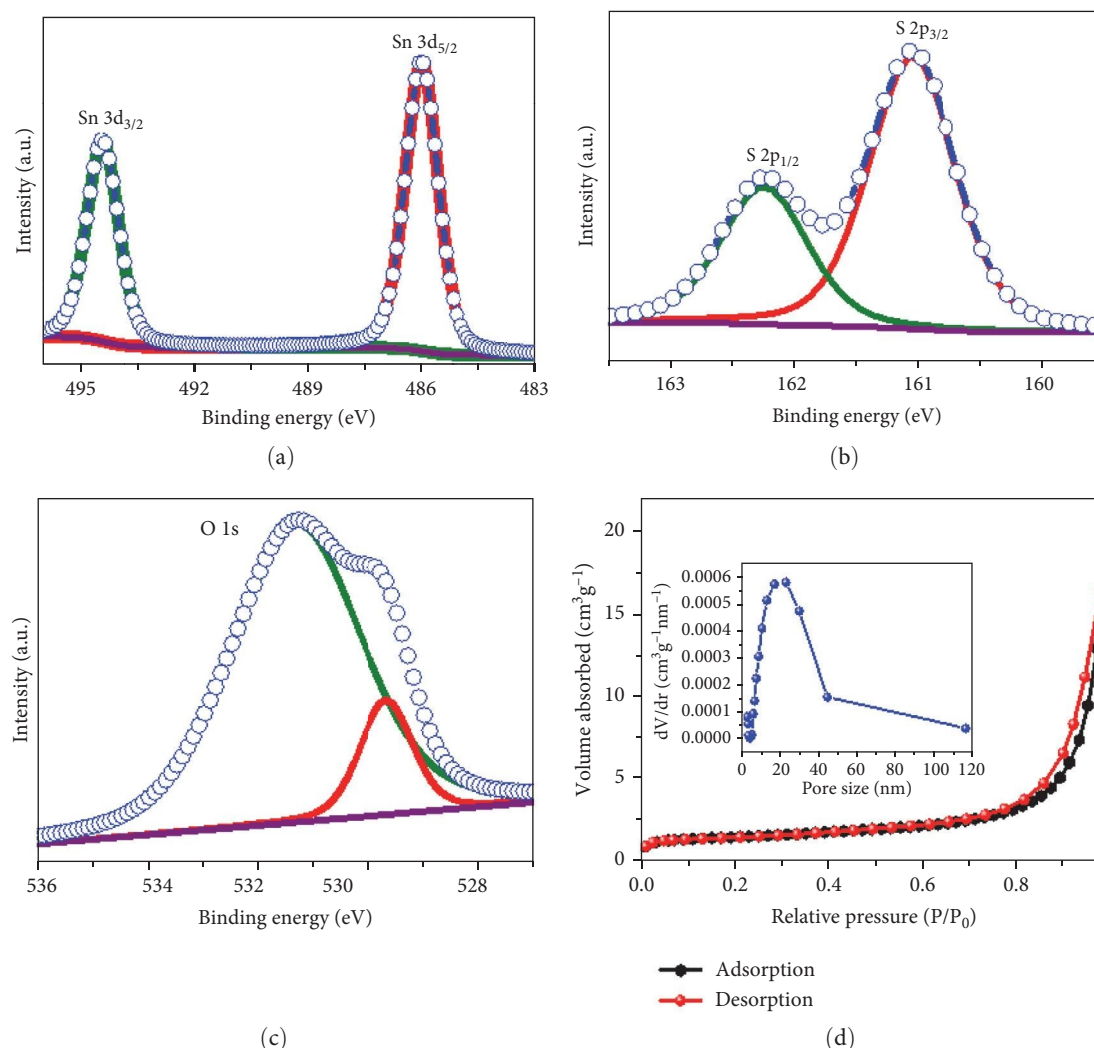


FIGURE 4: XPS spectra of nanostructured SnS_2 showing (a) Sn 3d, (b) S 2p, and (c) O 1s peaks. (d) N_2 adsorption–desorption isotherms with the corresponding pore size distribution (inset).

