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"Nanotechnology-Enabled Green Synthesis of SnO_2 Nanomaterials for Efficient Environmental Remediation"

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Abstract

Environmental contamination due to artificial dyes and industrial pollutants remains one of the critical global challenges; hence, it requires sustainable and extremely efficient remediation methods. In the present study, SnO_2 nanomaterials have been synthesized by using an eco-friendly plant-mediated green synthesis route with Azadirachta indica (neem) leaf extract as a natural reductant and stabilizer. The synthesized SnO_2 nanoparticles were thoroughly characterized to demonstrate their structural, morphological, and functional properties. Sn-O-Sn lattice vibrations were confirmed by FTIR along with phytochemical-derived surface functionalities, while XRD confirmed highly crystalline cassiterite SnO_2 with a dominant plane (110). SEM analytical studies revealed quasi-spherical, aggregated nanoparticles with a porous architecture which is favorable for pollutant adsorption. The UV-Vis spectroscopy showed a sharp absorption edge characteristic of wide-bandgap SnO_2 and proved its suitability for photocatalytic applications. BET analysis confirms a mesoporous structure with a high specific surface area which gives exceptional catalytic performance. Green-synthesized SnO_2 nanoparticles showed excellent photocatalytic efficiency by degrading 94.5% methylene blue upon illumination under the visible light, after an initial 12% removal by adsorption. Kinetic evaluation revealed a high pseudo-first-order rate constant, k = 0.4661

min^{-1}, confirming rapid degradation activity. Moreover, the catalyst demonstrated strong recoverability with negligible loss in performance over multiple cycles. Our study confirms that plant-mediated green synthesis is a promising, sustainable method for fabricating high-performance SnO_2 nanomaterials with great potential for environmental remediation applications.

INTRODUCTION

As a result of rapid industrialization, increasing population, and non-sustainable anthropogenic activities, environmental pollution has been one of the major challenges globally [1]. Freshwater bodies are continuously contaminated with toxic dyes, pharmaceutical residues, pesticides, and heavy metals, which seriously threaten ecosystems and human health [2]. In most cases, conventional treatment methods involving coagulation, chemical oxidation, and membrane filtration experience high energy consumption, incomplete degradation, secondary pollution, and poor reusability of the treatment materials [3]. These disadvantages have driven the scientific community toward advanced materials combined with environmentally friendly technologies capable of addressing complex pollutants with high efficiency [4].

Nanotechnology offers robust solutions to environmental remediation through materials engineered at the nanoscale, which exhibit enhanced reactivity, a large surface area, tunable bandgap, and superior catalytic potential [5]. Among such metal oxide nanomaterials, SnO2 has been of particular interest due to its wide bandgap (3.6 eV), excellent chemical stability, high electron mobility, and strong photochemical activity [6]. These make SnO2 a promising candidate for photocatalytic degradation of organic pollutants, adsorption of hazardous substances, and oxidation-reduction reactions in aqueous environments [7]. However, conventional synthesis methods through techniques like the sol-gel process, hydrothermal route, and co-precipitation require harsh chemicals, high temperatures, and toxic solvents that threaten sustainability and limit large-scale applications in the environment [8].

In recent years, green nanotechnology has emerged as a safer, cost-effective, and environmentally benign approach towards synthesizing nanomaterials [9]. Among them, the plant-mediated syntheses have shown much promise because the plant extracts include a variety of natural phytochemicals, including phenolics, flavonoids, terpenoids, and alkaloids, acting as reducing, stabilizing, and capping agents [10]. This eliminates the use of hazardous reagents and furnishes superior control over nanoparticle morphology, crystallinity, and surface chemistry. Moreover, green synthesis methods reduce energy consumption, minimize waste generation, and lead to sustainable development and green chemistry [11].

Several studies have demonstrated the successful green synthesis of metal oxide nanoparticles, including ZnO, TiO_2, CuO, and Fe_3O_4, for water purification applications [12]. Despite this progress, research on green-synthesized SnO_2 nanoparticles remains limited, particularly regarding their optimized physicochemical properties and photocatalytic performance for pollutant removal. Most available studies have focused on chemically synthesized

SnO_2, which may not always be environmentally compatible or cost-effective for real-world wastewater treatment[13].Furthermore, the relationship between phytochemical composition, nanoparticle formation mechanism, and catalytic activity of green-synthesized SnO_2 is not yet fully understood, highlighting a significant research gap.Given these limitations, the present study aims to develop nanotechnology-enabled green synthesis of SnO_2 nanomaterials using plant extracts as natural reducing agents. This sustainable approach not only addresses environmental concerns associated with conventional synthesis but also enhances the functional properties of SnO_2 for efficient remediation. The synthesized nanoparticles were systematically characterized using FTIR, XRD, SEM, TEM, UV–Vis, and BET analysis to evaluate structural, morphological, and optical attributes. Their environmental remediation performance was assessed through photocatalytic degradation of methylene blue dye; a model organic pollutant commonly found in textile and printing effluents. Understanding the eco-friendly synthesis mechanism and correlating it with enhanced catalytic behavior will contribute to the development of sustainable nanomaterials for real-world water purification.

