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Enhanced Photocatalysis of Methylene Blue by GO/SnO_2 Nanocomposites: A Public Health Perspective

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Abstract

This study successfully synthesized SnO_2 nanoparticles via co-precipitation and subsequently loaded them with varying weight percentages (1-4%) of graphene oxide (GO) using a hydrothermal method. The resulting GO/SnO_2 nanocomposites were comprehensively characterized using a suite of spectroscopic techniques, including SEM, TEM, XRD, elemental mapping, EDX, FT-IR, BET, PL, UV-Vis, and DRS. These analyses confirmed the successful formation of the desired nanostructures. Furthermore, the photocatalytic performance of the nanocomposites and pure SnO_2 was evaluated by monitoring the photodegradation of methylene blue under visible light irradiation, demonstrating the impact of GO loading on photocatalytic activity. The degradation efficiencies of the GO/SnO_2 were much higher than that of pure SnO_2. From the results obtained, we believe that this current study will provide relevant views for further fabrication of other novel nanostructures and exploration of their potential carcinogenic and environmental consequences.

Keywords: Nanocomposites, Photocatalysis, Graphene Oxide, Methylene Blue, Characterization.

INTRODUCTION

The usage of dyes as coloring agents in textile, paper, cosmetics, pharmaceutical, leather and food industries has attracted much attention over the years (Elshypany, 2021 & Helmy *et al*., 2018). This can be as a result of certain effects such as the contamination of water which mostly results from the textile industry discharge and the consequences of these is attributed to the fact that dye molecules are difficult to remove, majority of these colored dyes are of synthetic origin and usually consist of aromatic rings in their molecular structure, Inert and non-biodegradable when discharged into waste water without proper treatment (Sanakousar *et al*., 2022 & Giahi *et al*., 2019). Therefore, removal of such dyes from waste water requires urgency in a bid to protect human health and environmental resources. Methylene blue (MB), one of the most commonly used base dye, is considered to have multiple uses in the printing and dyeing industry (Elaouni *et al*., 2022). In spite of the importance of MB in many industries, its presence in the environment can be bridged if not managed effectively (Jiang *et al.*, 2021). MB is carcinogenic and does not degrade easily due to the characteristic stability of the aromatic rings in its molecular structure (Sanakousar *et al.*, 2022). Traditional biological, chemical and physical techniques such as adsorption and chemical precipitation are recognized for the treatment of waste water from dyeing industries in order to avert any public health crisis among biological beings (Kayode *et al.*, 2015). These methods are expensive, form sludge or generate secondary pollutants, such as dye adsorption on activated carbon, where the pollutant is only converted from the liquid phase to the solid phase, causing pollution. Therefore, the decomposition of dyes into non-toxic compounds is essential and recommended (Lei, & Liu, 2022). The Advanced oxidation processes (AOP) are presently

attracting a great deal of consideration in the field of water treatment (Gusain *et al*., 2019). These processes involve the use of mixture of photocatalysts composed of semiconductor heterojunctions (Mubarak *et al*., 2022). Photocatalyst semiconductors such as tin dioxide (SnO_2) has attracted research interest recently, this is due to its high chemical stability, anti-photo-corrosion, powerful oxidation strength, non-toxicity, low cost, and outstanding catalytic performance (Aniket *et al.,* 2016).

However, the application of SnO_2 for the photodegradation of organic pollutants in aqueous matrices suffers from quick recombination of photogenerated electron-hole pairs, small surface area and the low solar energy conversion efficiency (Binaya *et al*., 2021) owing to its large band gap of 3.6 eV. Hence, SnO_2 absorbs only UV light but visible light inactive (Aniket *et al.,* 2016). This study, therefore focuses on fabricating a novel photocatalyst that is capable of harnessing these limitations by modifying the structure of SnO_2 through doping with graphene oxide (GO) (Binaya *et al*., 2021 and Kent *et al.,* 2011) as well as the photocatalytic behaviors of the photocatalysts. The doping of semiconductors with Graphene Oxide (GO) is considered to be an attractive method as GO has the ability to drive charge separation efficiently, extend the lifetime of the charge carriers, and enhance the efficiency of the interfacial charge transfer to adsorbed dyes (Heba *et al*., 2023) due to its exceptional electrical conductivity and extremely efficient adsorption. Graphene oxide is a two-dimensional material with sp^2 bonded carbon atoms arranged in a honeycomb lattice known for its supportive nature in photocatalytic application due to its extraordinary advantages, such as large theoretical specific surface area ($2630 m^2/g$) superior electronic and excellent chemical stability (Dong *et al*., 2012).

