



Evaluation of Aqueous and Ethanolic Extracts for the Green Synthesis of SnO₂ Nanoparticles from Fresh *Senna alata* Leaves

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Abstract

Fresh leaves provided active phytochemicals that acted as reducing, capping, and stabilizing agents, while the solvent dictated their extraction and interaction with growing nanoparticles. Controlling the size, morphology, and optical properties of SnO₂ nanoparticles remains challenging due to limited understanding of how solvent selection influences phytochemical-mediated nanoparticle formation. This study addresses this problem by employing a green synthesis approach using a 1.0 M solution of tin (II) chloride dihydrate (SnCl₂·2H₂O) as a precursor and fresh *Senna alata* leaf extracts as an environmentally friendly reducing, stabilizing and capping agent prepared in water and ethanol. Structural, morphological, and optical properties of the synthesized nanoparticles were studied. X-ray diffraction confirmed phase-pure tetragonal rutile SnO₂, with ethanolic extracts producing larger crystallites (9.06 nm) and higher crystallinity than aqueous extracts (3.70 nm). FTIR revealed stronger surface coordination in ethanolic samples, and SEM/TEM showed smaller, more uniformly dispersed nanoparticles (8.73 nm) versus moderately agglomerated aqueous-derived particles (9.79 nm). Optical studies indicated enhanced UV absorption, higher transparency, and a lower band gap (3.05 eV) for ethanolic extract-mediated nanoparticles. These findings demonstrate that solvent choice critically influences nanoparticle properties, and fresh *Senna alata* extracts in ethanol offer a potential green route to SnO₂ nanoparticles with tunable structural, morphological, and optical characteristics for optoelectronic, photocatalytic, gas sensing, and solar energy applications.

Keywords: Green Synthesis, Solvent, Fresh *Senna alata* leaf, and SnO₂ nanoparticles

Introduction

Nanotechnology is the characterization, design, and application of a combination of systems, structures, and devices by size control as well as the shape of particles at the scale of 10⁻⁹m (Buniyamin *et al.*, 2023c). Their brilliant properties are unquestionable when the particles are scaled down to the nanoscale compared to the bulk size (Buniyamin *et al.*, 2022a, Basnet *et al.*, 2018). Through controlling and modifying the nanoparticles (NPs), an improvement in terms of unique thermal, optical, chemical, mechanical, electrical and magnetic characteristics can be obtained. These unique characteristics stimulated researchers' interest in synthesizing nanoscale materials with different sizes, shapes, and compositions. There has been extensive research on synthesizing and optimizing nanoparticles (Vani *et al.*, 2017, Buniyamin *et al.*, 2023a, Buniyamin *et al.*, 2023b, Kumar *et al.*, 2017).

According to Khan *et al.*, (2017) nanoparticles can be subdivided into carbon-based, metallic, metal oxides, ceramics, semiconductors, polymeric and lipid-based. Among these nanomaterials, metal oxide nanostructures have been popular in various fields ranging from the biomedical field, water treatment and so on (Raya & Pal 2017, Zhang *et al.*, 2012, Zhang *et al.*, 2015). Metal oxide nanoparticles (MO NPs) have been synthesized majorly by using physical and chemical methods. Physical methods include spray pyrolysis (Nazari *et al.*, 2017),

ultrasonication (Kumar *et al.*, 2000), chemical vaporization (An *et al.*, 2010) e.t.c. However, physical methods suffer many limitations such as non-uniformity in particle size and high instrumentation cost. Metal oxide nanoparticles can be chemically synthesized through oxidation–reduction reaction, or by the precipitation of the necessary metal ion precursor in an aqueous solution phase (Duan *et al.*, 2015, Arab *et al.*, 2017). Despite its success in the preparation of various inorganic nanoparticles with numerous morphologies, conventional chemical methods generally make use of toxic chemicals which are a threat to human health and the environment. This has led to the improvement of new synthetic methods which are environmentally friendly.

Biosynthesis has attracted tremendous interest as it is a cost-effective and environmentally friendly method to produce nanoparticles by eliminating or reducing the use of toxic reaction precursors. It is an emerging technique for remediation of nanoparticle toxicity usually associated with conventional chemical and physical methods of synthesis. It uses non-hazardous reagents, simple protocols and mild reaction conditions. Green synthesis methods include synthesis through different biomaterials such as bacteria, fungi, algae and plants e.t.c. as either stabilizing agents or reducing agents or both in some cases. Synthesis of nanoparticles using microorganisms and plants is referred to as biosynthesis (Zikalala

et al., 2018). The advantage of using plants instead of bacteria or fungi for NPs production is the lack of pathogenicity.

Among the nanoparticles, tin (IV) oxide nanoparticles (SnO₂ NPs) have been studied intensively because of their potential applicability to lithium-ion batteries, transparent conducting electrodes in ionic devices, anti-reflective coatings, solid-state gas sensors, solar cells, catalytic support materials, energy storage, medicals, etc. (Buniyamin *et al.*, 2022b, Ayeshamariam *et al.*, 2013, Naje *et al.*, 2013).