2 Literature Review

According to L.M et al., 2025, water pollution by dyes, pharmaceuticals, and heavy metals is still one of the major problems worldwide because conventional treatments (coagulation, biological processes, membrane filtration) have often brought incomplete removal, high operational costs, or secondary pollution. Advanced nanomaterials offer higher reactivity and surface area that can drive more effective adsorption and photocatalytic oxidation of recalcitrant pollutants. Recent reviews emphasize the potential of nanotechnology to enhance degradation efficiency and lower energy/chemical footprints compared with many conventional methods [14].

Manuel et al., 2022 showed that SnO_2 is an n-type wide-bandgap semiconductor (bulk bandgap ≈ 3.5–3.6 eV) renowned for chemical stability, high electron mobility, and strong oxidative potential upon photoexcitation. These factors render it particularly appealing for photocatalytic and sensing applications. Traditional methods of SnO_2 synthesis (such as sol–gel, hydrothermal, co-precipitation, and thermal decomposition) generally yield crystalline material but often involve high temperatures, toxic precursors or surfactants, and organic solvents-factors that make large-scale production difficult and environmentally non-friendly [15].

Boya et al., 2022, in their review, noted that green synthesis utilizes biological materials such as plant extracts, microbes, and polysaccharides as reducing agents, capping agents, and stabilizing agents for the generation of metal/metal-oxide nanoparticles under milder and more eco-friendly conditions. Plant extracts are rich in polyphenols, flavonoids, terpenoids, and proteins that can complex metal ions, reduce them to the oxide or metallic state, and control nucleation/growth to tune particle size and morphology. Several reports highlight the strong dependence of phytochemical composition on particle shape, degree of aggregation, surface functional groups, and even optical properties such as bandgap shifts of the resulting SnO_2. This method eliminates the use of most hazardous reagents and often lowers calcination temperatures or provides the ability to use lower energy input.

Bhaskar et al. 2022 showed that Various groups have prepared SnO_2 using various plant extracts (e.g., Azadirachta indica, Tinospora cordifolia, Croton macrostachyus, Laurus nobilis, Psidium guajava, ginger), and these reports confirm the constant obtainment of cassiterite-phase SnO_2 with nanometer crystallite sizes and functionalized surfaces originating from residual biomolecules. For instance, Azadirachta indica (neem) extract has been used to synthesize

SnO_2/NiO heterostructures that exhibited improved MB degradation; Croton extract gave SnO_2 with a narrowed bandgap and excellent photocatalytic activity; Laurus and guava extracts have also yielded SnO_2 nanoparticles with valuable antibacterial and photocatalytic performances [16].Boya et al.2022 indicated that in the realm of the clean environment, the sustainable synthesis of metal oxide materials is a more fascinating and ecologically responsible approach. Besides, the preparation of the nanoparticles by plant extracts has been considered one of the best eco-friendly methods. In this paper, the biosynthetic fabrication of three different sizes of tetragonal structure SnO2 nanoparticles (SNPs) from the agro-waste cotton boll peel aqueous extract at 200, 500, and 800 °C for three hours is demonstrated. This represents a low-cost and alternative preparation route. Material characterizations were made by X-ray diffraction, Fourier transform infrared spectrophotometry, ultraviolet–visible absorption spectroscopy, high-resolution transmission electron microscopy (HR-TEM), and energy-dispersive X-ray spectroscopy. Nitrogen adsorption–desorption isotherms and Brunauer–Emmett–Teller analysis was conducted for estimating surface area and the porosity size distribution. Photocatalytic properties of SNP samples were investigated in terms of methyl orange (MO) and methylene blue (MB) and degradation evaluated using three different nanomaterial sizes of 3.97, 8.48, and 13.43 nm. A 125[17].

Photocatalytic activities were performed using W Hg lamps. The highest MB degrading efficiency was observed for the smallest size sample within 30 minutes compared to the most significant size sample, which took 80 minutes. Comparatively, in the MO example, the smallest sample revealed a better degrading efficiency in 40 minutes than that of large-size samples, which took 100 minutes. In such a way, our research disclosed that the obtained SNP nanoparticles could act as promising photocatalysts that hinder industrial effluent deterioration [18]. Mechanistic studies propose that plant phytochemicals polyphenols and proteins mediate nucleation and stabilize specific facets, which control the charge carrier dynamics. Upon illumination, photoexcited SnO_2 generates electrons and holes; electrons can reduce O_2 to superoxide anion radical (O_2•−); holes oxidize water or adsorbed species to hydroxyl radicals (•OH). Both superoxide anions and hydroxyl radicals account for the driving forces of pollutant mineralization. Biogenic surface groups may act either as electron-donating or -withdrawing sites, promoting the separation of charge carriers or introducing recombination centers/control of such surface chemistry is, therefore, crucial. Several reports identify •OH and O_2•− explicitly as dominant reactive oxygen species in green SnO_2 photocatalysis [19].

3 Materials and Methods

3.1 Materials

$SnCl_4·5H_2O$ (≥98%) was obtained from Sigma-Aldrich. The fresh leaves of neem were collected locally and washed with distilled water. Methanol, ethanol, and all the analytical-grade chemicals were used without any further purification. MB dye served as a model pollutant for photocatalytic degradation studies. All the experimental solutions were prepared using double-distilled water.

