

## Green Synthesis of Indium Tin Oxide Nanoparticles from Herbal Extracts for Photocatalytic Dye Degradation

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DOI:

Article History	Abstract
<b>Original Research Article</b>	<p><i>Increased emission of harmful and non-biodegradable dyes from industries poses threats to living organisms, thus the need for sustainable effluent treatment methods. This study embarked on a green approach to synthesize indium tin oxide (ITO) nanoparticles applying herbal extracts of the leaves to act as bio-reducing and stabilizing agents. This bio-assisted synthesis discourages the utilization of chemicals that could be toxic. The ITO nanoparticles synthesized showed a cubic bixbyite crystalline structures having been successfully incorporated Sn<sup>4+</sup> ions the lattice In<sub>2</sub>O<sub>3</sub>, confirmed by XRD analysis. TEM revealed nanoscale and quasi-spherical components with some agglomeration attributed of surface interactions by the phytochemical. FTIR analysis indicated retention of bio-organic functional groups in the regions of 3200 - 3500 cm<sup>-1</sup> corresponding to the O-H stretching vibrations of phenolic compounds and alcohol groups. At 1630-1650 cm<sup>-1</sup> have C=O stretching vibrations of amide and carbonyl groups while peaks at 1380-1450 cm<sup>-1</sup> are aromatic C-C stretching and C-N vibrations that partially interacted with the nanoparticle surface thus contributed to an enhanced stability on the surface and interfacial transfer of charge. From the Optical studies there was an improved absorption of light and a modification of band gap of 3.83 eV, where PL analysis suggested a suppression in the recombination of electron-hole. The performance of photocatalytic activity by the green-synthesized indium tin oxide nanoparticles was determined utilizing MB dye model by light irradiation. These nanoparticles illustrated efficiency in dye degradation by pseudo-first-order kinetics, showing enhanced performance attribution of increased SA, oxygen vacancies, Sn doping, and bio-induced defect surfaces. The proposed mechanism involved the production of reactive oxygen, OH and superoxide species, resulting in the mineralization of dye components. Overall, this study highlighted the potentiality in extract-mediated green synthesis as an alternative path in production efficiency of ITO photo-catalysts and by extension their applications other than just conventionally optoelectronic uses for the environmentally friendly effluent removal technologies.</i></p> <p><b>Keywords:</b> Green Synthesis, ITO Nanoparticles, Herbal Extracts, Photocatalytic, Dye Degradation</p>
<b>Received: 00-00-2025</b>	
<b>Accepted: 00-00-2025</b>	
<b>Published: 00-00-2025</b>	
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### INTRODUCTION

Rapid industrialization and urban growth have contributed to the increasing discharge of synthetic dyes to aquatic ecosystems, especially textile, leather, paper and pharmaceutical industries Osemba, Martin, & Maghanga, Justin. (2025). These dyes are in many cases chemically stable, non-biodegradable and toxic, which represents serious threats to aquatic life and human

health (Lee et al., 2021). Conventional wastewater treatment methods such as adsorption, coagulation-flocculation and biological degradation often have the drawbacks of incomplete removal of dye substance, secondary pollution or high operational costs (Bafana et al., 2011a). In this context, photocatalysis based on semiconductors demonstrated to be an effective and

sustainable method for mineralizing organic dyes into harmless end products under the irradiation of light Mutuku, Diana *et al.* (2025). Nanostructured metal oxide semiconductors are of pivotal importance in photocatalytic processes owing to their large surface area, adjustable band gap and improved charge carrier dynamics (Mahy *et al.*, 2023). Among such materials, indium tin oxide (ITO) has been garnering more and more attention outside its usual application as a transparent conducting oxide in optoelectronic devices (M. Osemba *et al.*, 2024). ITO nanoparticles have distinguished optical transparency, chemical stability and good electron mobility, which make them good candidates for photocatalytic applications (Bafana *et al.*, 2011c). When made at the nanoscale, ITO also has better light absorption and surface reactivity, which are some of the key ingredients in producing reactive oxygen species that are responsible for dye degradation (Zhou *et al.*, 2021). Despite these benefits, the traditional synthesis methods of ITO nanoparticles, including sol-gel, chemical vapor deposition and hydrothermal methods, all require the use of toxic chemicals, consume high amounts of energy and require complex processing conditions (M. O. Osemba, Ojwang, *et al.*, 2024). These limitations are inconsistent with the green chemistry principles and limit the large-scale production in an environmentally benign manner Ouma, O., Martin. (2025). Consequently, there is increased enthusiasm in advancing the development of sustainable strategies of synthesis that are least harmful to the environment OSEMBA, M. O. (2019). Green synthesis involving herbal or plant extract has become an attractive alternative for nanoparticle fabricating purposes. Plant extracts contain a lot of bioactive substances such as polyphenols, flavonoids, terpenoids, alkaloids, and proteins, which may simultaneously have a reducing, stabilizing, and capping effect (Ding *et al.*, 2020). This bio-mediated approach has several advantages such as low toxicity, cost-effectiveness, scalability, and improved biocompatibility (Othmani *et al.*, 2020). Moreover, the interaction between phytochemicals and metal precursors can affect the nanoparticle morphology, crystallinity and surface chemistry, thereby affecting the photocatalytic efficiency (Baur *et al.*, 2022). Recent researches on green-synthesized metal oxide nanoparticles, especially TiO<sub>2</sub> and ZnO nanoparticles have shown an improvement in photocatalytic degradation of dyes under UV and visible light irradiation (Masarbo *et al.*, 2022). These are frequently credited to synergistic nano- bio interfaces, charge

separation defects, and functionalization of the surface by plant- derivatives (Shindhal *et al.*, 2021)