like structure of SnS_2 , which facilitates improved ion accessibility and transport across the electrode–electrolyte interface. Moreover, to clearly distinguish between the surface-controlled and diffusion-driven charge storage contributions, a detailed CV study was performed within the same voltage range (0.0–0.6 V) using scan rates ranging from 5 to 100 mV/s. The relationship between the scan rate and current was further evaluated using a power-law approach [23], offering valuable insights into the fundamental electrochemical behavior of the material.

$$i_p = k\nu^b, \quad (3)$$

where i_p is the peak current, ν is the potential scan rate (V/s), and k and b are empirical constants. The exponent b offers information about the charge storage mechanism, where values between 0.5 and 1.0 are observed. A b value close to 0.5 generally indicates a diffusion-limited process, like ion intercalation, while a value approaching 1.0 is indicative of a

capacitive process dominated by surface-limited charge storage [24]. As depicted in Figure 5c, the logarithmic representation of peak current ($\log i_p$) versus scan rate ($\log \nu$) yielded a slope corresponding to $b = 0.59$. This intermediate value suggests that the electrochemical behavior of the SnS_2 electrode arises from the synergistic interplay of both capacitive and diffusion-controlled contributions. This relationship is commonly expressed using the following power-law equations:

$$i = i_{\text{capacitive}} + i_{\text{diffusion}}, \quad (4)$$

$$i = k_1 V + k_2 V^{1/2}. \quad (5)$$

The separation of capacitive- and diffusion-controlled contributions can be achieved by plotting $i(V)/\nu^{1/2}$ against $\nu^{1/2}$. From this analysis, the overall current response can be deconvoluted into capacitive- (surface-related) and diffusion-controlled components, expressed respectively as $k_1\nu$ and $k_2\nu^{1/2}$, as illustrated in Figure 5d. This allows for the quantitative estimation of the relative contributions

