

Research Article

## Eco-Friendly Synthesis of Hierarchical SnS<sub>2</sub> Nanoflowers with Three-Dimensional Architecture for Advanced Biomedical Sensing Applications

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**Abstract.** Tin disulfide (SnS<sub>2</sub>), which belongs to the class of two-dimensional transition metal dichalcogenides, has attracted considerable interest because of its layered architecture, controllable physicochemical characteristics, adjustable band gap, and favorable compatibility with biological systems. These properties support its suitability for applications in nanoscale sensing technologies and advanced diagnostic platforms. In the present work, three-dimensional (3D) hierarchical SnS<sub>2</sub> nanoflower structures (3D h-SnS<sub>2</sub>) were prepared through a facile, environmentally friendly ultrasonic-assisted method at room temperature. The obtained materials were evaluated using optical microscopy, dynamic light scattering, and scanning electron microscopy combined with energy-dispersive X-ray analysis (SEM-EDX). Characterization results demonstrated uniform particle distribution, defined microstructural morphology, and an elemental composition consistent with the expected Sn<sub>1</sub>:S<sub>2</sub> stoichiometric ratio. Overall, the study confirms the effective synthesis of hierarchical f-SnS<sub>2</sub> *via* a green synthesis strategy and suggests its potential utility as a transducing component in sensor-related applications.

**Keywords:** Eco-Friendly Synthesis; SnS<sub>2</sub> Nanoflowers; Sonochemical.

### 1. Introduction

Tin disulfide (SnS<sub>2</sub>) is categorized as a two-dimensional transition metal dichalcogenide characterized by a layered structure in which a plane of tin atoms is positioned between two closely packed sulfur layers arranged in a hexagonal configuration [1]. In contrast to extensively investigated dichalcogenides such as MoS<sub>2</sub>, SnS<sub>2</sub> has emerged as a promising alternative owing to its distinct physicochemical properties and the adaptability of tin and sulfur [2, 3]. Structurally, it represents a semiconducting layered material composed of relatively abundant elements, with tin from group IV serving as the central metal species in place of conventional transition metals found in related compounds [4].

Notably, SnS<sub>2</sub> exhibits an indirect band gap in both its monolayer and bulk forms. Previous investigations combining experimental exfoliation of nanoflakes with first-principles theoretical analysis have clarified their fundamental electronic characteristics and highlighted their technological prospects [5]. Furthermore, its comparatively wider band gap among dichalcogenide materials enables device operation under higher voltage, temperature, and frequency conditions, underscoring its suitability for advanced sensing and bioelectronic applications [6, 7].

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Various approaches have been discovered to obtain highly crystalline SnS<sub>2</sub>, with ultrasonic-assisted methods offering particular advantages such as controllable morphology, tunable physicochemical properties, scalability, eco-friendliness, and economic feasibility [8, 9]. Engineering SnS<sub>2</sub> into nanoflower-like architectures further enhances its functional performance due to the increased surface area, improved charge carrier separation, and facilitated ion transport, which are beneficial for applications ranging from photocatalysis and electrocatalysis, smart wearable self-powered mechanosensor, water splitting, gas detection, and biomedical sensing [10-12]. In this work, three-dimensional hierarchical SnS<sub>2</sub> nanoflowers (3D h-SnS<sub>2</sub>) were prepared *via* an ultrasound-assisted method conducted at room temperature using a non-chelating solvent to support an environmentally friendly process. Tin chloride and thioacetamide served as the tin and sulfur precursors, respectively. The study distinguishes itself through the implementation of green experimental synthesis to produce high-quality SnS<sub>2</sub> nanomaterials with potential applications in biomedical sensing and bioelectronics.

## 2. Methods

### Materials and Instrumentation

Tin(II) chloride dihydrate (SnCl<sub>2</sub>·2H<sub>2</sub>O, ~99%) and absolute ethanol were obtained from Smart Lab, while thioacetamide (≥99.0%) was supplied by Sigma-Aldrich. All solutions were prepared using ultrapure deionized water to ensure high-purity conditions. The sonochemical synthesis process was carried out using an ultrasonic cleaning bath (Branson CPX1800H-E), which operated continuously throughout the reaction.

### Synthesis of 3D h-SnS<sub>2</sub> nanomaterials

3D h-SnS<sub>2</sub> nanoflowers were synthesized *via* an ultrasound-assisted method adapted from an earlier report [13, 14]. The sonochemical reaction was performed in 15 mL conical centrifuge tubes using an ultrasonic bath operating at a power output of 70 W and a frequency of 40 kHz. Initially, 20 mL of ethanol was transferred into a 50 mL conical flask, followed by the addition of tin(II) chloride dihydrate and thioacetamide in a molar ratio of 1:2.5. The mixture was magnetically stirred for 30 minutes to ensure homogeneity before being distributed evenly into four centrifuge tubes. These tubes were then subjected to ultrasonic irradiation for 220 minutes.