Specifically, the focus on SnO₂ has increased due to its properties like low electrical sheet resistance, high chemical stability and high transparency (Minami, 2000). SnO₂ is an n-type semiconductor that has a wide band gap (3.6 eV) which activated only UV irradiation (Liang *et al.*, 2019). This activity is restricted by the recombination of the charge carriers (electrons and holes).

The structural, morphological and optical characteristics of SnO₂ NPs synthesized via green methods are influenced by several factors, particularly the choice of extraction solvent, whether aqueous or ethanolic. The selected solvent affects the profile of metabolites, which subsequently influences the size, morphology, dispersion, and stability of the nanoparticles (Alamdari 2019). Research has shown that ethanolic extraction recovers a significant amount of phenolic and terpenoid compounds, while aqueous extraction is more effective for flavonoids and saponins. These differences influence the nucleation process and growth of nanoparticles (Bouttier-Figueroa *et al.*, 2024).

Recent research has been published on the biosynthesis of SnO₂ NPs utilizing various natural plant extracts (Buniyamin *et al.*, 2023c). *Senna alata* was selected as the biological reagent in this study due to its rich phytochemical compositions, position, wide availability, non-toxicity, and reported antioxidant activity (Sarwar *et al.*, 2025).

Recent studies have reported the use of similar plant such as *Tradescantia spathacea* in the production of ZnO nanoparticles (Trejo-Floris *et al.*, 2025). However, there is a lack of research on the capability of *Senna alata* to synthesize metallic oxides, such as SnO₂. Therefore, this study focuses on the green synthesis of SnO₂ nanoparticles using aqueous and ethanolic extracts of fresh *senna alata* leaf, to evaluate how the solvents influence the structural, morphological and optical properties of the obtained nanoparticles.

Materials

Fresh leaves of *Senna alata* (candlestick plant), also known as "Rai dore" in Hausa, "Asunwo oyinbo" in Yoruba, were harvested from a farm in the Baale Yaku area, located at 8.14319° North and 4.19674° East in Ogbomoso, Oyo State, Nigeria. Distilled water and ethanol were used as solvent for the extraction. Analytical grade of Tin (II) chloride dihydrate (SnCl₂·2H₂O) was purchased from a local supplier and utilized without undergoing additional purification.

Preparation of *Senna alata* Leaf Extracts

Fresh *Senna alata* leaves were first rinsed with clean water to remove dust and surface impurities. Distilled water and ethanol were selected as solvents for extracting phytochemicals because they efficiently dissolve a broad spectrum of bioactive compounds such as phenolics,

flavonoids, and terpenoids that act as reducing and stabilizing agents in green nanoparticle synthesis (Balaji *et al.*, 2025, Rauf *et al.*, 2025).

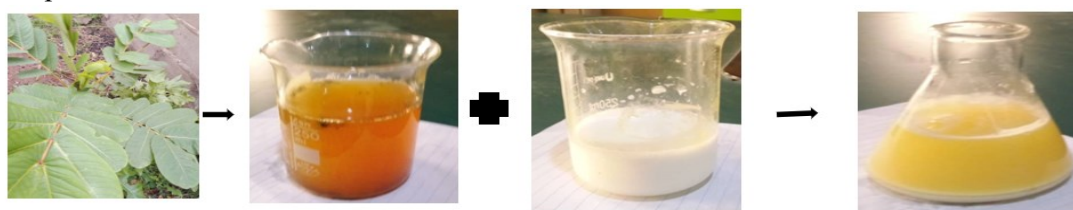
For each extract, 1.0 g of fresh *Senna alata* leaves was finely ground with 100 mL of distilled water using an electric blender for 10 min. The mixture was then filtered through Whatman No. 1 filter paper to obtain the aqueous extract. The same procedure was followed to prepare the ethanolic extract using ethanol as the solvent. The crude aqueous extract (FSAW) appeared amber brown, while the ethanolic extract (FSAE) appeared dark, likely due to solvent-dependent differences in phytochemical composition (Balaji *et al.*, 2025). Each extract was stored separately for further use in nanoparticle synthesis.

Synthesis of Tin Oxide Nanoparticles

A 1.0 M tin (II) chloride dihydrate ($\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$) solution was prepared by dissolving the salt in 100 mL of distilled water and stirring for 120 s using a magnetic stirrer, resulting in a milky white solution. Tin (II) chloride serves as a suitable precursor for synthesizing metal oxide nanoparticles in green methods (Balaji *et al.*, 2025).