Reagents and Materials

Graphene oxide, Stannous Chloride di-hydrate (98%), ammonia solution (25%), hydrochloric acid (37%), ethanol, methanol, and methylene blue (MB) were all purchased from Sigma Aldrich South Africa. Deionized water was used throughout this experiment. All chemicals used for this study were of analytical grade and used as received.

Preparation of Tin-Oxide (SnO_2)

SnO_2 was prepared using the liquid phase co-precipitation method. About 2g of Stannous Chloride di-hydrate ($SnCl_2.2H_2O$) was dissolved in 100ml deionized Water in a beaker after which ammonia solution (25%) was added drop wise with constant stirring. The resulting gel-type precipitate form was filtered off and dried at 80^oC for 24 hours to remove water molecules. Finally, tin oxide nano-products was obtained through calcination at 550^oC for 4-6 hours.

Preparation of Graphene Oxide-Tin Oxide (GO-SnO_2) Nanocomposite

About 1g of SnO_2 nanosheet was dispersed in 120ml beaker and ultrasonicated for 45min at room temperature. The sonicated SnO_2 suspension was stirred continuously at room temperature for 45min followed by the addition of different masses of GO (10,20,30,50 mg) to different aliquots to achieve equivalent weight percentages of 1,2,3 & 4 respectively. The resulting homogeneous mixtures was stirred, afterwards, 3ml of HCl was added to each of them. The resulting suspensions was stirred again for another 45min and then transferred into a 100ml Teflon-lined stainless autoclaves and kept at 180^oC in an oven and allowed to cool to room temperature. The resulting precipitates of the different coupled amounts of GO nanocomposites was obtained via centrifugation and thereafter, washed severally with deionized water and ethanol. It was dried overnight in a hot air oven at 80^oC to obtain needle like GO-SnO_2 nanocomposites which was grinded into GO-SnO_2 nano-powder.

Evaluation of the Photocatalytic Activity

The photocatalytic ability of the photocatalysts were measured by the degradation rate of methylene blue (MB) under visible light. 50mg of the synthesized SnO_2 as well as the various weight percentages of GO/SnO_2 (1%, 2%, 3% & 4%) was generally dissolved in 100ml of MB aqueous solution (10mg/L) at room temperature. Before irradiation, the solution was stirred well under dark conditions for 30min to attain adsorption/desorption equilibrium. 5mL of solution was taken every 20min for analysis under a UV-visible spectrometer for 180min. The visible light used in this test was replaced by a xenon lamp of 10W capacity. The degradation efficiency of MB was determined using the equation given below:

$$\text{Photodegradation efficiency (\%)} = [(C0 - Ct) / C0] = 100\% \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where C0 is the initial concentration of MB, Ct is the concentration of MB at time, t.

Mechanisms of SnO_2 Photocatalysts for the Degradation of MB

The mechanism of the photocatalytic reaction in the presence of SnO_2 photocatalysts comprises of a free radical reaction initiated by light irradiation (Loh *et al*., 2010) When the energy of solar radiation exceeds the bandgap of SnO_2 (i.e., photon energy reaches or exceeds its bandgap energy), the surface of the photocatalyst becomes excited, and the electrons transit from the valence band (VB) to the conduction band (CB). In the CB, corresponding electron holes are derived in the VB at the same time, forming electron–hole pairs (i.e., generating electron (e) and hole (H^+) pairs). VB holes have strong oxidation reaction activity (1.0~3.5 V) because they lose electrons and act as reducing agents, and electrons in the conduction band have good reducibility 0.5~1.5 V when they undergo reduction. Under light irradiation, positive holes and electrons are

generated in the VB (hv^+vb) and CB (e^-cb) of SnO_2 These holes can either form hydroxyl radicals or react directly with organic molecules which subsequently oxidize the organic molecules. The electrons can also react with organic compounds to produce reduction products. (Lin *et al*., 2013)

The role of oxygen is important as it reacts with the photogenerated electrons. Organic compounds can then undergo oxidative degradation through their reactions with hydroxyl and peroxide radicals, VB holes, as well as reductive cleavage via reactions with electrons yielding various byproducts and finally mineral end-products.