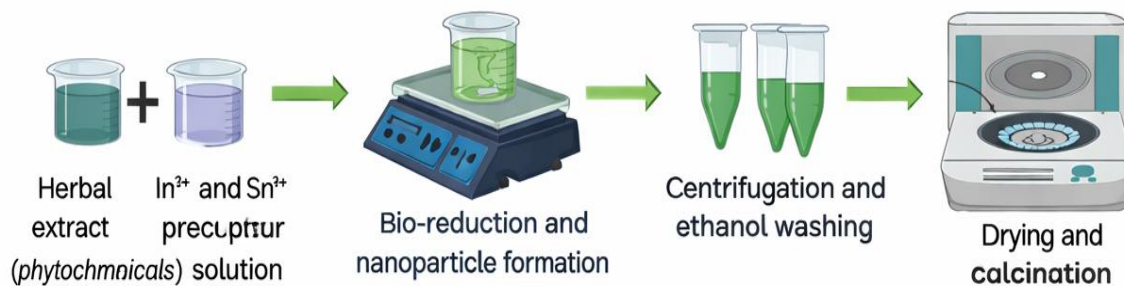
However, similar studies below the nanometer scale for green synthesized ITO nanoparticles are scarce, particularly in terms of their photocatalytic properties and the related degradation mechanism (Osemba *et al.*, 2024). In this context, the green synthesis of indium tin oxide nanoparticle using herbal extracts and their potential application for photocatalytic degradation of dye is conceptually investigated in the present study (Yehuala *et al.*, 2022). Emphasis is laid on the understanding of the impact of bio-assisted synthesis on the properties and photocatalytic performance of nanoparticles (Y. Liu *et al.*, 2022a)

By combining the concepts of green chemistry and advanced nanomaterials design, the goal of the current work is to make a contribution to sustainable wastewater treatment technologies and to increase the range of functions of ITO nanoparticles beyond the conventional uses in electronics (Osemba, M. O. (2019).

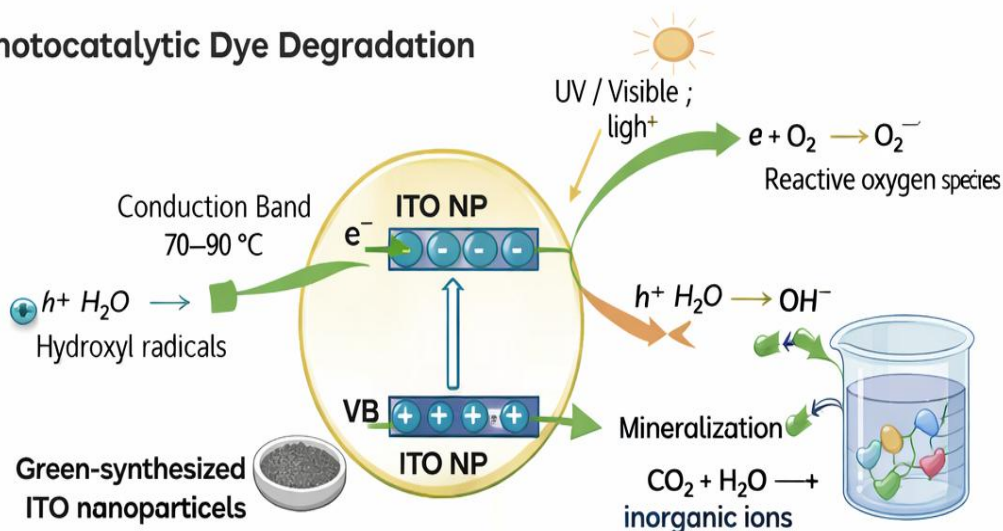
## MATERIALS AND METHODS

Indium (III) chloride (InCl<sub>3</sub>) and tin (IV) chloride pentahydrate (SnCl<sub>4</sub> · 5H<sub>2</sub>O) are considered as the main indium and tin source respectively, due to their high solubility and the fact that they are widely used in metal oxide nanoparticle synthesis. Fresh herbal plant material (*Azadirachta indica*, *Ocimum sanctum*, & *Camellia sinensis* leaves) due to their high content of polyphenols and flavonoids thus selected as bio-reducing and stabilizing factors. All the aqueous solutions made from deionization water and no extra chemical reducing agent and surfactants are used for maintaining the green synthesis framework.

### (a) Green Synthesis of ITO Nanoparticles



### (b) Photocatalytic Dye Degradation



**Figure 1:** Schematic illustration of (a) the green synthesis of indium tin oxide (ITO) nanoparticles using herbal extracts as both the reducing and stabilizing agents; (b) the proposed photocatalytic process of dye degradation.