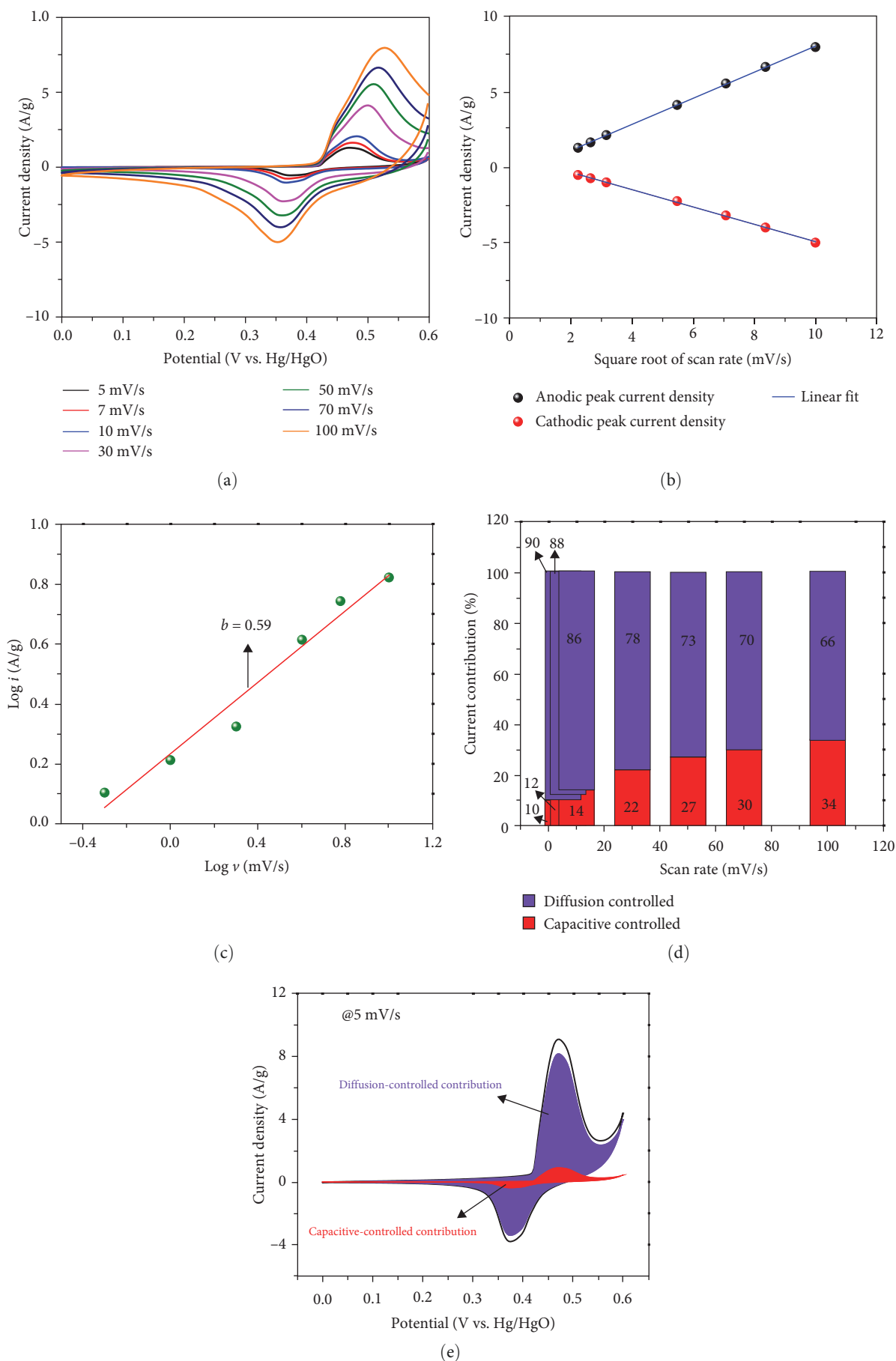


FIGURE 5: (a) Cyclic voltammety recorded at scan rates ranging from 5 to 100 mV/s, (b) variation of peak current density as a function of the square root of the scan rate, (c) log-log plot of current versus scan rate, (d) proportion of current contribution at different scan rates, and (e) areal current contribution measured at 5 mV/s.