$SnO_2 + hv \rightarrow SnO_2 + h^+ + e^-$…….. (2)

$h^+ + H_2O \rightarrow OH^- + H^+$ …… (3)

$SnO_2 (e^-) \rightarrow GO (e^-)$ …… (4)

$O_2 + GO (e^-) \rightarrow O_2^-$ …… (5)

$2H_2O + O_2^- \rightarrow 2OH^{\cdot} + 2OH$ …… (6)

$OH^{\cdot} + SnO_2 + MB \rightarrow CO_2 + H_2O +$ ……..... (7)

Characterization

The X-ray diffraction pattern of the prepared nanocomposites were obtained using a Shimadzu 6100 X-ray diffractometer with a CU Kα radiation source (Bruker D6). The UV–Vis diffuse reflectance spectra (DRS) of the synthesized SnO_2/GO composites were measured with Pelkin-Elmer UV–Vis spectrophotometer, the photoluminescence (PL) emissions were obtained via Perkin Elmer LS 55 spectrofluorometer. The BET analysis (Micrometrics Tristar 3000) of the synthesized composites were carried out to determine their specific surface areas and their textural characteristics Their surface morphologies were also determined using the Scanning Electron Microscopy instrument (Zeiss 10 kV field). Elemental analysis of the composites was also carried out by energy dispersive spectrometry (EDS, Shimadzu), while the interfacial interaction within the synthesized composites were obtained via High-resolution transmission electron microscopy (JEOL TEM), along with the selected area electron diffraction (SAED) pattern. The FTIR of the composites were measured on Perkin Elmer Series 100 Spectrum to determine the functional characteristics of the composites.

RESULT AND DISCUSSION

Structural Analysis

Fig 4.1 the principal diffraction peaks are at 2θ degrees 26.54, 34.02, 38.03, 51.72, 54.50, 65.88, and 78.54 corresponding to (110), (101), (200), (211), (002), (301), and (202) crystal planes which is compatible with the creation of pure cassiterite SnO_2 crystallite free of impurities. The results illustrated above suggests that there is a gradual increase in peak intensities corresponding to the loading of varying quantities of graphene oxide (GO). Furthermore, the characteristic peaks of GO are absent from the GO-SnO_2 composites due to the modest proportion of GO in these materials. Ultimately, the lack of additional peaks in the nanocomposite demonstrated that the photocatalysts were completely free of contaminants in their prepared state.

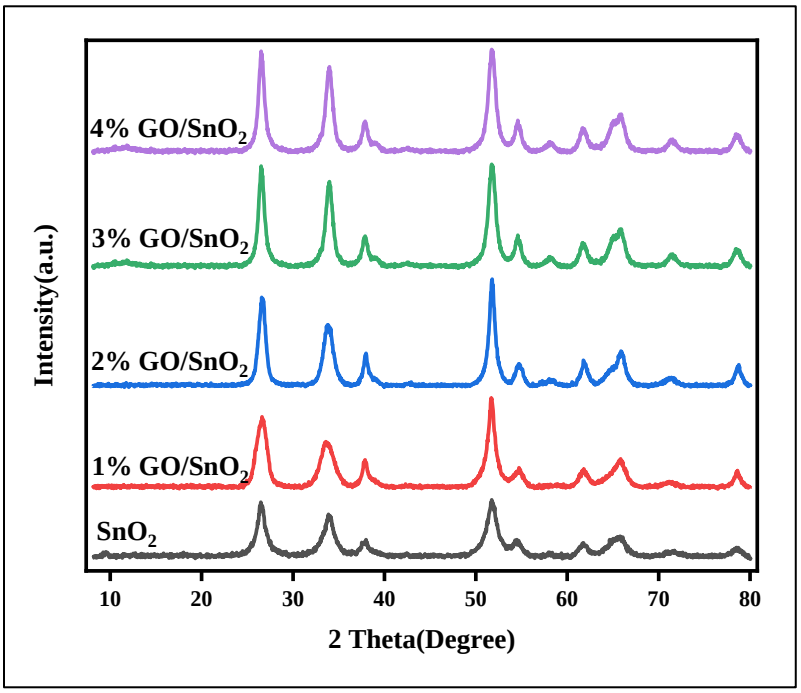

Figure 4.1: XRD patterns of SnO_2 and its respective GO-SnO_2 composites

Fig 4.2 There are several peaks present in the pure SnO_2 nanoparticles, which correspond to Sn–O and O–Sn–O, respectively, at around 528, and 668 cm^{-1}. O–H, CO_2, and C—O functionality can be attributed to the peaks at 3448, 1835, and 1724 cm^{-1}, respectively. Meanwhile, other functional groups with only slight differences are visible when different weight percentages of GO are incorporated into SnO_2.