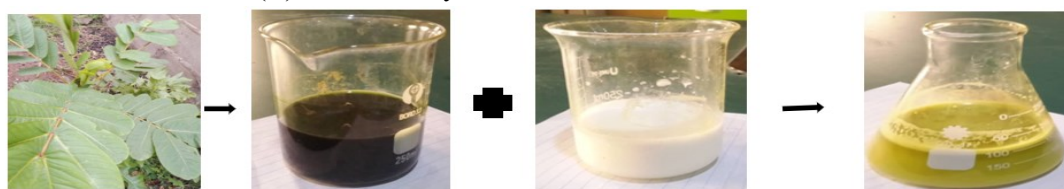
In a typical green synthesis procedure, the aqueous and ethanolic *Senna alata* leaf extracts were added dropwise to the tin (II) chloride solution at a 1:10 ratio (extract: metal salt solution) under continuous stirring, following the technique demonstrated by Usman *et al.*, (2024). Mixing the extracts with the tin solution induced visible colour changes from milky white to lemon-yellow with the aqueous extract and to yellow-green with the ethanolic extract which qualitatively indicates phytochemical-mediated reduction of metal ions and nanoparticle formation (Rauf *et al.*, 2025).

The resulting mixtures were centrifuged at 4000 rpm for 10 min to separate solid particles from the supernatant, and the pellets were dried in an oven at 60 °C for 24 h to obtain tin oxide nanoparticles for further characterization.



Senna alata leaves *Senna alata* leaf extract Solution of tin (II) chloride Synthesised SnO_2 NP

Plate 1: Synthesis of SnO_2 NP using fresh *Senna alata* leaves extract obtained with water and added to solution of tin (II) chloride dihydrate



Senna alata leaves *Senna alata* leaf extract Solution of tin (II) chloride Synthesised SnO_2 NP

Plate 2: Synthesis of SnO_2 NP using fresh *Senna alata* leaves extract obtained with ethanol and added to solution of tin (II) chloride dihydrate

A solution of tin (II) chloride dihydrate was prepared in distilled water (SnCl₂ solution). Aqueous and ethanolic extracts of fresh *Senna alata* leaf were obtained using distilled water and ethanol and designated as FSAW and FSAE, respectively. In addition, two mixtures were prepared by combining the aqueous fresh *Senna alata* leaf extract with the tin (II) chloride dihydrate solution (FSAW + SnCl₂ solution) and the ethanolic fresh *Senna alata* leaf extract with the tin (II) chloride dihydrate solution (FSAE + SnCl₂ solution).

Characterization Techniques

X-ray diffraction (XRD) (model: Rigaku) was used to determine the crystallographic structure. The functional groups and component composition of the nanoparticles were determined using Agilent Technology Cary 630 FTIR spectroscopy. The surface morphology and elemental composition were carried out using Scanning Electron Microscope (SEM) with EDX Spectroscopy (model: JEOL JBM-7600F) and high-resolution Transmission Electron Microscope (TEM) (model: Verios 460I). The optical properties of the SnO₂ nanoparticles were analysed by UV-vis spectroscopy (model: JASCO-V670) in the range of 200-900nm and the optical bandgap was estimated from optical absorption spectrum.

XRD Analysis

The X-ray diffraction (XRD) patterns of the synthesized SnO₂ nanoparticles are illustrated in Figure 1. Distinct diffraction peaks observed at planes indexed as (002), (101), (200), and (220) correspond to the tetragonal rutile crystal structure of SnO₂, in agreement with the standard JCPDS card no. 41-1445. The appearance of intense and narrow diffraction peaks, particularly along the (002) plane, confirms the formation of well-crystallized SnO₂ nanoparticles. The absence of additional diffraction peaks indicates that the samples are phase-pure, suggesting that the plant-mediated synthesis route effectively prevented the formation of secondary phases or impurities. Similar structural features have been reported for SnO₂ nanoparticles synthesized using plant extracts in recent studies (Anita *et al.*, 2023; Mutukwa *et al.*, 2024).

The structural parameters calculated from the XRD data are presented in Tables 1 and 2. The average crystallite size of the SnO₂ nanoparticles synthesized using the ethanolic leaf extract (FSAE + SnCl₂) was found to be 9.06 nm, which is significantly larger than that obtained for the aqueous extract-mediated sample (FSAW + SnCl₂), which showed a crystallite size of 3.70 nm. This variation can be attributed to differences in solvent polarity and phytochemical composition. Ethanol-extracted phytochemicals are known to promote slower nucleation and sustained crystal growth, resulting in larger and more ordered crystallites. In contrast, the aqueous extract likely facilitated rapid nucleation due to higher concentrations of polar biomolecules, leading to smaller crystallite sizes. Similar solvent-dependent crystallite growth behavior has been documented in recent green synthesis studies of metal oxide nanoparticles (Batoool *et al.*, 2024; Rauf *et al.*, 2025).

The relatively larger crystallite size obtained for the FSAE-mediated SnO₂ nanoparticles may be beneficial for optoelectronic applications, as improved crystallinity and reduced grain

boundary density can enhance charge transport properties and reduce recombination losses (Mutukwa *et al.*, 2024).