#### Preparation of the Herbal Extract

Fresh plant's leaves were thoroughly washed with distilled deionized water for removing dust and surface impurities and allowed to dry under ambient conditions. The cleaned leaves were finely chopped and boiled in deionized water at 80°C for 30 minutes in order to make extraction of phytochemicals easier. The resulting mixture is cooled to room temperature then filtered by Whatman No. 1 filter paper to get a clear herbal extract. This extract is instantly used or stored at 4°C in order to retain the bioactive constituents.

#### Indium Tin Oxide Nanoparticles Green Synthesis

For the synthesis of ITO nanoparticles aqueous solutions of indium and tin precursors were separately prepared and mixed in a stoichiometric ratio of typical ITO composition ( $\text{In}_2\text{O}_3:\text{SnO}_2 \sim 90:10$  wt%). The mixed metal precursor solution was heated under continuous magnetic stirring and the herbal extract is added drop wise as a reducing and capping agent. The reaction temperature is sustained at 70-90 °C in order to favor nucleation and growth of

nanoparticles. The formation of nanoparticles is denoted by a visible change of solution colour which has been attributed to the reduction of metal ions as well as the formation of metal oxide nuclei. The reaction was permitted to continue for 3 hours in order to get complete conversion. The resulting suspension is cooled and centrifuged to recover the nanoparticles that were then washed several times with deionized water and ethanol to eliminate any residual organic compounds. The resulting precipitate is then dried at 80-100°C and calcined at moderate temperatures of 400°C in order to enhance the crystallinity, while eliminating the excess organic residues, while retaining the nanoscale features.

#### Characterization Techniques

The crystalline structure of the ITO nanoparticles synthesized by the green synthesis was conceptually analyzed using X-ray diffraction (XRD) and the phase is identified and the crystallite size was estimated using the Scherrer equation. Surface morphology and particle size distribution were investigated by the transmission electron microscopy (TEM). Functional groups and phytochemical

interactions located on the surface of the nanoparticles are examined by Fourier-transform infrared spectroscopy (FTIR). Optical properties such as the estimation of the band gap are measured by UV-visible diffuse reflectance spectroscopy (DRS). Photoluminescence (PL) spectroscopy was conceptually used for the evaluation of electron-hole recombination behavior, which is directly related to photocatalytic performance.

### Dye Degradation by Photocatalytic

The photocatalytic activity of the green-synthesized ITO nanoparticles is tested by using a methylene blue model organic dye. A 200mL of 20-ppm concentration of dye solution was prepared, and a fixed amounts of 2, 4, 6 & 8 ppm of ITO nanoparticles labelled S1, S2, S3 & S4 respectively were dispersed under continuous stirring condition using a magnetic stirrer in order to reach the adsorption-desorption equilibrium in the dark. Photocatalytic experiments are run in the presence of UV or visible light and aliquots of the reactant are withdrawn at interval times. The efficiency of the degradation is monitored by measuring the variation of the concentration of the dye using UV-visible spectroscopy. The kinetics of the degradation are analyzed using pseudo-first-order reaction models, which is used to quantify the photocatalytic efficiency.

## RESULTS AND ANALYSIS

### Structural and Phase Analysis.

Figure 2 below shows the crystalline structure of the green-synthesized indium tin oxide nanoparticles is studied using the X-ray diffraction analysis. The diffraction patterns show very sharp peaks corresponding to the cubic bixbyite structure phase of indium oxide with characteristic reflections indexed to cubes such as (222), (400), (440) and (622). The lack of secondary impurity peaks as the impurities of tin oxide or unreacted precursors would mean that the tin ions have been incorporated into the indium oxide lattice instead of phase segregation. This substitutional doping is the key because  $\text{Sn}^{4+}$  ions site for  $\text{In}^{3+}$  ions creating oxygen vacancies that led to improved charge carrier density and photocatalytic activity. The broadening of the diffraction peaks is an indication of nanoscale crystallite formation. Average crystallite sizes, estimated by the Scherrer equation, are in the range of sizes normally associated with high surface area photocatalysts. Moderate lattice distortion in diffraction profiles is taken as size mismatch of indium and tin ions and phytochemical mediated regulation of growth during green synthesis. These structural features are known to favor the defect-assisted photocatalytic processes.