Upon completion of sonication, the reaction mixtures were purified by centrifugation at 3000 rpm for 10 minutes. The supernatant was discarded, and the collected precipitate was redispersed in 10 mL of fresh ethanol, sonicated for 15 minutes, and recentrifuged under similar conditions. This washing cycle was repeated three times to enhance material purity. Formation of a light orange suspension signified the successful development of the SnS<sub>2</sub> nanoflower structures. Residual solvents were removed prior to subsequent material characterization.

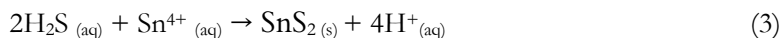
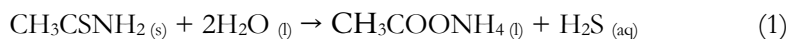
### Characterization of 3D h-SnS<sub>2</sub> nanomaterials

Preliminary evaluation of the synthesized 3D h-SnS<sub>2</sub> samples was performed by visual inspection and optical imaging using a binocular optical microscope (XSZ 107 BN) under ambient laboratory conditions. The hydrodynamic particle size distribution and zeta potential were determined with a Malvern Zetasizer Pro Blue ZSU 3200 to assess dispersion characteristics and surface charge. Morphological properties and elemental composition were examined through scanning electron microscopy (SEM, JEOL JSM-6510LA) coupled with energy-dispersive X-ray spectroscopy (EDX).

## 3. Results and Discussion

Tin(II) chloride dihydrate and thioacetamide served as respective precursors for tin and sulfur. The measured reactants were introduced into ethanol and solubilized using magnetic stirring at 1200 rpm for 30 minutes to obtain a uniform solution. The homogeneous mixture was subsequently exposed to ultrasonic treatment for 220 minutes, promoting the formation of crystalline, flower-like SnS<sub>2</sub> structures at the submicron scale dispersed throughout the medium.

The corresponding chemical reactions governing the ultrasound-assisted formation of 3D h-SnS<sub>2</sub> are presented in **Equations 1 to 3**.