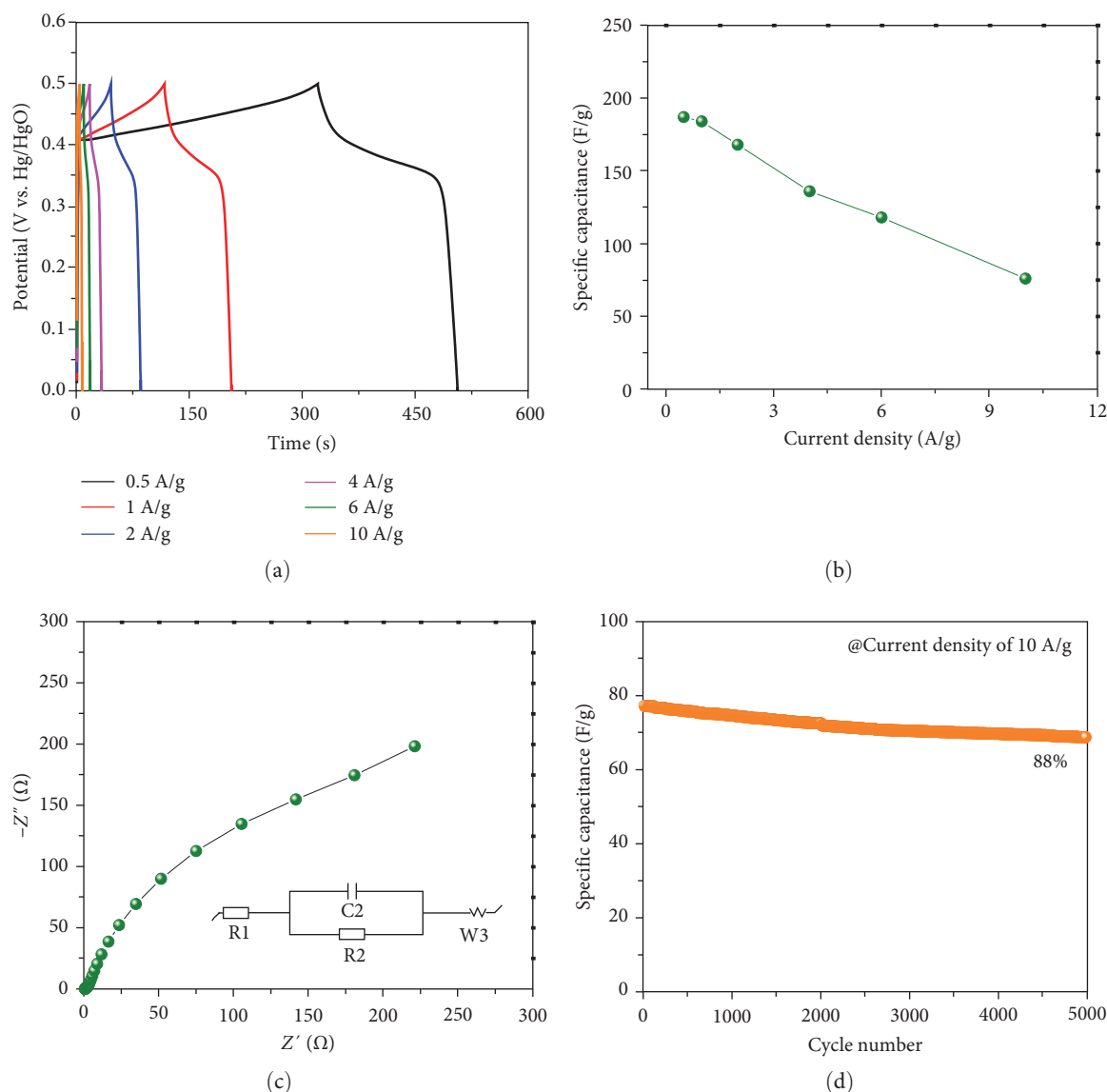


FIGURE 6: (a) Chronopotentiometry curves obtained at a range of current densities between 0.5 and 10 A/g, (b) specific capacitance versus the current density, (c) Nyquist plot, and (d) cycling stability of the SnS_2 electrode at a current density of 10 A/g.

observed at several scan rates. For instance, at a scan rate of 5 mV/s, the SnS_2 electrode demonstrated a dominant diffusion-controlled contribution of nearly 90%, while the capacitive contribution was limited to around 10%. This predominance of the diffusion behavior is attributed to effective and deep ion intercalation into the electrode matrix, thereby enhancing the specific capacitance at reduced scan rates. When the scan rate was raised to 100 mV/s, the diffusion-controlled contribution decreased to 66%, whereas the capacitive component increased to 34%. Despite this shift, diffusion-dominated kinetics remained predominant across the entire scan rate range, indicating that the SnS_2 electrode exhibited a pseudocapacitive behavior governed mainly by ion diffusion mechanisms. Figure 5e further illustrates the areal contributions of the total, diffusion, and capacitive currents at 5 mV/s, exhibiting values of 100%,

90%, and 10%, respectively, confirming the strong diffusion-controlled characteristics of the material.

Figure 6a displays the chronopotentiometry profiles of the SnS_2 electrode at a range of current densities between 0.5 and 10 A/g, recorded within a potential window of 0–0.5 V. The observed nonlinear nature of these curves aligned closely with the CV data, further supporting the pseudocapacitive nature of the electrodes. The specific capacitance (C_s) was determined using the following expression [25]:

$$c_s = \frac{I\Delta t}{m\Delta V}, \quad (6)$$

where I is the discharge current (A), Δt is the discharge time (s), m is the mass of the active material (g), and ΔV is the potential window (V).