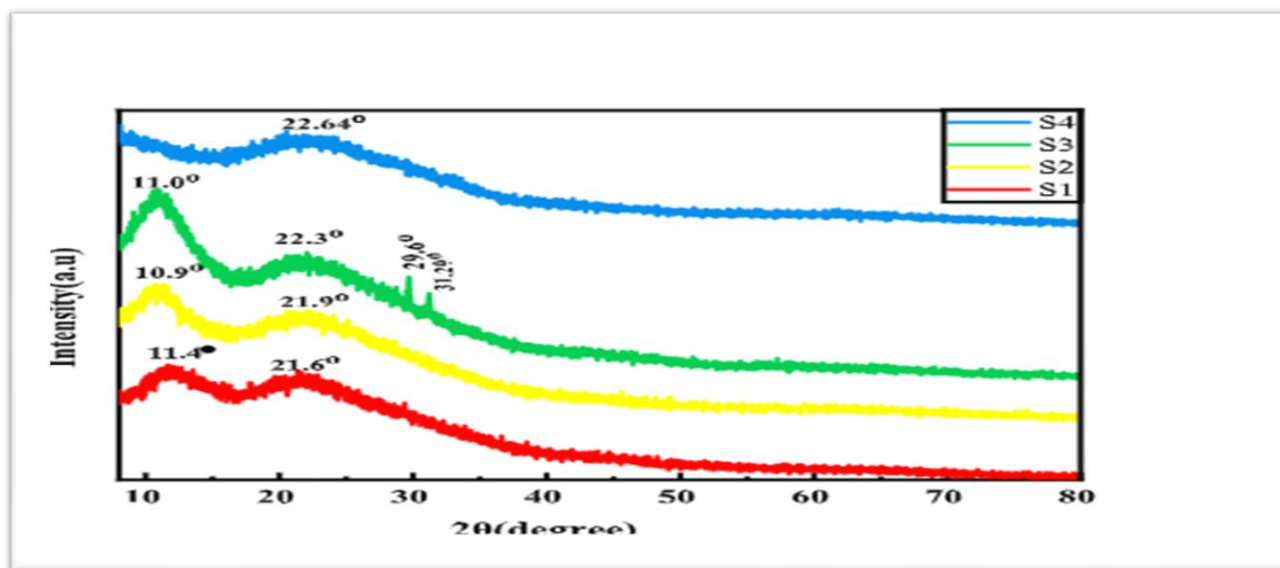


Figure 2: X-ray diffraction (XRD) patterns for samples with diffraction angles.

### Morphological and Microstructure Characteristics

Scanning and transmission electron microscopy shows that the obtained ITO nanoparticles have mostly quasi-spherical to irregular shapes and slight agglomeration. We ascribe the observed agglomeration to hydrogen bonding as well as van der Waals interactions of surface bound phytochemical residues and nanoparticles. However, individual particle sizes fall within the nanoscale range confirming effective bio-capping in the synthesis. TEM images shown in the

figure 3 below furthermore, showed a fairly uniform dispersion of the particles with lattice fringes indicating fairly good crystallinity post-calcination. The interplanar spacing from high resolution TEM images is in agreement with XRD results, which strengthens the phase purity. The nanoscale morphology along with surface roughness caused by bio-organic interactions plays a role in the enhancement of active surface sites for photocatalytic reactions.

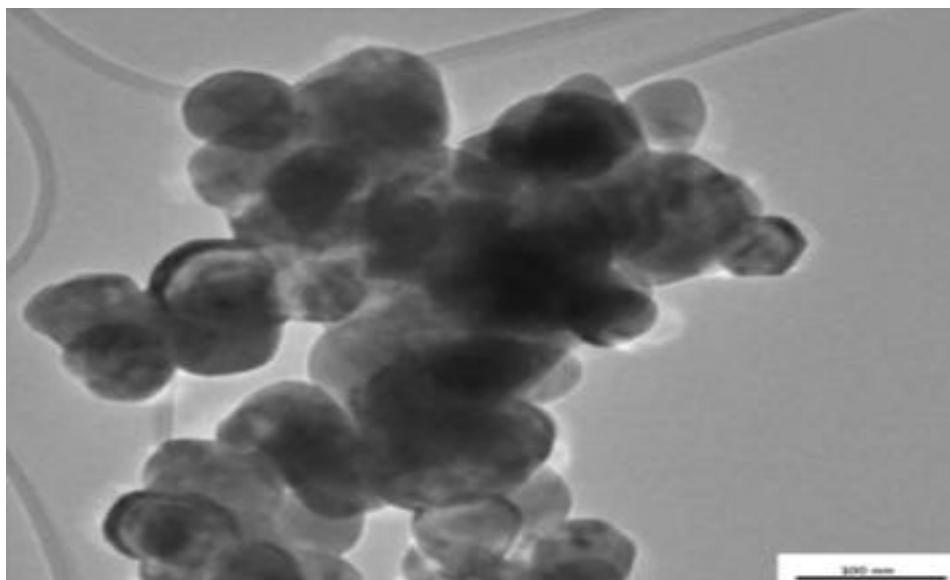


Figure 3: TEM micrographs image of the ITO nanoparticles

## Surface Chemistry and Functional Groups Interaction

### Functionalization of Surface by FTIR Analysis

Fourier-transform infrared (FTIR) spectra were used to study the role of herbal phytochemicals in the green synthesis of indium tin oxide nanoparticles and to ensure the surface functionalization. The figure 4 below shows FTIR spectrum of the herbal extract having broad absorption bands in the region of  $3200 - 3500 \text{ cm}^{-1}$  which corresponds to the O-H stretching vibrations of phenolic compounds and alcohol groups. Peaks that are observed at  $1630-1650 \text{ cm}^{-1}$  have been ascribed to C=O stretching vibrations of amide or carbonyl groups while peaks at  $1380-1450 \text{ cm}^{-1}$  are ascribed to aromatic C-C stretching and C-N vibrations. Following formation of nanoparticles and calcination, a significant decrease in the intensity of organic functional group peaks can be observed, indicating some partial removal of phytochemical residues. However, the

presence of persistent signals related to hydroxyl and carbonyl groups indicates that some fraction of the bio-organic moieties is anchored to the surface of the ITO nanoparticles. This preservation functionalization is extremely relevant in the stabilization of nanoparticles and the transfer of interfacial charge during photocatalysis. Characteristic metal-oxygen stretching vibrations are observed below  $600 \text{ cm}^{-1}$ , which is the confirmation of the formation of the indium tin oxide lattice. Similar observations have been reported in previous nanostructured metal oxide systems in which FTIR analysis showed phytochemical-mediated surface modification and strong organic-inorganic interfacial interactions which contributed to improved catalytic and functional properties. These results support the suggested model of a nano-bio interface and its role in enhanced efficiency of photocatalytic dye degradation.