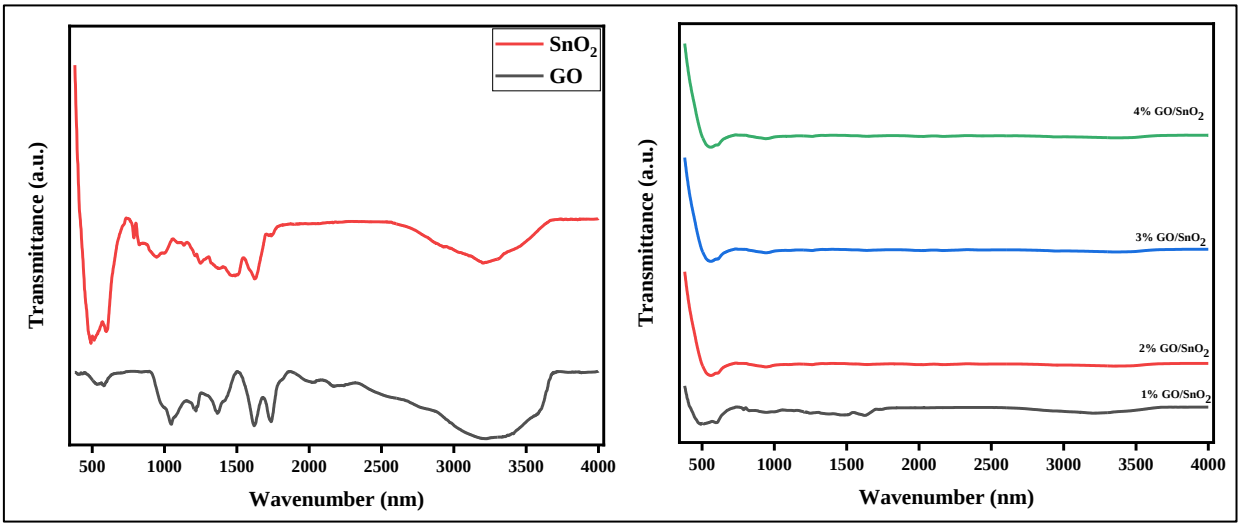

Figure 4.2: FTIR spectra of the synthesized composites

Fig 4.3 The chemical composition of the nanoparticles is confirmed by the EDS of the produced GO-SnO_2 samples, which is also reported. The EDS spectra of the modified GO/SnO_2 showed the presence of the following element Sn, C, N and O, with C and N having lower atomic percentages which could be as a result of the low weight percentages of GO used in the synthesis.