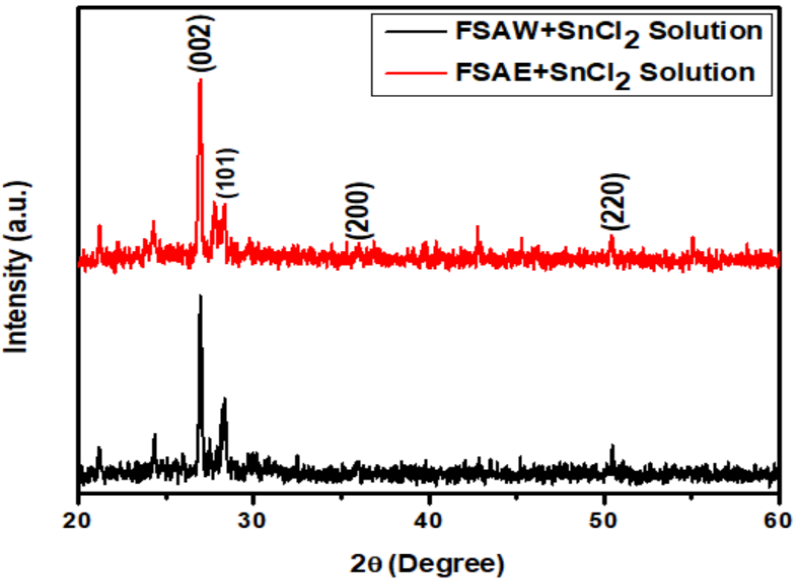


Figure 1: XRD patterns of synthesized SnO₂ nanoparticles extracted FSAW+SnCl₂ and FSAE+SnCl₂

Table 1: Structural parameter of SnO₂ Nanoparticles: FSAW + SnCl₂ and FSAE + SnCl₂

2θ (°)		L (nm)		β (°)		d (nm) × 10 ⁻¹	
2θ _a	2θ _b	L _a	L _b	β _a	β _b	d _a	d _b
27.0	27.5	3.63	10.80	2.35	1.05	3.3	3.3
28.0	28.5	3.64	8.35	2.35	1.05	3.1	1.6
36.1	36.4	3.66	8.51	2.35	1.05	2.9	1.6
50.2	51.0	3.90	8.59	2.35	1.05	1.8	1.8

Table 2: The average crystallite size, Full Width at Half Maximum and d spacing of Synthesized SnO₂

Sample	Leaf Type	Solvent	Crystalline (nm)	Size	FWHM (°)	d-Spacing (nm)
FSAW+SnCl ₂	Fresh	Water	3.70		2.35	0.2775
FSAE+SnCl ₂	Fresh	Ethanol	9.06		1.05	0.2075

FTIR Analysis

Fourier transform infrared (FTIR) spectroscopy was employed to identify functional groups associated with phytochemical capping and to evaluate solvent effects on surface chemistry (Figure 2). The broad absorption band observed at 3482 cm⁻¹ for FSAW + SnCl₂ and its shifted counterpart at 3296 cm⁻¹ for FSAE + SnCl₂ is attributed to O–H stretching vibrations arising

from surface hydroxyl groups or adsorbed water molecules. These hydroxyl groups are commonly observed in biosynthesized metal oxide nanoparticles and play a crucial role in nanoparticle stabilization (Akhtar *et al.*, 2025).

The absorption peaks appearing near 2926 cm^{-1} and 2920 cm^{-1} correspond to C–H stretching vibrations, confirming the presence of organic moieties derived from plant metabolites on the nanoparticle surface. Peaks in the range of $1622\text{--}1648\text{ cm}^{-1}$ are associated with nitrate stretching vibrations, while the band around 1050 cm^{-1} corresponds to C–O stretching modes. The observed peak shifts and reduced intensities in the FSAE-mediated sample indicate stronger interaction between ethanol-extracted phytochemicals and the SnO_2 surface. Such solvent-induced variations in FTIR spectra have been widely reported in recent green synthesis literature and reflect effective surface functionalization and stabilization (Batool *et al.*, 2024; Akhtar *et al.*, 2025).