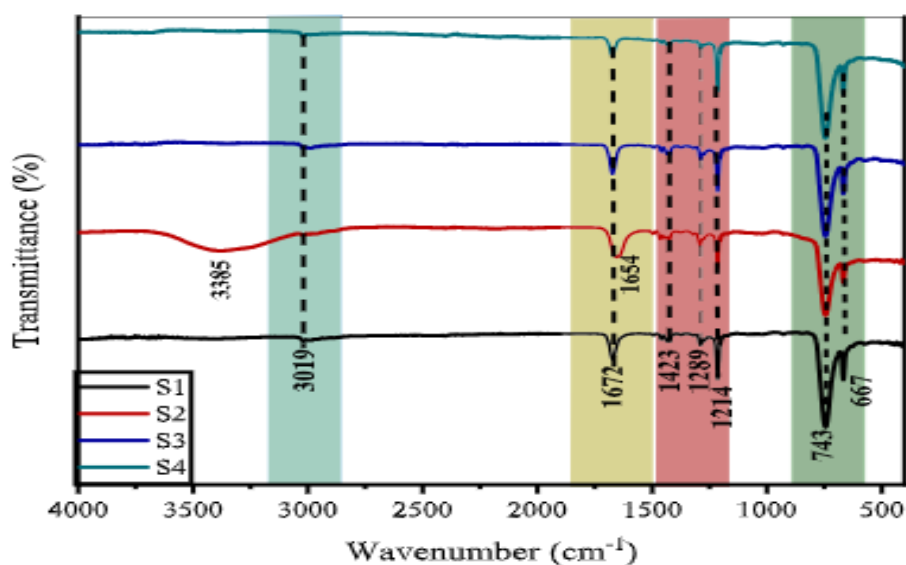
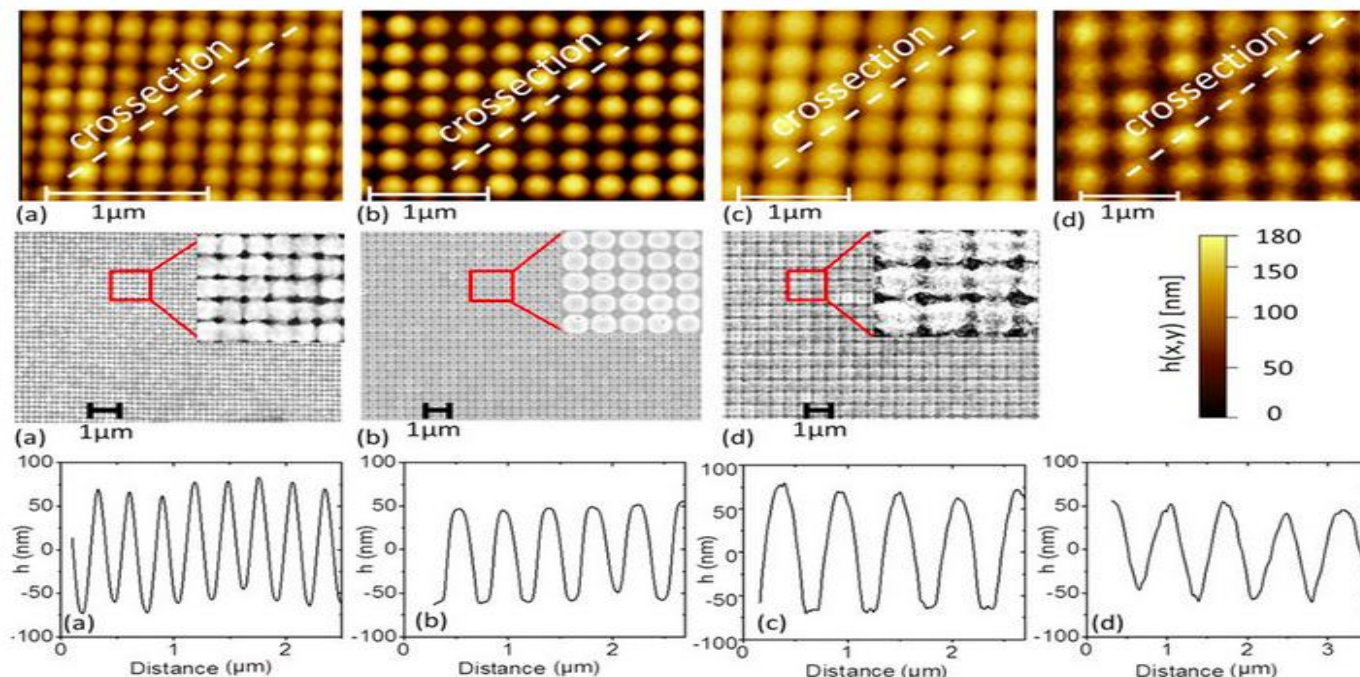


Figure 4: Fourier transform infrared (FTIR) spectra for samples with different wavelength ranges.