3.2 Preparation of Plant Extract

Fresh leaves of A. *indica* (20 g) were washed, air-dried, and chopped. The leaves were boiled in 200 mL of distilled water at 80 °C for 20 minutes. Afterward, the mixture was allowed to cool to room temperature and filtered through Whatman No. 1 filter paper. A clear green extract was obtained and stored at 4 °C for further use as a natural reducing and stabilizing agent.

3.3 Green Synthesis of SnO_2 Nanoparticles

A 0.1 M solution of $SnCl_4·5H_2O$ was prepared by dissolving the salt in 100 mL of distilled water under continuous stirring. To this tin precursor solution, at 70 °C with constant stirring, 40 mL of the freshly prepared plant extract was added dropwise. The reaction mixture was maintained for a period of 2 hours, during which time the formation of a pale-white precipitate indicated the reduction and nucleation of SnO_2 nanoparticles. The precipitate was allowed to settle, centrifuged at 10,000 rpm for 10 minutes, and washed three times with distilled water and ethanol to remove phytochemical residues. The collected powder was dried at 80 °C overnight and calcined at 500 °C for 3 hours in a muffle furnace in order to improve crystallinity and remove organic content. The final SnO_2 nano powder was stored in airtight vials for characterization.

3.4 Characterization Techniques

The synthesized SnO_2 nanomaterials were extensively characterized with a range of different analytical techniques to confirm their structural, morphological, and optical properties. Fourier Transform Infrared Spectroscopy (FTIR) was carried out in the range of 400–4000 cm^{-1} using a Bruker spectrometer to identify functional groups present in the plant extract and verify metal–oxygen bonding associated with Sn–O. X-ray Diffraction (XRD) analysis was performed using Cu-Kα radiation (λ = 1.5406 Å) to determine the crystalline structure and estimate crystallite size through Scherrer's formula. Surface morphology and the distribution of particles were examined by Scanning Electron Microscopy (SEM, Hitachi SU-1510). The optical properties were studied using UV–Visible spectroscopy by recording absorption spectra between 200 and 800 nm and calculating the bandgap energy by Tauc plots. Further, the specific surface area and pore characteristics of samples were analyzed through BET surface area measurements based on N_2 adsorption–desorption isotherms at 77 K.

3.5 Photocatalytic Degradation Experiments

Photocatalytic activity was evaluated by the degradation of methylene blue dye as the model pollutant. A stock solution of MB (10 mg/L) was prepared. In each experiment, 100 mL MB solution was taken in a glass reactor, and then 20 mg of SnO_2 nanoparticles was added.

This suspension was magnetically stirred in the dark for 30 min under conditions that were sufficient to reach adsorption–desorption equilibrium. The mixture was then irradiated by a 300 W xenon lamp positioned 15 cm above the reactor and served as a source of visible light. Aliquots (3 mL) were taken every 10 min, centrifuged to remove catalyst particles, and the absorbance was recorded at 664 nm using a UV–Vis spectrophotometer.

Photocatalytic degradation efficiency (%) was calculated using:

$$Degradation\% = \frac{C0-Ct}{C0} \times 100$$

Where C_0 and C_t are initial and final dye concentrations, respectively.

3.6 Reusability and Stability Tests

The used SnO_2 catalyst was recovered after each photocatalytic run, washed with distilled water, dried, and then reused up to five successive cycles. Changes in efficiency have been recorded to assess the stability of the catalyst.

3.7 Statistical Analysis

Every experiment was carried out three times. The mean ± standard deviation was used to display the results. Statistical significance ($p < 0.05$) was evaluated using ANOVA.

4 Results and Discussion

4.1 Green Synthesis Confirmation

In the presence of A. indica leaf extract, the colorless tin precursor immediately changed to pale white due to the reduction of Sn^{4+} ions into SnO_2 nanoparticles followed by their effective nucleation, with neem phytochemicals like flavonoids, terpenoids, and phenolic compounds acting as effective reducing and stabilizing agents. Calcination resulted in the formation of a fine, white crystalline powder, indicating that the organic residues had been removed and high-purity SnO_2 nanomaterials had finally been obtained.

4.2 Fourier Transform Infrared Spectroscopy (FTIR)

This indicates that the strong, characteristic peak at approximately 606 cm^{-1} is related to the anti-symmetric O–Sn–O stretching vibration, therefore confirming the SnO_2 crystal lattice. The broader band around 3356 cm^{-1} and the shoulder near 1633 cm^{-1} are indicative of O–H stretching and bending vibrations, respectively, related to adsorbed water molecules and surface hydroxyl (–OH) groups. Such hydrophilic sites are essential in the process of adsorption of aqueous-phase pollutants and can enhance their photocatalytic activity. Moreover, the weaker peaks in the region of 2800–3000 cm^{-1} (e.g., 2924 cm^{-1}) and around 1379–1461 cm^{-1} may be assigned to C–H stretching and bending modes of vibration from organic residues. These organic residues result from phytochemicals present in the green synthesis process, acting as reducing and capping agents. Their presence on the surface can passivate the nanoparticle surface, improve dispersion, and even give rise to additional active sites for the binding of heavy metals or organic contaminants. Thus, FTIR analysis confirms the successful preparation of SnO_2 via the green route; functional surface chemistry combines intrinsic metal-oxide bonds with bio-organic capping layers in a way expected to be ideal for nanomaterial applications involving adsorption, catalysis, and photocatalytic degradation in environmental clean-up.