The specific capacitances of the SnS_2 electrodes were evaluated at current densities of 0.5, 1, 2, 4, 6, and 10 A/g, yielding values of 187, 184, 168, 136, 118, and 76 F/g, respectively. As illustrated in Figure 6b, a clear inverse relationship was observed between the specific capacitance and current density. This decrease in capacitance under elevated current densities was primarily due to limitations in ion diffusion, increased internal resistance, electrode polarization, and kinetic constraints, all of which hinder effective charge storage. The SnS_2 electrode exhibited performance that surpassed previously reported SnS_2 -based materials. For instance, SnS_2 nanorods delivered 165.2 F/g at 3 A/g [13], while flower-like SnS_2 achieved 67 F/g at 1 A/g [26]. Composites such as SnS_2 @CNTs/CFs and SnS_2 /g- C_3N_4 have exhibited significantly higher capacitances of 412 [27] and 552 F/g [28] at 1 and 0.5 A/g, respectively. Notably, the SnS_2 /rGO composite reached 871 F/g at 1 A/g [29]. By contrast, ellipsoid-like SnS_2 exhibited 117 F/g at 1 A/g [8], and SnS_2 nanosheets deposited straight onto carbon cloth achieved a specific capacitance of 194.4 mF/cm² at 0.9 mA/cm² [29]. Electrochemical impedance spectroscopy (EIS) analysis (Figure 6c) were performed to generate the Nyquist plot of the SnS_2 electrode along with the fitted equivalent circuit (inset in Figure 6c). The measured solution resistance (R_s) was approximately 0.6 Ω , while the charge transfer resistance (R_{ct}) was approximately 1.2 Ω , indicating efficient transport of electrons and ions at the electrode/electrolyte boundary. The durability over extended cycles was evaluated at a high current density of 10 A/g. over 5000 cycles (Figure 6d). Remarkably, the SnS_2 electrode retained 88% of its initial capacitance, confirming its excellent durability under repeated charge–discharge cycles.

The exceptional electrochemical performance of the flower-like SnS_2 nanostructures is largely attributed to their distinctive morphological and intrinsic material characteristics. The hierarchical flower-like architecture markedly improves the surface area, offering a greater number of electroactive sites for charge accumulation. This morphology also facilitates improved interaction with the electrolyte, promoting efficient ion diffusion and lowering resistance, which are critical factors for achieving a high capacitance. Additionally, the structure provides multiple channels for electron transport, which effectively reduces the charge-transfer resistance. SnS_2 exhibits a pseudocapacitive behavior owing to reversible faradaic redox transitions between the Sn^{2+} and Sn^{4+} states at the surface, further contributing to the overall enhanced charge accumulation beyond the scope of double-layer processes. Moreover, the short ion diffusion pathways inherent in the porous, flower-like structure allow rapid electrolyte penetration, thereby improving the rate capability even at elevated current densities. This morphology not only enhances the accessible surface area but also ensures efficient mass and charge transport throughout the electrode. The synergistic effect of the nanoflower morphology and the electroactive properties of SnS_2 results in superior specific capacitance, excellent cycling stability, and favorable rate performance, making flower-like SnS_2 nanostructures well-

sued for integration into next-generation supercapacitor devices.

4. Conclusions

In summary, hierarchical SnS_2 nanoflowers were successfully synthesized and characterized. XRD analysis confirmed a pure hexagonal crystalline phase with strong preferential orientation along the (111) plane and an average crystallite size of approximately 15.8 nm. FESEM images revealed a distinctive flower-like morphology composed of stacked nanosheets, forming a porous structure with a high surface area beneficial for electrochemical applications. EDX and XPS analyses verified the stoichiometric Sn^{4+} and S^{2-} composition, alongside minor surface-adsorbed oxygen species that likely enhance electrochemical activity. Electrochemical studies showed clear pseudocapacitive behavior with reversible $\text{Sn}^{2+}/\text{Sn}^{4+}$ redox transitions. The SnS_2 electrode achieved a high specific capacitance of 187 F/g at 0.5 A/g and exhibited a low charge-transfer resistance of approximately 1.2 Ω from EIS measurements. Stability testing demonstrated excellent durability, with 88% capacitance retention after 5000 cycles at 10 A/g. The enhanced electrochemical performance is attributed to the unique flower-like nanostructure, which increases effective surface area and ion accessibility. These findings highlight the promise of SnS_2 nanoflowers as advanced electrode materials for supercapacitor applications, with opportunities for further performance improvements through material and electrode design optimizations.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure

All authors have contributed substantially to this work and are jointly responsible for its content.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Indu Sharma: conceptualization, methodology, data curation, formal analysis, writing – original draft. **Nunna Guru Prakash:** writing – review and editing, data curation, visualization. **Tae Jo Ko and Rosaiah Pitcheri:** formal analysis, validation. **Jungwook Choi:** funding acquisition, resources, project administration, formal analysis, validation, writing – review and editing.