## Optical Properties and Analysis of Band Gap

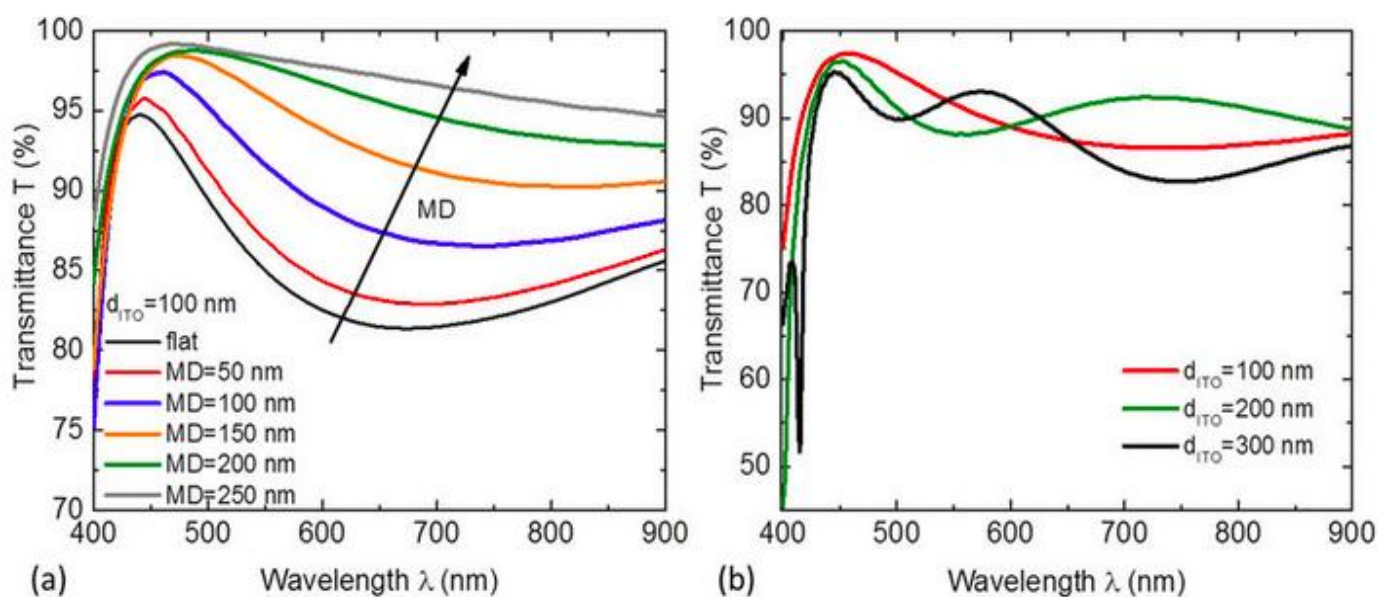
UV-visible diffuse reflectance spectra reveal the increase in light absorption at the UV and visible range as compared to bulk ITO. The absorption edge is slightly red-shifted and this is attributed to Sn doping, oxygen vacancy formation and surface defect states introduced during green synthesis. Tauc plot analysis in figure 5 below, shows a decrease in the effective band gap as compared to pristine indium oxide allowing for better utilization of visible light.



**Figure 5:** AFM (top and bottom panels) and SEM (middle panels) characterization of nanostructured ITO films with period  $\Lambda$  and modulation depth MD of (a)  $\Lambda = 200$  nm (MD = 120 nm), (b)  $\Lambda = 300$  nm (MD = 110 nm), (c)  $\Lambda = 400$  nm (MD = 120 nm) and (d)  $\Lambda = 500$  nm (MD = 110 nm)

## Photoluminescence Analysis

Photoluminescence spectra shown in the figure 6 below shows a decreased emission intensities which indicated a suppressed electron-hole recombination rate. This behavior is favorable for the photocatalysis because the longer-lived charge carriers increase the probability of surface redox reactions. The synergistic property of bio-induced defects and the tin doping play an important role in modulating the electronic structure of the nanoparticles.



**Figure 6: Transmittance spectra for (a) variation of modulation depth MD as indicated in the graph and fixed ITO thickness ITO = 100 nm and (b) changed ITO thickness ITO and fixed MD = 100 nm. The period was set as  $\Lambda = 200$  nm and the angle of incidence was  $\theta = 0^\circ$**