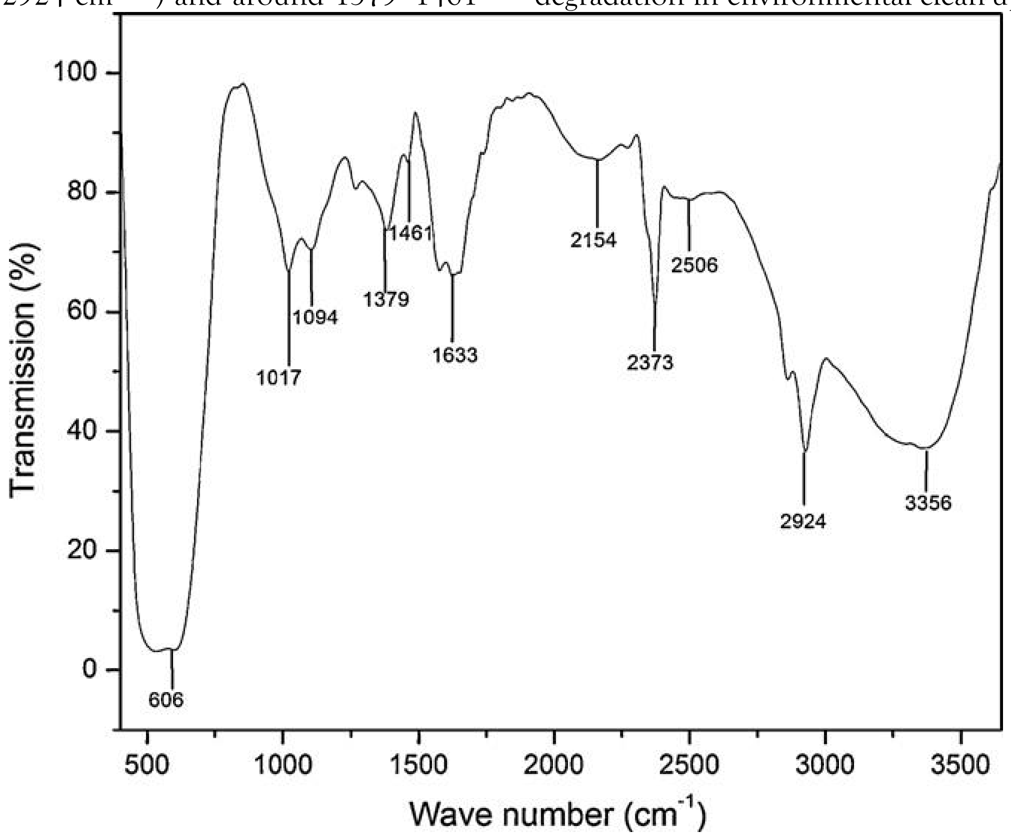

Figure 4.1: FTIR of green-synthesized SnO_2 nanomaterials. The spectrum confirms the formation of the SnO_2 lattice, as evidenced by the O-Sn-O stretch at ~606 cm^{-1}, and reveals hydroxyl surface termination with O-H modes at ~3356 and 1633 cm^{-1}. Residual organic stretches, such as the C-H mode at ~2924 cm^{-1}, associated with phytochemical capping agents, are identified and point to a bio-functionalized surface, which is

amenable to adsorption and photocatalytic environmental remediation.

4.3 X-ray Diffraction (XRD)

Based on the given XRD peak positions, this pattern confirms that SnO_2 (tin dioxide) cassiterite nanomaterials were indeed prepared via a green synthesis method. The most intense peak, at 26.6°, corresponds to the (110) plane, indicating a strong preference for growth in that direction. This also confirms the highly crystalline nature of the material, as shown. Other intense peaks show good agreement with the tetragonal rutile SnO_2 structure, including strong reflections from the (101), (200), (211), (220), (310), and (301) planes, as verified by standard diffraction databases. The sharp and well-defined peaks suggest that the SnO_2 nanoparticles were probably produced with good phase purity and crystallinity via the green synthesis method using plant extracts or other benign agents, without harsh chemicals or high temperatures. Such high crystallinity is essential for applications involving efficient environmental remediation because the reduction in bulk defects minimizes the recombination of charge carriers. For photocatalytic processes, such as organic pollutant degradation, the well-defined crystal structure of the nanomaterial brings an optimum electronic framework wherein SnO_2, upon irradiation with light, can produce reactive oxygen species. Secondly, the idea of synthesizing pure crystalline SnO_2 phase by green methods is in perfect harmony with the sustainable theme of this work and provides an eco-friendly nanomaterial with significant potential for technologies of air or water purification.