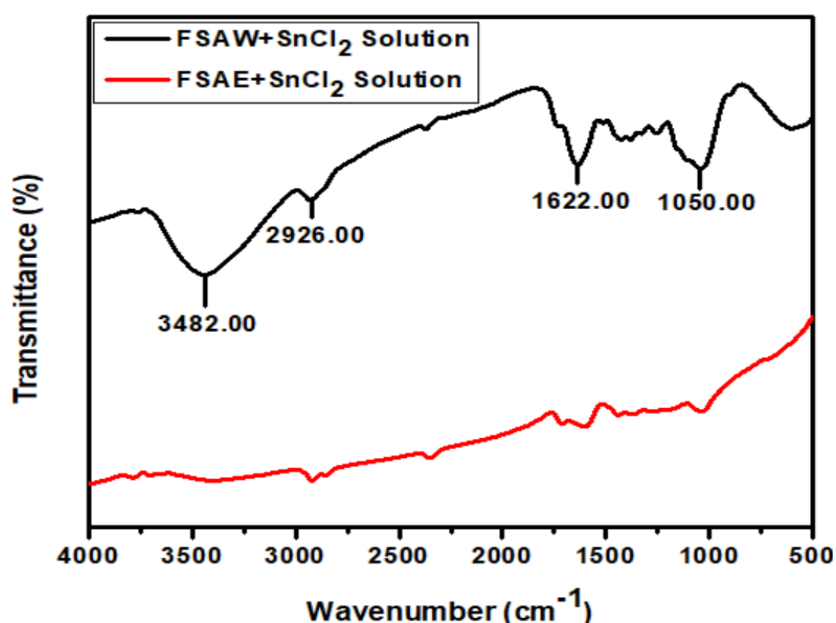


Figure 2: FTIR spectra of synthesized SnO_2 nanoparticles extracted: FSAW+ SnCl_2 and FSAE+ SnCl_2

Table 3: Summary of bond types and wavenumber in synthesised SnO_2 Nanoparticles: FSAW + SnCl_2 and FSAE + SnCl_2

Peak	Wave number (cm^{-1})		Bond type
	FSAW+ SnCl_2	FSAE+ SnCl_2	
1	3482.00	3296.00	OH stretch
2	2926.00	2920.00	C-H stretch
3	1622.00	1648.00	NO_3^- stretch
4	1050.00	1049.00	C-O stretch

SEM Analysis

Scanning electron microscopy (SEM) images of the synthesized SnO₂ nanoparticles are presented in Figure 3. The micrographs reveal relatively uniform particle distribution with predominantly spherical morphology and partial agglomeration. Such aggregation is typical in plant-mediated nanoparticle synthesis due to hydrogen bonding and van der Waals interactions among phytochemical-capped nanoparticles. The FSAE + SnCl₂ sample exhibits improved surface homogeneity, higher grain boundary density, and better-defined crystallites compared to the FSAW + SnCl₂ sample.

The enhanced smoothness and crystallinity observed in the ethanolic extract-derived nanoparticles suggest stronger coordination between ethanol-soluble functional groups and the SnO₂ surface. Comparable improvements in surface morphology have been reported in recent studies where ethanol was used as the extraction solvent in green nanoparticle synthesis (Mutukwa *et al.*, 2024; Rauf *et al.*, 2025).

TEM Analysis

Transmission electron microscopy (TEM) images (Figure 4) further confirm the successful formation of nanosized SnO₂ particles with quasi-spherical morphology. The aqueous extract-mediated sample (FSAW + SnCl₂) displays noticeable agglomeration, with particle sizes ranging from 8.36 to 12.70 nm and an average diameter of 9.79 nm. The broader size distribution observed in this sample is attributed to strong intermolecular interactions among water-soluble phytochemicals during nanoparticle growth.

In contrast, the ethanolic extract-mediated SnO₂ nanoparticles (FSAE + SnCl₂) exhibit improved dispersion and reduced agglomeration. Particle sizes in this sample range from 6.52 to 10.40 nm, with an average size of 8.73 nm, indicating a narrower size distribution. This enhanced uniformity is attributed to more effective steric stabilization provided by ethanol-extracted phytochemicals, which suppress excessive particle growth. Similar solvent-controlled size variations have been reported in recent plant-mediated nanoparticle synthesis studies (Batoool *et al.*, 2024; Akhtar *et al.*, 2025).

EDX Analysis

Energy-dispersive X-ray (EDX) spectra (Figure 5) confirm that the synthesized nanoparticles primarily consist of tin (Sn) and oxygen (O), verifying the formation of SnO₂. The absence of chlorine peaks indicates effective removal of residual precursor ions during synthesis. Minor signals corresponding to carbon and trace elements are attributed to phytochemical residues from the leaf extracts and background contributions from the analytical instrumentation. Similar elemental compositions have been reported for green-synthesized SnO₂ nanoparticles in recent studies (Anita *et al.*, 2023; Mutukwa *et al.*, 2024).