### Ultraviolet diffusion reflectance spectroscopy

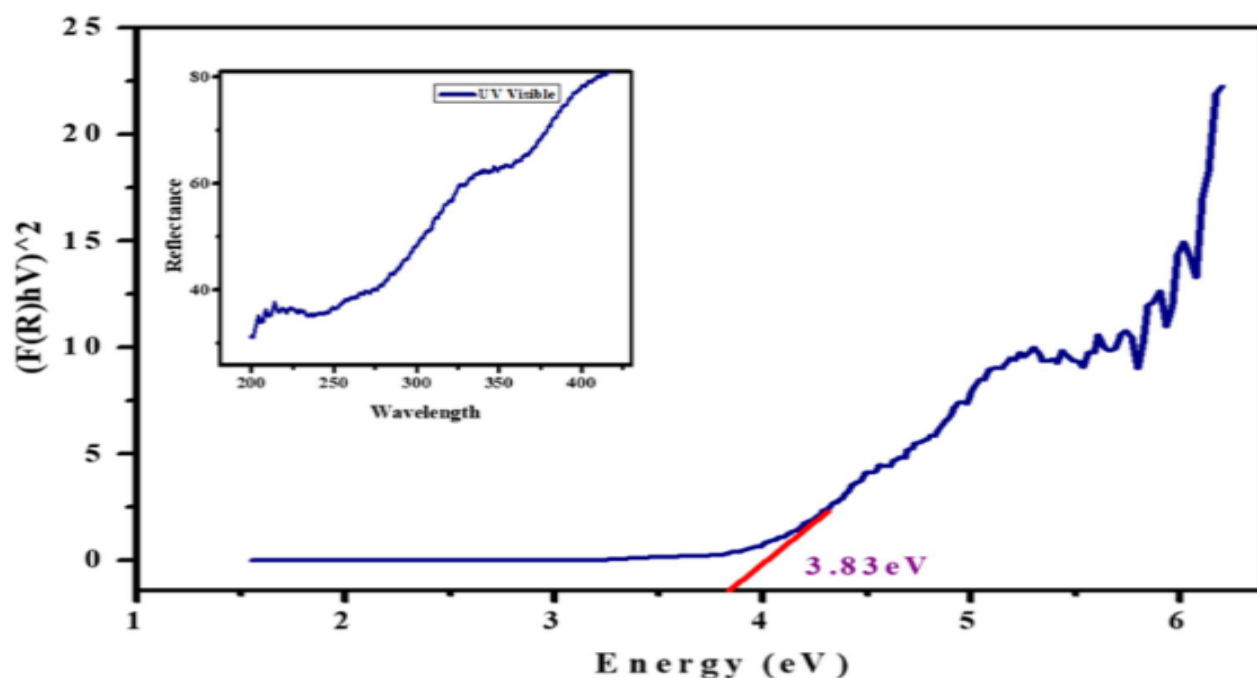
The specific equation expressing Kubelka–Munk function, was applied to demonstrate the aspect of band gap.

$$F(R) = \frac{(1 - R)^2}{2R}$$

The UV spectroscopy reflectance and diffusion mode applied the optical aspects of the ITO nanoparticles as demonstrated in Fig. 7 below in which, R = diffuse reflectance & F(R) = Kubelka. Tauc plot shows a relationship existing between absorption coefficient & band gap energy and the, expressed by the equation below,

$$F(R)h\nu)^n = A (h\nu - E_g) m$$

where,  $\alpha$  = sample linear absorption coefficient,  $h\nu$  is the energy of a photon, A = energy independent constant,  $E_g$  = optical energy band gap and m = constant band gap dependent. The direct energy band gap of the ITO nanoparticles to the MB dye in a 1:1 ratio was found to be 3.83 eV, as shown in Fig. 5 below. These nanoparticles synthesized showed a reflectance wavelengths between 200–375 nm, demonstrating bandgap energy. Furthermore, the light absorption aspects of the photocatalysts were greatly induced by the ITO nanoparticles.

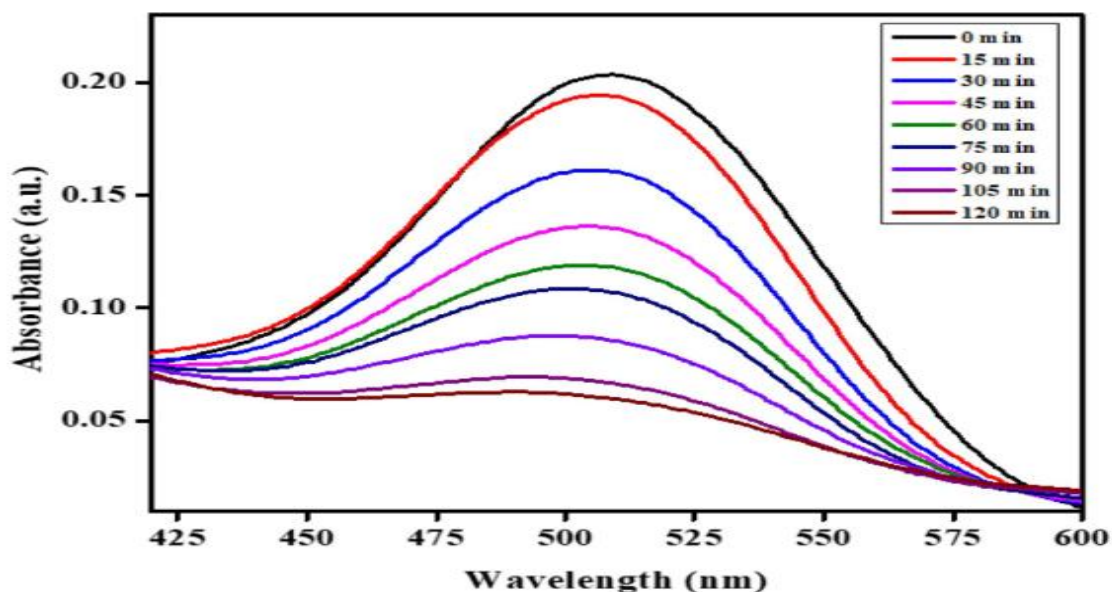


**Figure 7: Energy band gap plot of ITO nanoparticles**

### Dye Degradation Performance of Photocatalytic

The photocatalytic activity of the green-synthesized ITO nanoparticles of concentrations 2, 4, 6 & 8 ppm were tested with the 20 ppm of 200mL methylene blue model organic dye for the degradation under light irradiation. A large reduction of the 20-ppm dye concentration is seen when increased irradiation time of 120 minutes with application of the prepared 8 ppm ITO nanoparticles, proving an efficient photocatalytic activity. Figure 8 below shows the photodegradation process of MB dye using green synthesized ITO nanoparticles as photocatalyst.