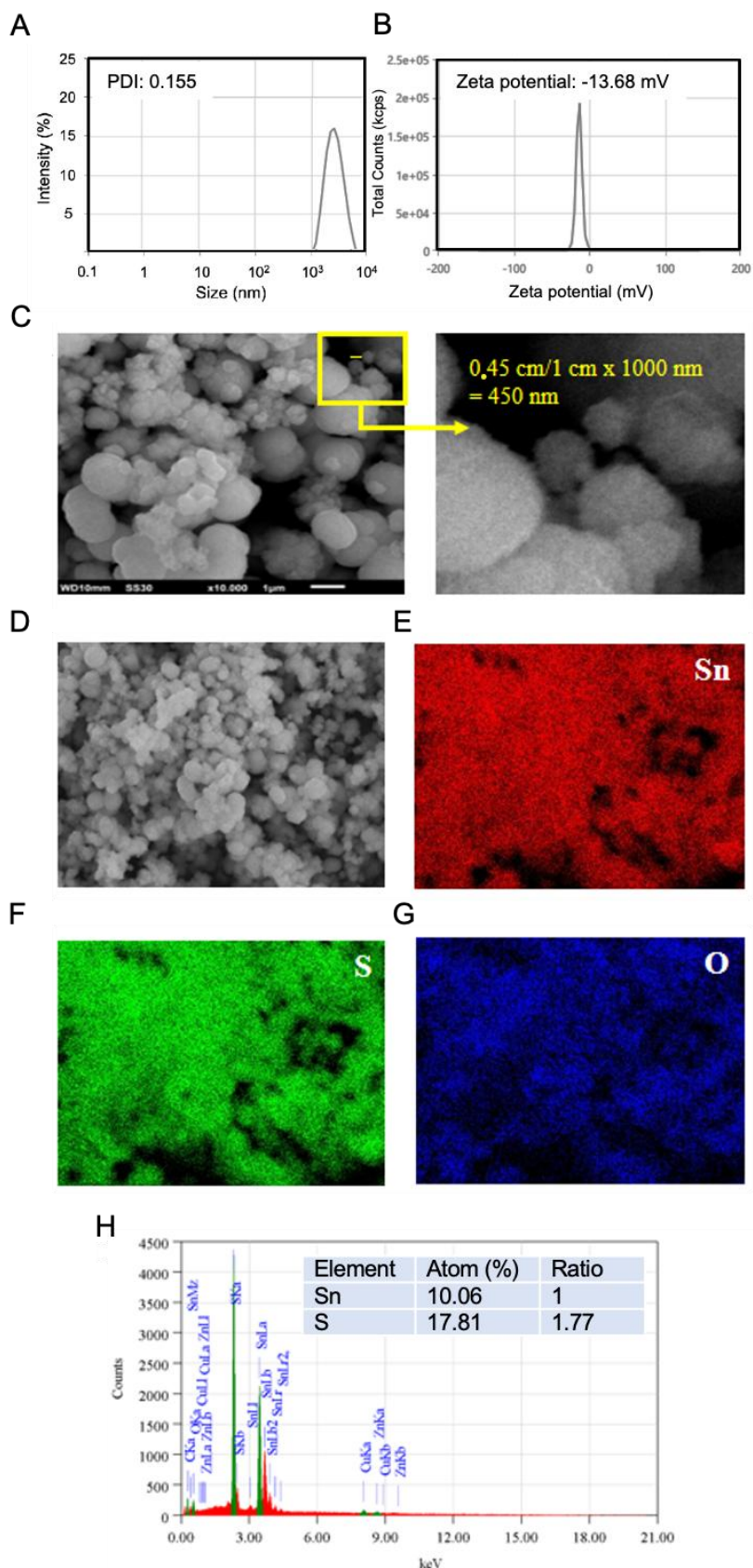


Under ultrasonic irradiation, thioacetamide decomposes to produce H<sub>2</sub>S, which reacts with tin ions to form SnS<sub>2</sub>. The use of absolute ethanol as the solvent favored the selective formation of SnS<sub>2</sub>, evidenced by the appearance of an orange colloidal suspension, while minimizing the formation of other tin sulfide phases [13]. Maintaining the liquid level in the ultrasonic bath consistent with that in the reaction vessel ensured effective energy transfer [15]. Extended sonication time promoted improved crystallinity and more uniform particle growth, as confirmed by deeper orange coloration and optical microscopy observations showing well-dispersed, homogeneous colloids [14]. In particular, 220 minutes of irradiation resulted in more consistent SnS<sub>2</sub> formation with a subtle glittering appearance under ambient light [14, 16]. After irradiation, the product was separated by centrifugation and purified to enhance material quality. The observed color and optical response are attributed to the strong light interaction and relatively wide band gap of SnS<sub>2</sub> [2], supporting its successful synthesis *via* the sonochemical approach.

The particle size distribution and colloidal stability of the synthesized 3D h-SnS<sub>2</sub> were evaluated using particle size analysis based on hydrodynamic measurements. Prior to analysis, the dispersion was diluted tenfold to minimize potential interference from multiple light scattering and viscosity-related effects. The results indicated an average hydrodynamic diameter of approximately 2391 nm (Figure 1(A)). The material exhibited a considerably narrow size distribution, reflected by a low polydispersity index (PDI) of 0.155, suggesting a highly uniform and monodisperse microscale population. Such a low PDI value supports the suitability of the material for applications requiring consistent particle characteristics, including biocompatible sensing platforms. Surface charge properties were further examined through zeta potential measurements, which provide insight into colloidal stability [17]. The 3D h-SnS<sub>2</sub> particles displayed a negative zeta potential of -13.68 mV (Figure 1(B)), indicating the presence of negatively charged surfaces in suspension.

SEM was employed to observe the development of the three-dimensional hierarchical architecture. The micrographs demonstrate that SnS<sub>2</sub> assembled into flower-like, spherical structures composed of interconnected nanosheets. The overall aggregate dimensions were observed to range from approximately 450 to ~2500 nm (Figure 1(C)). This structural feature is consistent with previously described morphologies [13, 14] and is advantageous for sensing-related applications, as the nanosheet edges can provide abundant reactive sites suitable for surface functionalization.

Elemental composition was further examined using EDX analysis. Elemental mapping confirmed a uniform dispersion of Sn and S throughout the microstructures (Figure 1(D-G)), with a measured atomic ratio of approximately 1:1.77 (Figure 1(H)), closely approaching the expected stoichiometric proportion of SnS<sub>2</sub>. A minor carbon signal was also detected, which is likely attributable to residual solvent and the possible side product upon synthesis [14].



**Figure 1.** (A) Average particle size distribution and (B) zeta potential of the 3D h-SnS<sub>2</sub> nanoflower structures. (C) Scanning electron micrographs of the 3D h-SnS<sub>2</sub> nanoflower structures acquired at magnifications of 1 × 10<sup>4</sup>. EDX mapping of 3D h-SnS<sub>2</sub> corresponding to (D) electron image, (E) Sn atoms, (F) S atoms, and (G) O atoms. (H) Elemental analysis of 3D h-SnS<sub>2</sub> with the calculated ratio between Sn and S.

#### 4. Conclusions

3D h-SnS<sub>2</sub> nanoflower structures were successfully prepared through a facile, eco-friendly ultrasound-assisted sonochemical method carried out at room temperature. The sonochemical approach supports green synthesis principles by minimizing the use of hazardous reagents and employing more sustainable solvents. Macroscopic observation and particle size measurements confirmed the development of uniformly distributed, sphere-like hierarchical architectures. Further structural and compositional evaluation using SEM and EDX analyses demonstrated well-organized growth of SnS<sub>2</sub> with an Sn:S elemental ratio close to the 1:2 stoichiometry. EDX elemental mapping showed a dominant and homogeneous distribution of tin and sulfur throughout the structures, substantiating the effective formation and compositional integrity of the synthesized SnS<sub>2</sub> nanomaterials.

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**Data Availability Statement:** The authors confirm that all data underlying the results presented in this work are included within the article. Additional raw datasets related to the study can be obtained from the corresponding author upon reasonable request.

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**Conflicts of Interest:** 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.

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