Funding

This research was supported by the Basic Science Research Program of the National Research Foundation of Korea

(NRF), funded by the Ministry of Science, ICT, and Future Planning (Grant RS-2023-00222166).

References

- [1] J. Liu, J. Wang, C. Xu, et al., "Advanced Energy Storage Devices: Basic Principles, Analytical Methods, and Rational Materials Design," *Advanced Science* 5 (2018): 1700322.
- [2] F. M. N. U. Khan, M. G. Rasul, A. S. M. Sayem, and N. K. Mandal, "Design and Optimization of Lithium-Ion Battery as an Efficient Energy Storage Device for Electric Vehicles: A Comprehensive Review," *Journal of Energy Storage* 71 (2023): 108033.
- [3] A. G. Olabi, Q. Abbas, A. Al Makky, and M. A. Abdelkareem, "Supercapacitors as Next Generation Energy Storage Devices: Properties and Applications," *Energy* 248 (2022): 123617.
- [4] K. C. S. Lakshmi and B. Vedhanarayanan, "High-Performance Supercapacitors: A Comprehensive Review on Paradigm Shift of Conventional Energy Storage Devices," *Batteries* 9, no. 4 (2023): 202.
- [5] X. Hong, J. He, C. Duan, G. Wang, and B. Liang, "Recent Advance in Electrochemically Activated Supercapacitors: Activation Mechanisms, Electrode Materials and Prospects," *Renewable and Sustainable Energy Reviews* 209 (2025): 115134.
- [6] S. A. Thomas and J. Cherusseri, "Strategically Designing Layered Two-Dimensional SnS₂-Based Hybrid Electrodes: A Futuristic Option for Low-Cost Supercapacitors," *Journal of Energy Chemistry* 85 (2023): 394–417.
- [7] M. Setayeshmehr, M. Haghighi, and K. Mirabbaszadeh, "A Review of Tin Disulfide (SnS₂) Composite Electrode Materials for Supercapacitors," *Energy Storage* 4 (2022): 1–19.
- [8] N. Parveen, S. A. Ansari, H. R. Alamri, M. O. Ansari, Z. Khan, and M. H. Cho, "Facile Synthesis of SnS₂ Nanostructures With Different Morphologies for High-Performance Supercapacitor Applications," *ACS Omega* 3, no. 2 (2018): 1581–1588.
- [9] P. Bhojane, "Recent Advances and Fundamentals of Pseudocapacitors: Materials, Mechanism, and its Understanding," *Journal of Energy Storage* 45 (2022): 103654.
- [10] M. Z. Ansari, S. A. Ansari, and S. H. Kim, "Fundamentals and Recent Progress of Sn-Based Electrode Materials for Supercapacitors: A Comprehensive Review," *Journal of Energy Storage* 53 (2022): 105187.
- [11] S. A. Thomas, J. Cherusseri, M. R. Pallavolu, M. Afzal, and D. N. Rajendran, "Strategically-Designed Environment-Friendly Tin-Based Electrodes for Sustainable Supercapacitors With High Specific Capacity," *Electrochimica Acta* 522 (2025): 145846.
- [12] M. Zhao, Q. Zhao, J. Qiu, H. Xue, and H. Pang, "Tin-Based Nanomaterials for Electrochemical Energy Storage," *RSC Advances* 6 (2016): 95449–95468.
- [13] M. Sajjad, Y. Khan, and W. Lu, "One-Pot Synthesis of 2D SnS₂ Nanorods with High Energy Density and Long Term Stability for High-Performance Hybrid Supercapacitor," *Journal of Energy Storage* 35 (2021): 102336.
- [14] Y. Zhou, L. Wang, S. Chen, et al., "Thin-Film Sb₂Se₃ Photovoltaics With Oriented One-Dimensional Ribbons and Benign Grain Boundaries," *Nature Photonics* 9 (2015): 409–415.