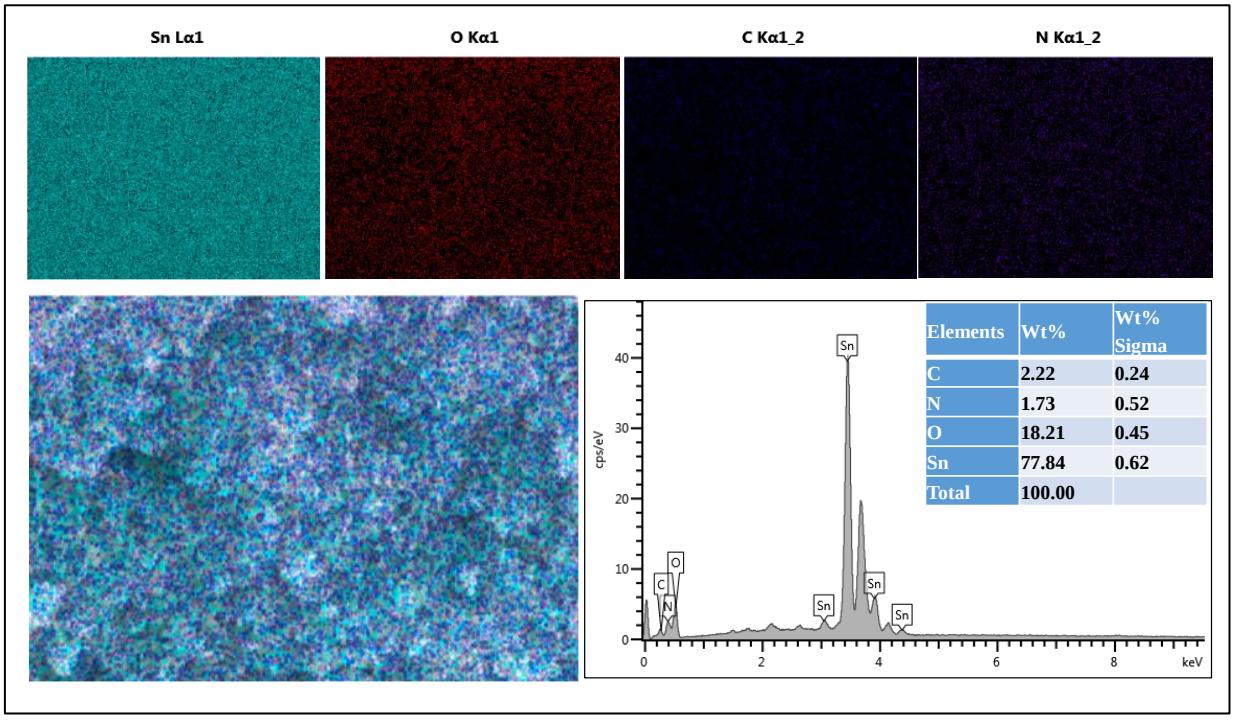

Figure 4.3: SEM-EDS elemental mapping and EDS spectrum of GO-SnO_2

Fig 4.4 the PL spectrum shows that the SnO_2 peak intensity is decreased by the GO nanosheet when GO serves as an electron sink. It can be seen that the PL spectral intensity of the different masses of the composites of GO/SnO_2 nanocomposites are all lower than that of pure SnO_2 nanoparticle, indicating that there is a formation junction between GO and SnO_2 which can facilitate photo-generated charge transfer. In addition, 3%GO/SnO_2 shows extremely low PL spectrum intensity, suggesting a noticeable improvement in the suppression of charge recombination (Khan *et al*., 2013).

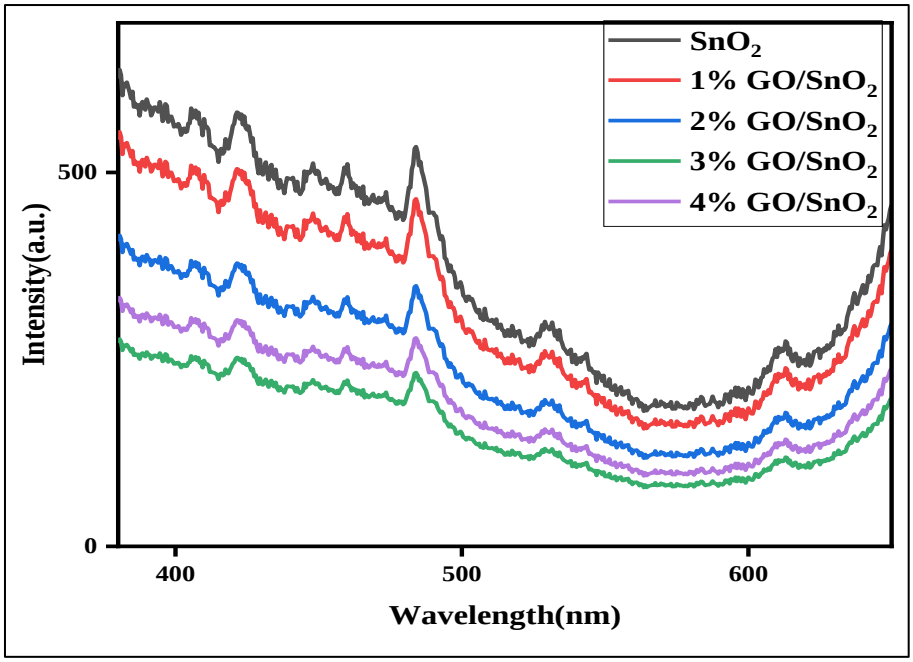

Figure 4.4: PL spectrum of SnO_2 and GO/SnO_2 composites

Morphological Analysis

Fig 4.5, is evident that graphene oxide (GO) has a sheet-like structure, which is a sign of a well synthesized material while the SnO_2 particles have a surface morphology that is almost uniform, and they appear to be in a mixed condition that includes both parted and agglomerated forms. It is clear that tiny GO nanoparticles aggregate to form bigger clusters on the surface of SnO_2, a characteristic shared by all nanocomposite morphologies.