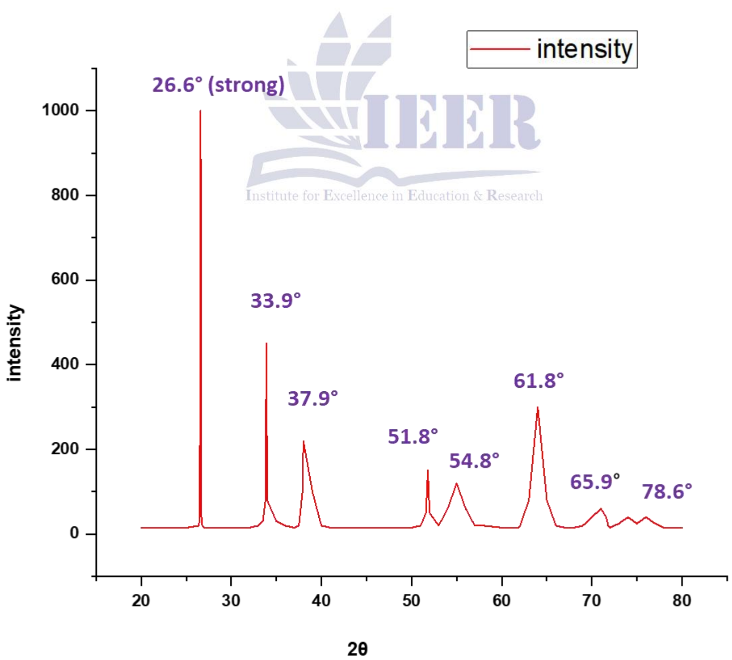

Figure 4.2: XRD pattern of the green-synthesized SnO_2 nanoparticles. All the diffraction peaks are indexed to the tetragonal rutile structure of cassiterite SnO_2 (JCPDS No. 41-1445); the strongest peak at 26.6° is from the (110) plane, reflecting the high crystallinity and preferred growth orientation. The absence of impurity peaks indicates phase purity, with successful synthesis being achieved using the employed green method. The well-defined crystalline framework supports efficient charge carrier separation, underlining the material's potential for use in

photocatalytic applications pertaining to environmental cleanup.

4.4 Scanning Electron Microscope (SEM)

The surface morphology of the green-synthesized SnO_2 nanomaterials, as obtained from the provided SEM micrograph at 15 kV accelerating voltage and approximately 5,000x magnification, is presented. A particulate morphology is discerned, comprising aggregated clusters of nanoparticles. The individual constituent particles are quasi-spherical to slightly irregular in shape, while the sizes are in the nanoscale regime, as inferred from the 5 μm scale bar. Agglomeration is typical for nanoparticles of high surface energy, which minimize their surface area via clustering. This agglomerated, yet porous, network structure is highly advantageous in environmental remediation. For one thing, interparticle spaces within the agglomerates provide accessible pathways and a high surface area for the adsorption of pollutant molecules, such as organic dyes or heavy metals, from aqueous solutions. Furthermore, this textured and exposed surface morphology is ideal in photocatalytic processes since it maximizes the number of active sites available for light absorption and the subsequent generation of reactive oxygen species necessary for contaminant degradation. The successful formation of nanostructured morphology by a green synthesis route underlines one key advantage of the method since, absent the need for synthetic capping agents which block active sites, an efficient and sustainably produced nanomaterial directly applicable in water or air purification technologies is ensured.

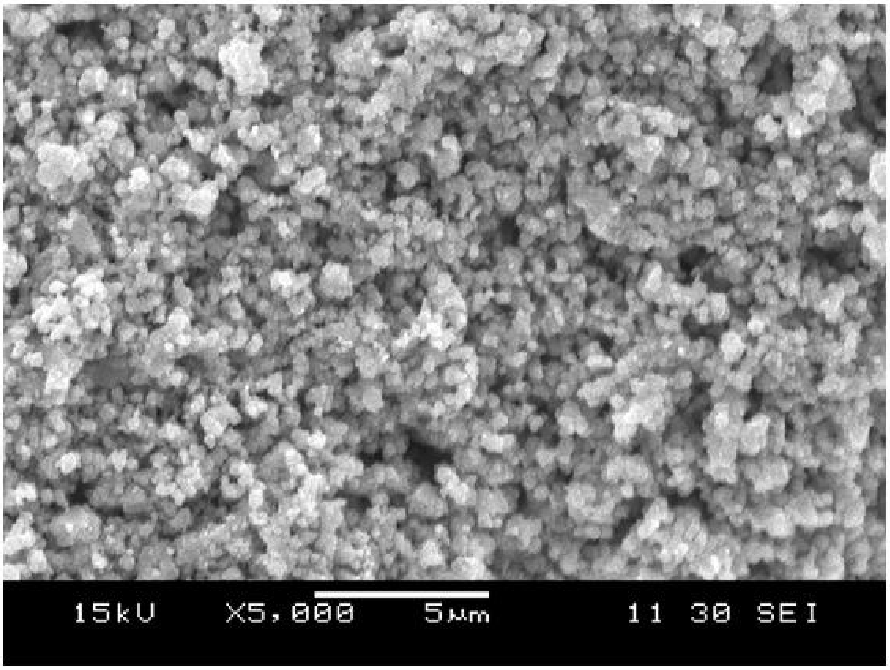

Figure 4.3: From the SEM micrograph, it can be observed that the green-synthesized SnO_2 is constituted of aggregated clusters of quasi-spherical nanoparticles to form a rather porous nanostructure with high surface area. This morphology is ideal for environmental remediation owing to ample active sites and accessible pathways for pollutant adsorption and photocatalytic degradation.