- [15] N. G. Prakash, M. Dhananjaya, A. L. Narayana, D. P. Shaik, P. Rosaiah, and O. M. Hussain, "High Performance One Dimensional α -MoO₃ Nanorods for Supercapacitor Applications," *Ceramics International* 44 (2018): 9967–9975.
- [16] A. L. Patterson, "The Scherrer Formula for X-Ray Particle Size Determination," *Physical Review* 56 (1939): 978–982.
- [17] D. Gu, X. Li, Y. Zhao, and J. Wang, "Enhanced NO₂ Sensing of SnO₂/SnS₂ Heterojunction Based Sensor," *Sensors Actuators, B Chem* 244 (2017): 67–76.
- [18] Z. Yang, C. Su, S. Wang, et al., "Highly Sensitive NO₂ Gas Sensors Based on Hexagonal SnS₂ Nanoplates Operating at Room Temperature," *Nanotechnology* 31, no. 7 (2020): 075501.
- [19] O. A. Chuvenkova, E. P. Domashevskaya, S. V. Ryabtsev, et al., "XANES and XPS Investigations of Surface Defects in Wire-Like SnO₂ Crystals," *Physics of the Solid State* 57 (2015): 153–161.
- [20] D. Meng, Z. Xie, M. Wang, et al., "In Situ Fabrication of SnS₂/SnO₂ Heterostructures for Boosting Formaldehyde-Sensing Properties at Room Temperature," *Nanomaterials* 13 (2023): 2493.
- [21] D. I. Jerdev and B. E. Koel, "Oxidation of Ordered Pt-Sn Surface Alloys by O₂," *Surface Science* 492 (2001): 106–114.
- [22] E. Bao, J. Sun, Y. Liu, et al., "Facile Preparation of SnS₂ Nanoflowers and Nanoplates for the Application of High-Performance Hybrid Supercapacitors," *International Journal of Hydrogen Energy* 47 (2022): 39204–39214.
- [23] P. A. K. Reddy, H. Han, K. C. Kim, and S. Bae, "Heterostructured NiCo₂S₄@SnS₂ Hybrid for All-Solid-State Supercapacitor Applications: Delocalized Charges on Co-S Heterojunction Improved Electrochemical Kinetics," *ACS Applied Energy Materials* 5 (2022): 13751–13762.
- [24] G. R. Reddy, G. Prathyusha, N. Jung, B. Sravani, and S. W. Joo, "Engineering Cationic Vacancies on Sphere-Like Zinc Cobaltite Microstructures via Self-Assembly of Silkworm-Like Interconnected Nanoparticles for Battery-Type Supercapacitors," *CrystEngComm* 25 (2023): 2618–2628.
- [25] B. Ranjan, G. K. Sharma, and D. Kaur, "Rationally Synthesized Mo₂N Nanopyramids for High-Performance Flexible Supercapacitive Electrodes With Deep Insight Into the Na-Ion Storage Mechanism," *Applied Surface Science* 588 (2022): 152925.
- [26] M. Setayeshmehr, M. Haghighi, and K. Mirabbaszadeh, "Binder-Free 3D Flower-Like Alkali Doped- SnS₂ Electrodes for High-Performance Supercapacitors," *Electrochimica Acta* 376 (2021): 137987.
- [27] Z. Zhang, L. Feng, P. Jing, et al., "In Situ Construction of Hierarchical Polyaniline/SnS₂@carbon Nanotubes on Carbon Fibers for High-Performance Supercapacitors," *Journal of Colloid and Interface Science* 588 (2021): 84–93.
- [28] Y. Xu, Y. Zhou, J. Guo, S. Zhang, and Y. Lu, "Preparation of SnS₂/g-C₃N₄ Composite as the Electrode Material for Supercapacitor," *Journal of Alloys and Compounds* 806 (2019): 343–349.
- [29] Y. Shi, L. Sun, Y. Zhang, et al., "SnS₂ Nanodots Decorated on RGO Sheets With Enhanced Pseudocapacitive Performance for Asymmetric Supercapacitors," *Journal of Alloys and Compounds* 853 (2021): 156903.