Control experiments were performed without ITO catalyst and the degradation was found to be negligible thus proving that the process is photo catalytically driven. The degradation kinetics are pseudo-first order and rate constants suggest the superior performance of the photocatalyst as compared to many previously produced metal oxides photocatalysts using conventional synthesis. Enhanced activity is attributed to high surface area, enhanced light absorption, as well as efficient charge separation caused by green synthesis routes.



**Figure 8: Photodegradation of MB dye using green synthesized ITO nanoparticles as photo-catalyst**

### Mechanistic Clues towards Photocatalytic Degradation.

Upon light irradiation, electrons in the valence band of ITO are excited to the conduction band and positively charged holes remain. Tin doping and oxygen vacancies act as electron traps which decrease the recombination and increase the charge carrier lifetime. The conduction band electrons react with the dissolved oxygen to form superoxide radicals ( $O_2^-$ ) and the valence band holes oxidize the surface-bound water or hydroxyl groups to form hydroxyl radicals (OH). These reactive oxygen species are highly oxidative and attack dye molecules, causing the cleavage of chromophore molecules and their subsequent mineralization to  $CO_2$ ,  $H_2O$  and inorganic ions. The residual phytochemical functional groups on the surface of the nanoparticles may also promote the transfer of electrons and the adsorption of the dye, which may improve the nano-bio interface and the photocatalytic efficiency.

### Comparative and Perspectives of Sustainability

Compared to chemically synthesized ITO nanoparticles, the green-synthesized ones show similar or better photocatalytic performance and have a lot of environmental advantages. The elimination of toxic reducing agents, lower synthesis temperatures and the use of renewable plant resources are in good agreement with the principles of sustainable nanotechnology. In addition, the bio-assisted synthesis approach gives intrinsic surface modification, so post-synthesis functionalization is not required.

### Limitations and future scope

Despite the promising photocatalytic performance exhibited by green-synthesized indium tin oxide nanoparticles, there are a few limitations that should be admitted. One of the main limitations is the inherent

variability of herbal extracts because the concentration and composition of phytochemicals in herbal extracts can vary depending on the species of the plant, the growth conditions, and the extraction parameters. This variability may affect the nanoparticles size, morphology and surface chemistry, and may present challenges for reproducibility and large-scale standardization.

Additionally, although green synthesis reduces the use of dangerous chemicals, it is less certain to control the stoichiometry and defect density than is the case with traditional chemical routes. The presence of residual organic compounds, which is positive for surface activity, may also impair long-term stability or result in deactivation over a long period of time under irradiation. Furthermore, the physicochemical studies performed for photocatalysis are usually carried out with model dyes in controlled conditions in laboratories, which may not reflect the complexity of the industrial wastewater with mixed pollutants and competing ions.

From a future research perspective, systematic optimization of synthesis parameters, such as extract concentration, pH, reaction temperature and calcination conditions could be used to increase reproducibility and catalytic efficiency. Advanced spectroscopic and electrochemical methods should be used to provide more insight into the charge transfer dynamics and role of bio-induced defects. Expanding the investigations to visible light driven photocatalysis and testing against real wastewater samples would do much better in terms of practical relevance.

Moreover, the incorporation of green-synthesized ITO nanoparticles into hybrid systems such as polymer-supported films or heterojunction composites for the improvement of catalyst recovery and reusability is a good

direction. Life-cycle assessment and toxicity studies are also critical in order to assess the wider environmental impact and to ensure the safe use of these nanomaterials on a large-scale water treatment application.

## Conclusions

This study conceptually proves the potential of herbal extract mediated green synthesis as a sustainable pathway for the synthesis of indium tin oxide nanoparticles with superior photocatalytic absorption. The bio-assisted synthesis approach provides a way for effective control over the formation of nanoparticles while simultaneously imparting surface defects, oxygen vacancies and functional groups that are favorable for photocatalytic processes. Structural and optical analyses show successful incorporation of tin into the indium oxide lattice, nanoscale crystallinity and lower electron-hole recombination that are responsible for enhanced dye degradation performance.

The green-synthesized ITO nanoparticles have efficient photocatalytic degradation ability of organic dyes under light irradiation which is driven by the formation of reactive oxygen species and enhanced nano-bio interfaces. Compared to traditional synthesis techniques, this one has great environmental benefits such as chemical toxicity reduction, low energy consumption, use of renewable resources of plant origin, which can also be considered in accordance with the principles of green chemistry and sustainable nanotechnology.

While there are still some issues that can be addressed regarding reproducibility and large-scale application, the results point to the versatility of ITO nanoparticles beyond their traditional optoelectronic applications. Overall, this work highlights the potential of nanomaterials that are synthesized through green chemistry as good photocatalysts for wastewater treatment and it offers a basis for future experimental verification, mechanism research, and real-world treatment applications.

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