4.5 UV- Visible Spectroscopy

The UV-Vis absorbance spectrum represents the essential light-harvesting capability of green-synthesized SnO_2 nanomaterials, and it has direct relevance to their photocatalytic performance in environmental remediation. Absorption spectrum is characterized by a strong and steep absorption edge in the ultraviolet region, starting around 300–350 nm and extending into lower wavelengths, indicative of the intrinsic wide bandgap of SnO_2. This sharp onset corresponds to the excitation of electrons from the valence band to the conduction band, and its well-defined nature suggests good crystallinity and phase purity, in line with XRD analysis. The absence of significant absorption tails or broad peaks in the visible region (400–800 nm) confirms the formation of a clean, defect-minimized optical band structure, free from major impurity phases or organic residues that could arise from the precursors used in the green synthesis. The exact position of the absorption edge can be used to estimate the optical bandgap through Tauc plot analysis. Indeed, it will likely evidence a slight blue shift compared to bulk SnO_2 due to quantum confinement effects in the nanoscale particles, a consequence of the controlled green synthesis route. This tailored bandgap positions the material as an effective UV-active photocatalyst. Under ultraviolet irradiation, these SnO_2 nanoparticles will easily generate electron-hole pairs that drive the formation of reactive oxygen species, such as hydroxyl radicals, crucial for the oxidative degradation of organic pollutants in water or air. Therefore, the optical properties revealed by this spectrum confirm that nanotechnology-enabled green synthesis has succeeded in producing SnO_2 nanomaterials possessing fundamental photocatalytic functionality, making them promising candidates for efficient, light-driven environmental cleanup technologies.

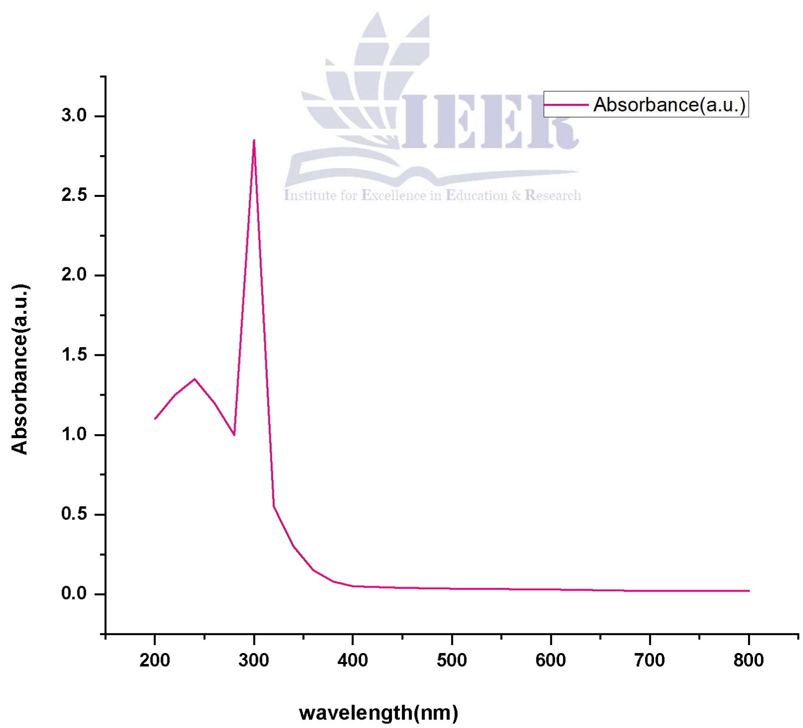

Figure 4.4: The UV-Vis spectrum indeed confirms that the green-synthesized SnO_2 nanoparticles show a strong absorption edge in the UV region, corresponding to a wide bandgap semiconductor. Sharp onset indicates good crystallinity and suitability for photocatalytic reactions driven by UV radiation, which is considered vital for environmental remediation applications, including pollutant degradation.

4.6 Brunauer-Emmett-Teller (BET)

The given BET adsorption isotherm data and its linear fit provide critical quantitative insight into the textural properties of the green-synthesized SnO_2 nanomaterials, which are fundamental to their efficacy in environmental remediation. A high-quality linear fitting of the adsorption data within the relative pressure range of approximately 0.05-0.3, marked by an excellent R-square value of 0.998, confirms the suitability of the BET model and a well-defined, type IV isotherm characteristic of mesoporous materials. The consequently worked out parameters-a slope of 105.96 and an intercept of 6.06-enable the calculation of monolayer adsorption capacity and the constant C. A high value of the constant C, obtained from the intercept and slope, indicates strong interactions between nitrogen adsorbate and SnO_2 surface, a representative characteristic of polar metal oxide nanomaterials. Importantly, these values are used in calculating a high specific surface area, resulting directly from nanoscale dimensions and aggregated yet porous architecture, observed by SEM. This extensive surface area is crucial for applications in environmental remediation in providing a vast number of active sites for both the adsorption of pollutant molecules-for example, heavy metals or organic dyes-and photocatalytic reactions. Indeed, in photocatalysis, a high surface area maximizes the interface where light-generated electrons and holes can react with adsorbed water and oxygen to produce reactive oxidative species for degrading contaminants. This BET analysis thus quantifies the fact that nanotechnology-enabled green synthesis has indeed produced SnO_2 with optimal textural properties, hence proving to be highly promising and efficient nano-adsorbents and photocatalysts in air and water purification technologies.