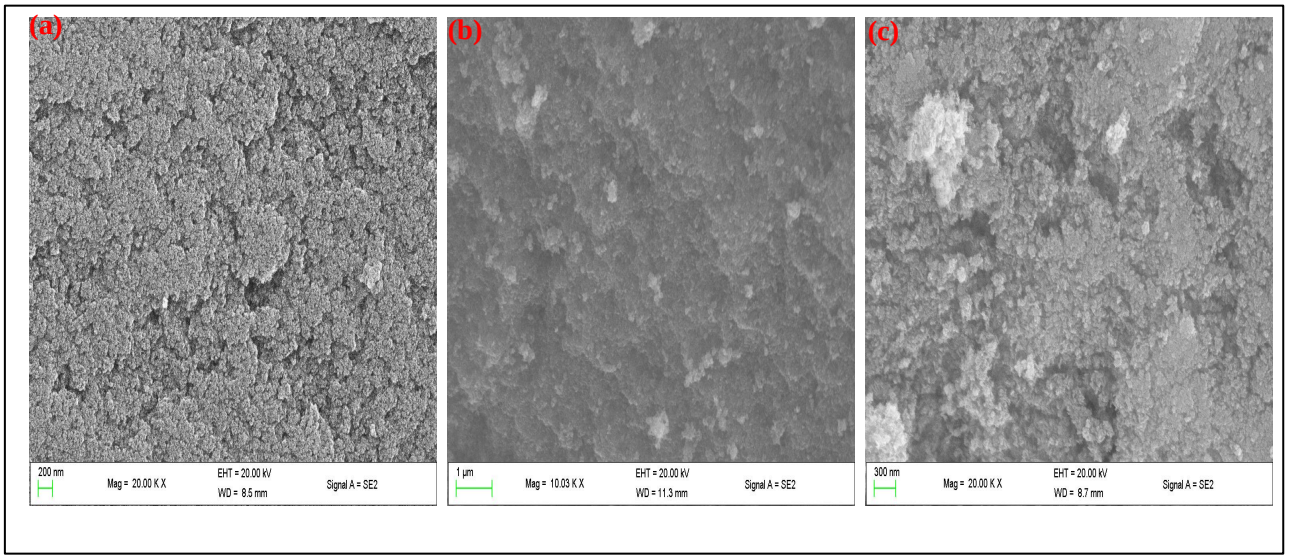

Figure 4.5: SEM image of synthesized (a) GO, (b) SnO_2 and GO/SnO_2 composites

Fig 4.6(b) the TEM pictures reveals that the sheets that make up GO have a curly morphology, with the edges of the sheets somewhat folded and scrolled. The TEM image of SnO_2 nanoparticles depicts an agglomeration of almost tiny spherical particles. As illustrated in Figure 4.5(c), the GO-SnO_2 showed dispersion of GO on the composites of GO-SnO_2 which means the successful construction of heterojunctions between GO nanosheet and SnO_2 nanoparticles (Lei 2022). The SAED spectrum of the composites in Figure 4.5(d) shows that the crystallinity of the SnO_2 nanoparticle remains intact even with the inclusion of GO purposely due to the low quantity of GO in the composites.

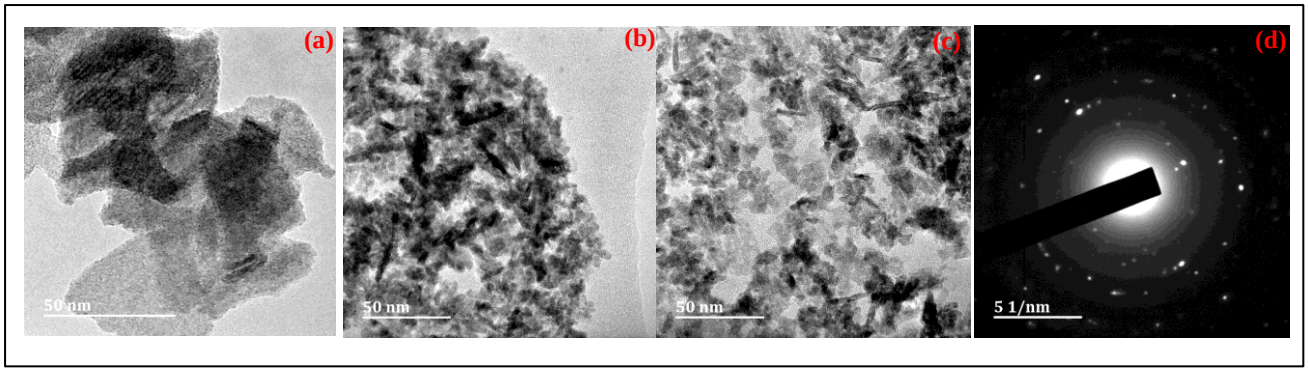

Figure 4.6: TEM images of (a) GO, (b) SnO_2, (c) GO-SnO_2 and (d) SAED spectrum of GO-SnO_2

Fig 4.7 the GO-SnO_2, SnO_2, and synthesized GO surface areas were measured utilizing the nitrogen adsorption and desorption isotherm of a BET analyzer. Adsorption-desorption profile followed type IV characteristic with type H3 hysteresis loop, indicating mesoporous structure development for all the synthesized composites. In comparison to SnO_2, the synthesized varying masses of the composite materials showed an increase in BET specific surface area. In particular, the addition of GO, which has a surface area of 1392.28 m^2/g, caused the surface area of SnO_2 to rise from 12.26 m^2/g to 39.37 m^2/g. The cross-sectional area of the pollutants and the adsorption surface area grew together, improving the composite's photocatalytic efficacy.