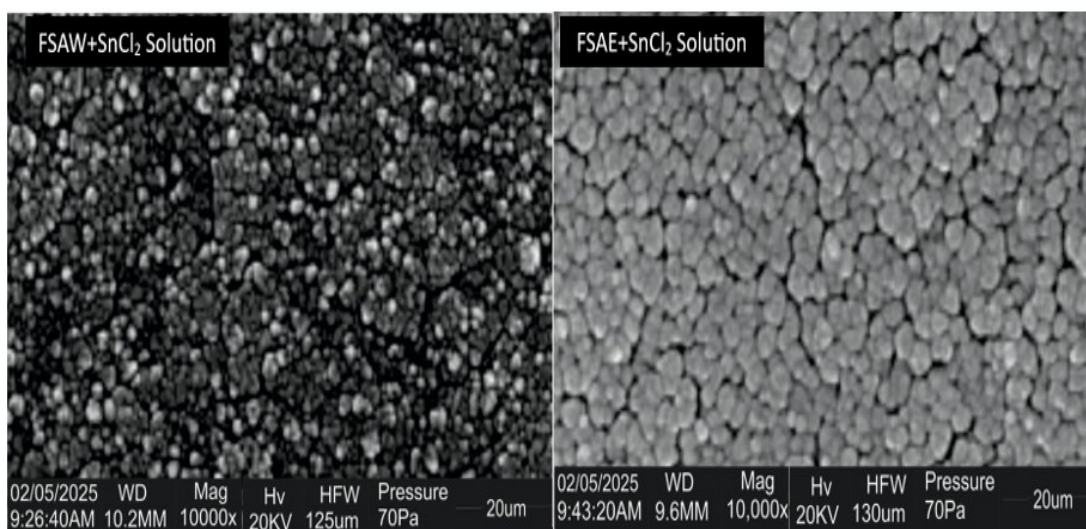


Figure 3: SEM images of synthesized SnO₂ nanoparticles extracted: FSAW+SnCl₂ and FSAE+SnCl₂

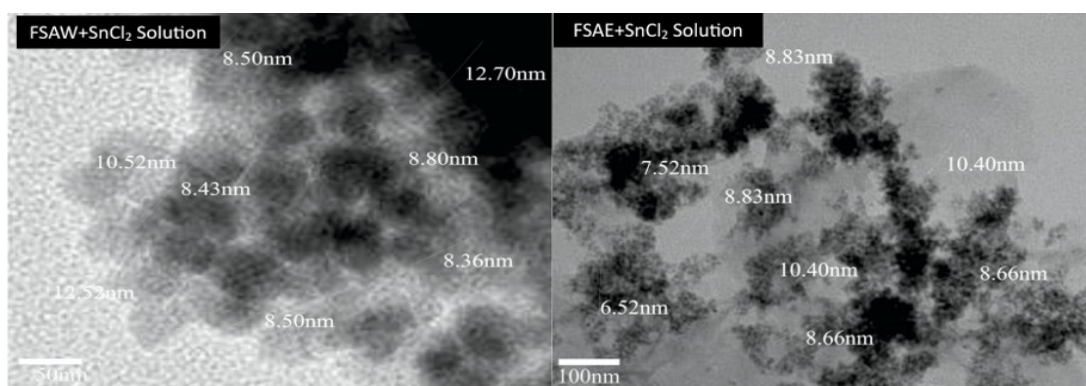


Figure 4: TEM images of synthesized SnO₂ nanoparticles extracted: FSAW+SnCl₂ and FSAE+SnCl₂

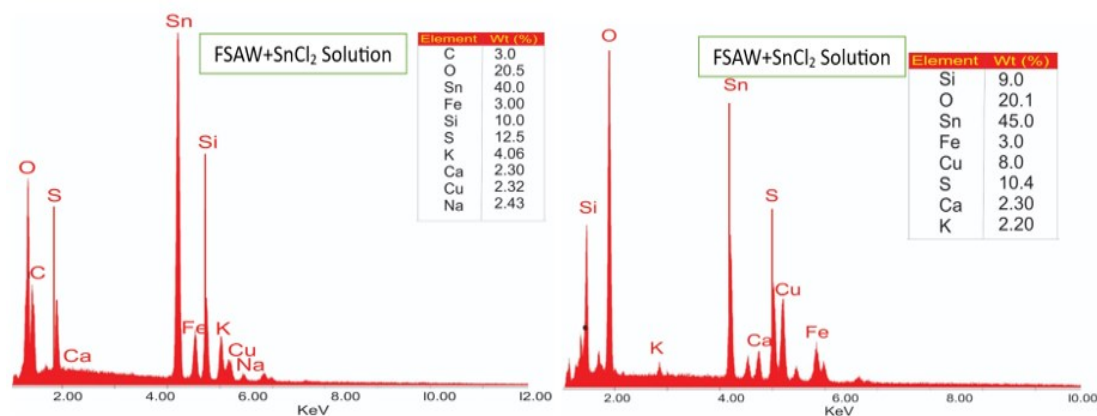


Figure 5: EDX Spectra of synthesized SnO₂ nanoparticles extracted: FSAW+SnCl₂ and FSAE+SnCl₂

UV–Visible Absorption Analysis

The UV–Visible absorption spectra of the precursor solution, plant extracts, and synthesized nanoparticles are shown in Figure 6. The SnO₂ nanoparticle samples exhibit enhanced absorption intensity and a noticeable red shift in the absorption edge compared to the precursor and extract-only solutions, confirming nanoparticle formation. The FSAE + SnCl₂ sample shows the highest absorbance intensity, indicating more efficient nanoparticle formation and stabilization in the ethanolic medium. Similar absorption behavior and red-shift trends have been reported for plant-mediated SnO₂ nanoparticles and are associated with surface phytochemical interactions and quantum confinement effects (Rauf *et al.*, 2025).