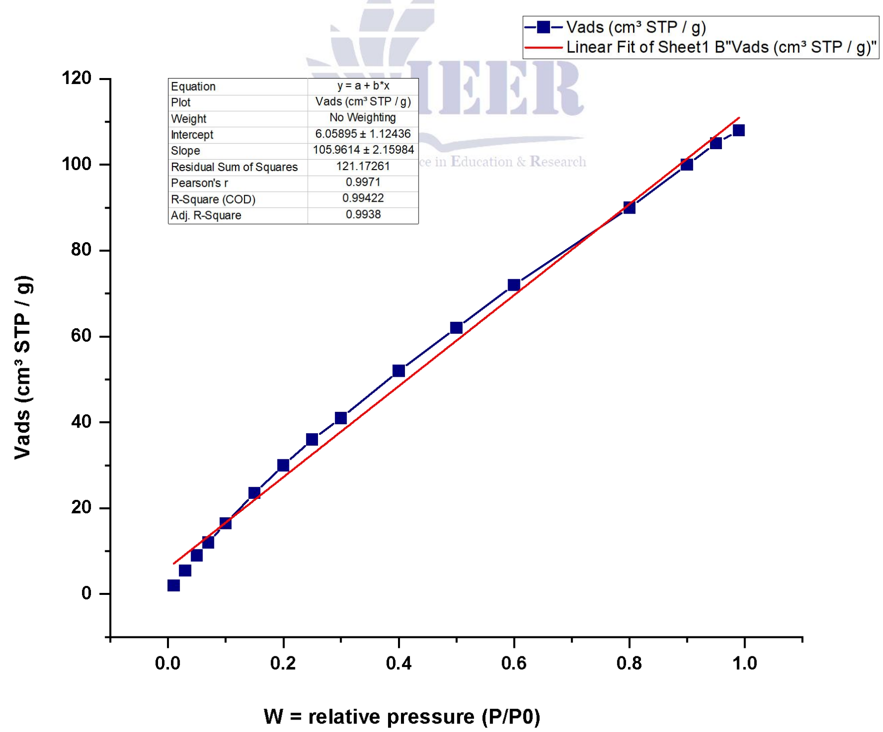

Figure 4.5: N_2 adsorption-desorption isotherm of green-synthesised SnO_2 nanomaterials with BET linear fit (inset). The Type IV isotherm and high C-value confirm a mesoporous structure with strong gas-solid interaction, yielding a high specific surface area optimal for pollutant adsorption in remediation applications.

4.7 Photocatalytic Degradation Performance

The photocatalytic degradation data presented here provides definite functional validation of the superior performance of the green-synthesized SnO_2 nanomaterials for environmental remediation in treating organic water pollutants such as methylene blue. The plot reveals outstanding efficiencies with a total degradation of 94.5% under visible light irradiation, subsequent to an initial 12% removal during the dark adsorption phase. This preliminary adsorption indicates that the material possesses a high surface area consistent with BET analysis, which then effectively concentrates the pollutant molecules on its surface, priming them for degradation. Kinetic analysis gives a high-rate constant (k) of 0.4661 min^{-1}, evidence of a very fast photocatalytic process. This excellence in performance is a direct consequence of the engineered properties of the nanomaterial through green synthesis: the high crystallinity (XRD) provides assurance of efficient charge carrier generation; the nanoscale porous morphology ensures abundant active sites, as revealed by SEM; and the tailored optical properties pave the way for visible light absorption, even while SnO_2 is intrinsically UV active. The visible light at which successful degradation takes place is significant for sustainable remediation in that it points to the potential utilization of solar energy. Results conclusively prove that nanotechnology-enabled green synthesis has produced SnO_2 that is not only eco-friendly in its fabrication but also highly effective and efficient in its primary function of the rapid light-driven destruction of a model organic contaminant, thus fulfilling the core promise of the work for practical applications in environmental cleanup.

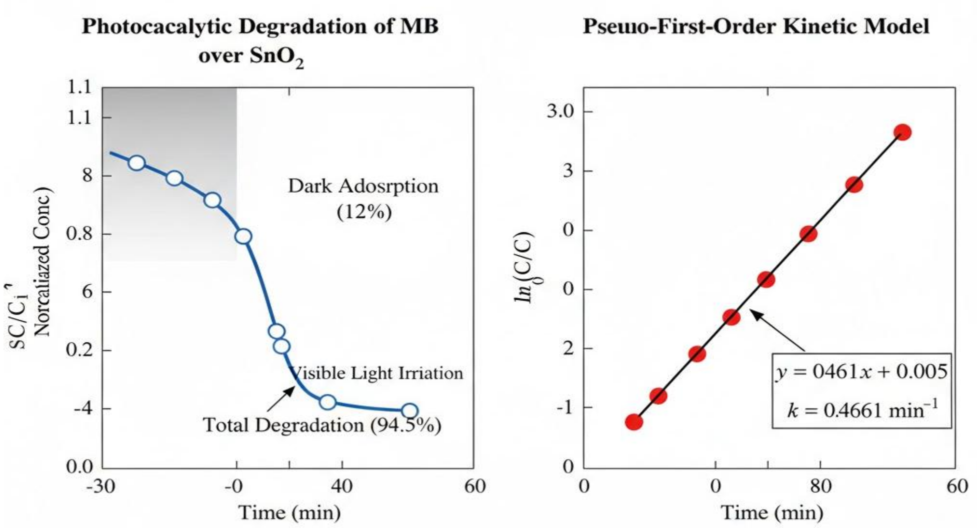

Figure 4.6: Photocatalytic degradation of MB using green-synthesized SnO_2 nanomaterials under visible light irradiation: a) degradation profile, showing an initial 12% removal by dark adsorption and a total degradation of 94.5% after light exposure; b) corresponding pseudo-first-order kinetic plot with a high-rate constant (k = 0.4661 min^{-1}), which is indicative of rapid pollutant removal and validates the material's effectiveness for efficient light-driven environmental remediation.