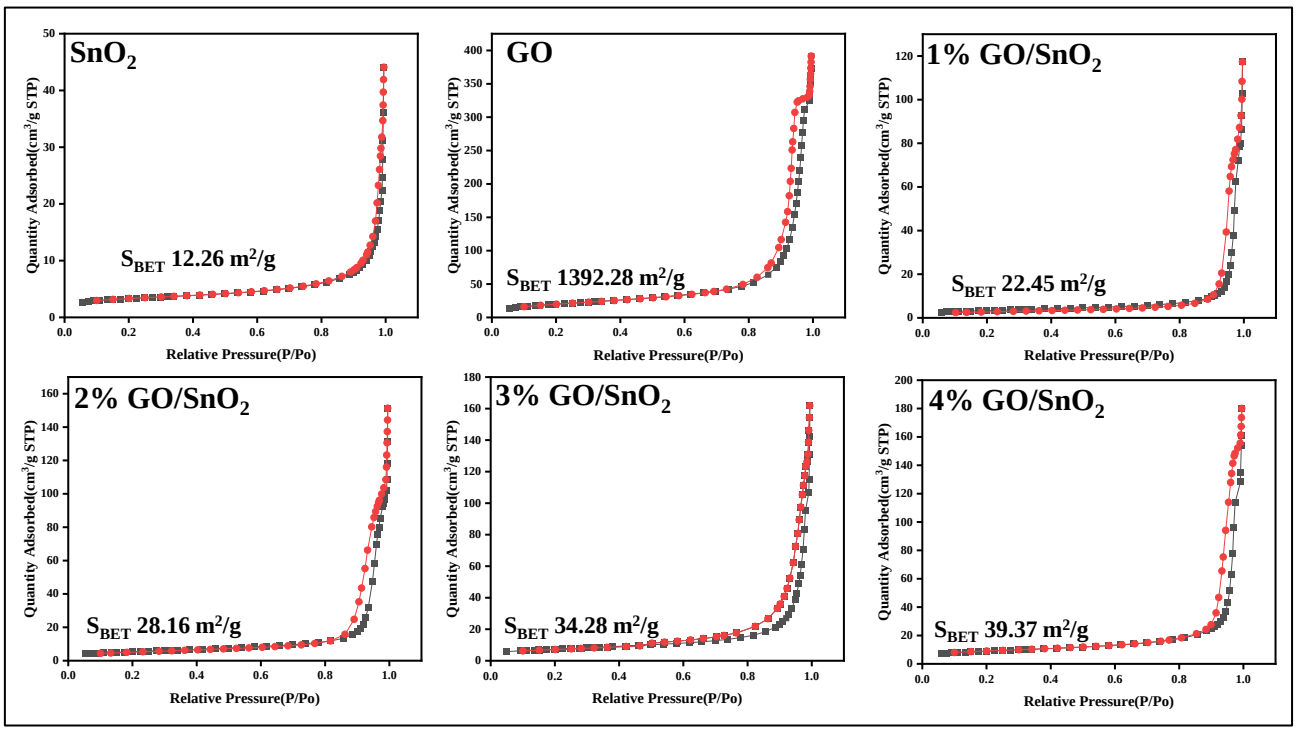

Figure 4.7: Nitrogen adsorption-desorption isotherms of the synthesized materials

In fig 4.8a the UV-vis absorption spectra shows that the optical absorption edges of SnO_2 nanoparticles are at about 410 nm, which cannot make full use of visible light while for the difference masses of GO/SnO_2 nanocomposites, the absorption shows a broad elevated background in the visible region with increasing content of GO nanosheet implying that the GO could optimize the optical absorption ability of GO/SnO_2 nanocomposites. This phenomenon indicates that more solar energy can be absorbed by the photocatalyst, which is beneficial for photocatalytic degradation of organic pollutants. Furthermore, in Figure 8(b), the Eg (band gap) values of SnO_2 nanoparticles and the difference masses of GO/SnO_2 are 3.12, 2.75 and 2.62 eV, respectively. It is obvious that the optical band gap of GO/SnO_2 nanocomposites is gradually decreased with the increasing amount of GO when compared to pristine SnO_2 nanoparticle.