Optical Transmittance

The transmittance spectra (Figure 7) reveal that the FSAE + SnCl₂ sample exhibits higher transparency in the visible region compared to the FSAW + SnCl₂ sample. This enhanced transparency is attributed to improved dispersion, smaller particle size, and reduced agglomeration. High visible transparency combined with strong UV absorption makes the biosynthesized SnO₂ nanoparticles particularly attractive for optoelectronic and transparent conducting applications, consistent with recent reports (Mutukwa *et al.*, 2024).

Optical Band Gap Analysis

The optical band gaps of the synthesized SnO₂ nanoparticles were estimated using Tauc plots (Figure 8). The band gap values were determined to be approximately 3.30 eV for the FSAW + SnCl₂ sample and 3.05 eV for the FSAE + SnCl₂ sample. These values fall within the reported range for SnO₂ nanoparticles synthesized via green routes. The slightly reduced band gap observed for the ethanolic extract-mediated sample is attributed to improved crystallinity, enhanced surface passivation, and the presence of defect states such as oxygen vacancies. Comparable band gap narrowing effects have been reported in recent green synthesis studies of SnO₂ nanoparticles (Anita *et al.*, 2023; Rauf *et al.*, 2025).

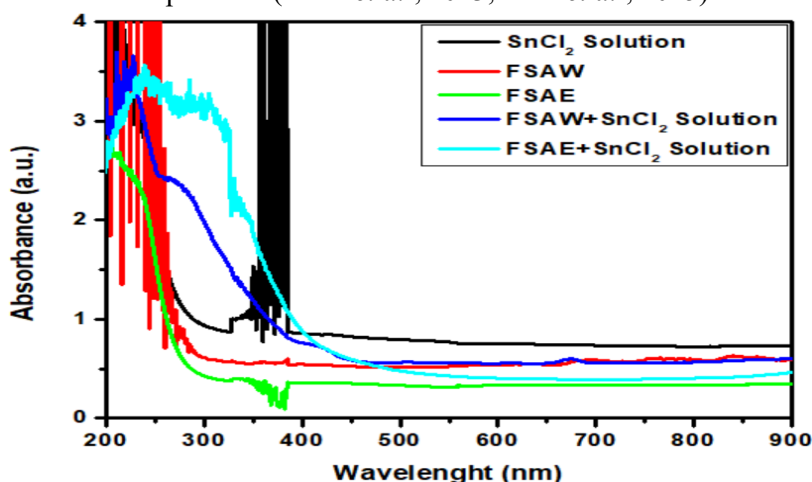


Figure 6: Absorbance-wavelength plots of synthesized SnO₂ nanoparticles extracted: SnCl₂, FSAW, DSAW, FSAW+SnCl₂ and DSAW+SnCl₂.

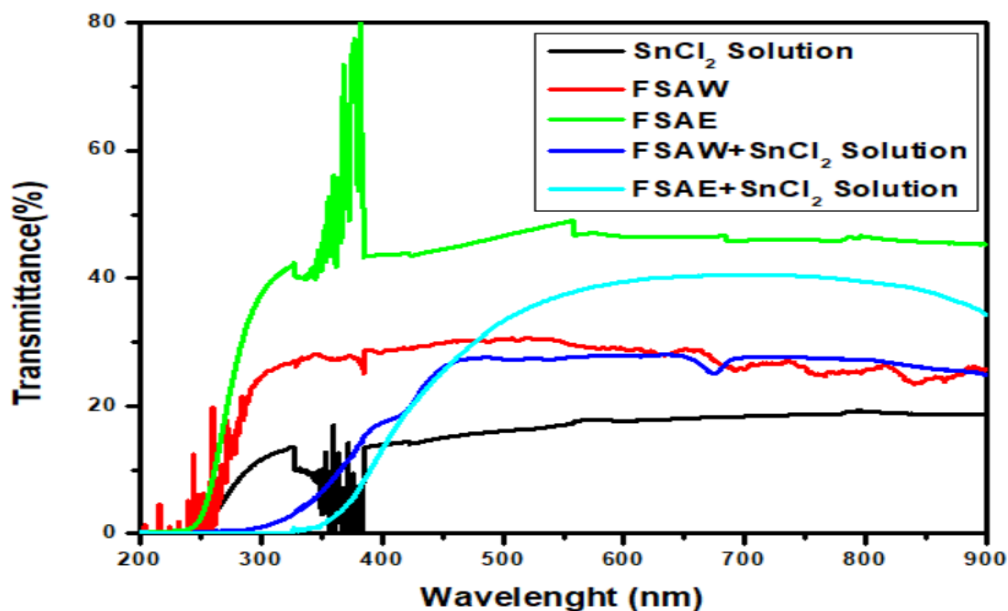


Figure 7: Transmittance-wavelength plots of synthesized SnO₂ nanoparticles: SnCl₂, FSAW, DSAW, FSAW+SnCl₂ and DSAW+SnCl₂