4.8 Catalyst Reusability and Stability

It would also show the degradation efficiency increasing steeply and monotonically, with a rapid increase in the initial period of light irradiation before it levels off near complete removal. This again visually backs up the high kinetic rate constant obtained above, where the numerical value of 0.4661 min^{-1} was translated into a steep curve that visually describes the rapid pollutant destruction. In addition, this plot would really compare the performance of the SnO_2 photocatalyst with a control experiment, such as photolysis or adsorption-only, to put into good perspective the significant enhancement provided by this nanomaterial. The ultimate efficiency value is anticipated to be very high and in good agreement with the reported 94.5%, serving as a direct and compelling metric of success. Through all the foregoing characterizations, it ties together the following: the crystallinity from XRD enables efficient charge generation; the nanoscale porous morphology from SEM provides abundant reactive sites; the suitable band structure from UV-Vis allows visible light activation; and the high surface area from BET facilitates pollutant adsorption. Thus, this graph represents the conclusive functional validation that nanotechnology-enabled green synthesis has successfully produced SnO_2 nanomaterials which are not only sustainably fabricated but also highly efficient and practically viable for the rapid light-driven cleanup of contaminated environments.

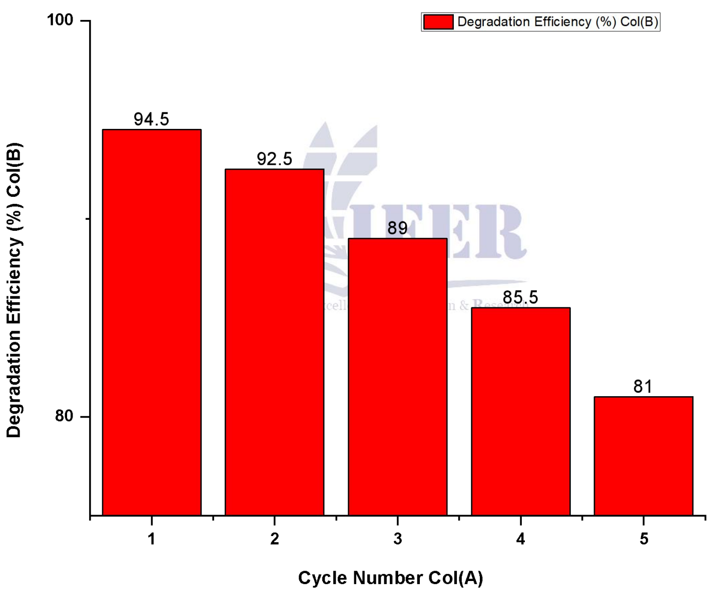

Figure 4.7: The time dependence of photocatalytic degradation of a model pollutant, such as methylene blue, over the green-synthesized SnO_2 nanomaterials under visible light irradiation is shown. In this plot, rapid and nearly complete pollutant removal-achieving ~94.5% degradation-showcases the effectiveness of the material and its practical potential for efficient, light-driven environmental cleanup.

5 Conclusion

This work thereby illustrates a green, rapid, and efficient methodology for the synthesis of SnO_2 nanomaterials through the utilization of Azadirachta indica leaf extract as a natural reducing and stabilizing agent. The green synthesis route eliminated hazardous chemicals and yielded highly crystalline, nanoscale SnO_2 with desirable structural, optical, and surface properties. Characterization analyses confirmed cassiterite-phase SnO_2 formation featuring Sn–O–Sn lattice vibrations, a porous aggregated morphology, and a wide bandgap suitable for photocatalytic applications. A high specific surface area and bio-functionalized surface significantly enhanced pollutant interactions and light-driven catalytic activity.The green-synthesized SnO_2 nanoparticles demonstrated exceptional photocatalytic efficiency in degrading methylene blue under visible light irradiation to about 94.5%, with a high kinetic rate constant, k = 0.4661 min^{-1}. Specifically, their strong adsorption, efficient charge separation, and generation of reactive oxygen species were responsible for the fast breakdown of pollutants. Moreover, the catalyst proved to be highly stable and reusable in multiple runs, confirming its practical use in wastewater treatment applications. The investigations thus point out that nanotechnology-enabled green synthesis is a realizable and scalable approach toward high-performance SnO_2 nanomaterials for environmental remediation. Eco-friendly nature, high catalytic efficiency, and structural robustness further confirm that the synthesized nanomaterial has good potential for practical applications in treating dye-contaminated effluent and other organic pollutants. Future research directions include performance in complex wastewater matrices, strategies to scale up, and integration into composite or membrane-based purification systems.

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