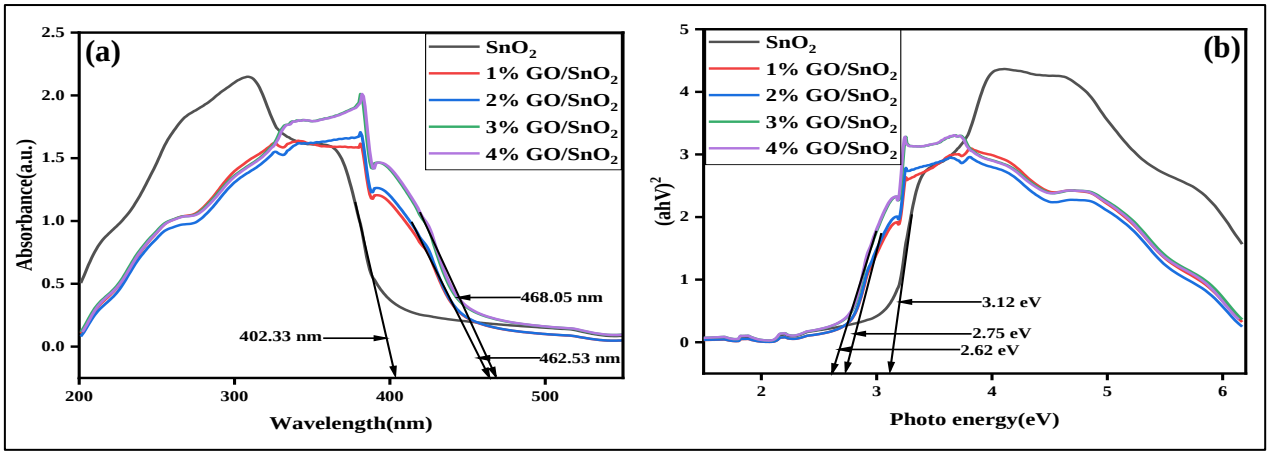

Figure 4.8: (a) UV–vis DRS spectrum and (b) Kubelka-Munk plot of the synthesized composite

Photocatalytic Performance

Fig 4.9 the photocatalytic performance of SnO_2 and the varied masses (1, 2, 3 & 4) wt. % of GO/SnO_2 nanocomposites achieved degradation efficiencies of 44.70%, 75.18%, 86.97%, 93.42% and 90.01% respectively with methylene blue removal under visible light irradiation in 180 minutes. This indicates that the degradation rate improved with increasing GO content, with optimal performance being reached at 3% GO/SnO_2 weight percentage. Increase in GO content above this weight percentage decreased the amount of photocatalytic activity, probably because the GO aggregated within the SnO_2 nanosheet, reducing its active surface area and introducing recombination sites. Kinetic analyses were employed to compare the methylene blue degradation rate of the composites according to the logarithmic ratio of C_0 (initial concentration of the MB) and Ct (the concentration of the MB at the time of t), which the following relationship has carried:

$$\ln C_0/Ct = k_{abs}t$$

Where k_{abs} is the rate constant of the absorption. If the ln C_o/Ct vs.t plotting is drawn by matching the data with straight lines, then the slope of these lines will indicate the absorption rate of the samples. These results are presented in Fig. 4.9(b) shows that the 3% GO/SnO_2 nanocomposites show the most excellent k(abs) which can be attributed to the synergetic effects of GO on SnO_2.

Public Health Implications

Graphene-based tin oxide (SnO_2) composites offer significant potential for photocatalytic applications like methylene blue degradation. However, a prudent evaluation necessitates careful consideration of their potential carcinogenic and environmental consequences. While SnO_2 is generally considered non-carcinogenic, graphene's ability to induce oxidative stress and DNA damage raises concerns (Sanakousar *et al.*, 2022). Furthermore, methylene blue is a known carcinogen, and its degradation may produce harmful byproducts. Environmentally, these composites may contribute to water and soil pollution, with the production process potentially releasing nanoparticles into the air. Mitigation strategies are crucial. These include safe handling protocols, comprehensive toxicity assessments of both composites and degradation products, the development of green synthesis methods, and the pursuit of biodegradable composite designs. By prioritizing risk assessment and implementing preventative measures, the benefits of graphene-based SnO_2 composites can be realized while minimizing their potential negative impacts on human health and the environment (Sanakousar *et al.*, 2022; Jiang *et al*., 2021).

CONCLUSION

The enhanced photocatalytic activity of graphene oxide (GO)-functionalized SnO_2 observed in this study, and its efficacy in removing methylene blue, has a significant implication for the health of the public. While the current conclusion highlights the potential of this composite material for removing carcinogenic organic dyes from water, framing it within a public health perspective amplifies its value. The availability of clean and safe water is a fundamental determinant of public health, and the presence of organic contaminants, including dyes like methylene blue, poses a direct threat through potential carcinogenic effects and other toxicities. This research, therefore, contributes to the development of a cost-effective and easily implemented water remediation strategy. Future studies should focus on scaling up this technology, evaluating its long-term stability, and assessing its effectiveness against a broader spectrum of waterborne contaminants relevant to public health concerns. By emphasizing the link between this photocatalytic approach and the reduction of exposure to harmful substances in drinking water, the scientific value of the research is further enhanced within the context of safeguarding public well-being.

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