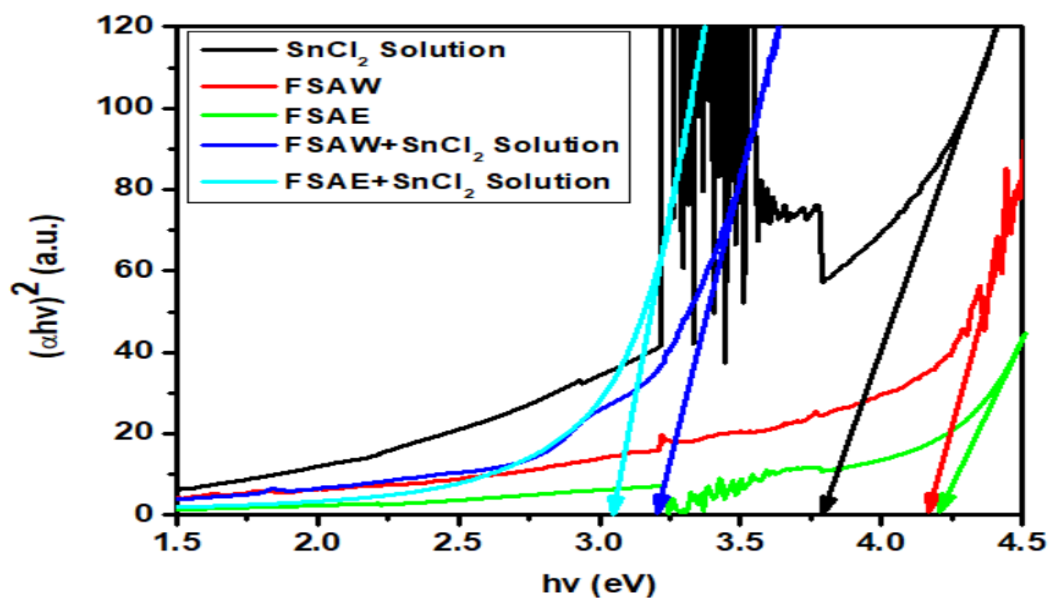


Figure 8: Absorption coefficient-energy gap plots of synthesized SnO₂ nanoparticles extracted: SnCl₂, FSAW, DSAW, FSAW+SnCl₂ and DSAW+SnCl₂.

Conclusion

This study confirms that the combined use of **fresh *Senna alata* leaf extract** and solvent selection plays a decisive role in controlling the synthesis and properties of SnO₂ nanoparticles. The use of fresh leaves ensured the availability of active phytochemicals in their

native, non-degraded state, thereby enhancing their effectiveness as green reducing, capping, and stabilizing agents during nanoparticle formation.

XRD analysis showed that fresh *Senna alata* extracts in both water and ethanol successfully produced phase-pure tetragonal rutile SnO₂ nanoparticles. However, the ethanolic fresh leaf extract yielded significantly larger crystallite sizes (9.06 nm) and improved crystallinity compared to the aqueous fresh leaf extract (3.70 nm). This indicates that ethanol selectively extracts less polar phytochemicals from fresh leaves, which favor slower nucleation and controlled crystal growth, whereas the aqueous fresh leaf extract promotes rapid nucleation due to the abundance of highly polar bioactive compounds.

FTIR results revealed distinct solvent-dependent interactions between fresh leaf phytochemicals and SnO₂ nanoparticle surfaces. The observed peak shifts and intensity reductions in the ethanolic extract-mediated sample indicate stronger coordination and surface passivation, confirming that phytochemicals from fresh leaves remain chemically active and responsive to solvent polarity.

Morphological analyses (SEM and TEM) further demonstrated that fresh leaf extracts play a crucial stabilizing role. The aqueous fresh leaf extract resulted in moderately agglomerated SnO₂ nanoparticles with an average particle size of 9.79 nm, while the ethanolic fresh leaf extract produced smaller, more uniformly dispersed nanoparticles with an average size of 8.73 nm. The improved dispersion observed in the ethanolic system highlights the synergistic effect of fresh phytochemicals and solvent environment in controlling nanoparticle growth.

Optical characterization confirmed solvent- and extract-dependent tuning of optical properties. SnO₂ nanoparticles synthesized using ethanolic fresh leaf extract exhibited enhanced UV absorption, higher optical transparency, and a reduced optical band gap (3.05 eV) compared to those synthesized using aqueous fresh leaf extract (3.30 eV). These variations are attributed to differences in particle size, crystallinity, and surface states induced by the fresh phytochemical composition.

In summary, the results demonstrate that **fresh *Senna alata* leaf extract is a highly effective green reagent for SnO₂ nanoparticle synthesis**, and that **ethanol is a more suitable extraction solvent than water** for maximizing the functional potential of these fresh phytochemicals. The synergistic influence of fresh leaf bioactivity and solvent polarity enables precise control over structural, morphological, and optical properties, making the synthesized SnO₂ nanoparticles promising candidates for optoelectronic, photocatalytic, gas sensing, and dye-sensitized solar cell applications.

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