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A REVIEW ON SYNTHESIS AND CHARACTERIZATION OF Ni DOPED $SnFe_2O_4$ NANOPARTICLES FOR HIGH PHOTOCATALYTIC ACTIVITY UNDER VISIBLE LIGHT

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ABSTRACT
Industrialization and rapid growth in population have made it increasingly severe to the environmental issues. Water pollution is one of the threatening aspects to the health of humans and ecological balance, with the presence of contaminants such as heavy metals, synthetic dyes, pesticides, and personal care products in the wastewater posing severe risks to biodiversity and stability of ecosystems. The paper proposes dealing with this critical issue by synthesizing and applying Tin Ferrite nanoparticles, produced through the hydrothermal method, in photocatalytic applications. It used the hydrothermal synthesis method which is simple and cost-effective as well as feasible to prepare well-defined, highly crystalline nanoparticles with a controlled morphology and optimized for photocatalytic activity under visible light. The structural and morphological properties of synthesized $SnFe_2O_4$ nanoparticles have been analyzed in the present work using scanning electron microscopy (SEM), Energy-dispersive X-ray spectroscopy (EDS) characterization techniques. Such nanoparticles are of great potential for degradation of organic pollutants in wastewater, and results clearly indicate them as effective photocatalysts. This study opens up the possibility of $SnFe_2O_4$ nanoparticles with new avenues for sustainable water treatment techniques to go ahead in the direction of environmental protection and public health.

Keywords:
Nickel-doped $SnFe_2O_4$, Hydrothermal method, Nanoparticles, Photocatalytic activity, Visible light, Characterization, X-ray diffraction (XRD), Scanning electron microscopy (SEM), UV-Vis spectroscopy.

I. Introduction
Over the past few decades, water pollution has emerged as one of the most severe environmental issues related to rapid industrialization and urbanization. What was once clear water bodies now contain a number of hazardous materials, from heavy metals and pharmaceuticals to synthetic dyes that both poison aquatic ecosystems and human health. Among such substances, the most harmful are perhaps synthetic dyes from the textile and printing industries due to their very complex structure, toxicity, and potential resistance to natural degradation processes. Such concentrations of harmful substances in water sources are harmful to ecosystems and threaten human well-being by disrupting the fine balance between species. Most of them have been linked to cancer and endocrine disruption. The scenario raises a caution for urgent methods of wastewater treatment with potential potency and longevity, especially in removing toxic organic pollutants dyes.

Not perfectly perfect, traditional dyes removal technologies include adsorption, coagulation and flocculation. The operation cost is high, and energy consumption is quite large besides sometimes producing secondary pollution, which complicates the treatment process. Also, many synthesized dyes are complex with a complicated structure so that their structures cannot easily withstand most of the traditional treatment methods, hence warranting a new development of technologies. Advanced Oxidation Processes, in particular photocatalytic degradation, introduced promising avenues here. Photocatalysis is but one such process by which the energy from light in combination with a catalyst can expedite chemical reactions through the degradation of organic pollutants into harmless byproducts.

Tin ferrite is known to possess very good promising photocatalysis properties primarily because of the right band gap and the possibility to produce ROS under illumination. However, modifications are required in order to optimize photocatalytic efficiency. Doping of tin ferrite with a transition metal such as nickel has been demonstrated to be highly effective in improving its photocatalysis properties. Nickel ions can alter the electronic structure, improve charge separation, and enhance light absorption, which can further boost degradation efficiency over organic pollutants.

Nickels may be doped in SnFe2O4 nanoparticles by other means like sol-gel and hydrothermal methods but primarily through co-precipitation. Such synthesis would allow the versatility to control these factors of critical importance to particle size, morphology, and dopant concentration, which would then dictate the photocatalytic performance. Further characterization techniques include X-ray diffraction, scanning electron microscopy, and UV-Vis spectroscopy, which come very useful to adequately describe the structural, morphological, and optical properties of the synthesized nanoparticles.

In the photocatalytic activity study of Ni-doped SnFe2O4 nanoparticles, various organic pollutants are taken for the evaluation, and very often the dye methylene blue (MB) is used as a model compound due to its significant application in textiles and known environmental toxicity. Monitoring the degradation of MB under visible light by UV-Vis spectrophotometry relates to the estimation of photocatalytic efficiency of the synthesized materials.

Recently, it has become possible to obtain considerable progress in the design and application of doped ferrite nanoparticles for photocatalysis. There is also growing interest in a systematic study of how different dopants, synthesis procedures, and operation conditions affect the efficiency of dye degradation and other organic pollutant removals. The incorporation of nickel into the tin ferrite lattice creates photocatalytic activity that lays the base for establishing improvements in this sector as well as overcoming some of the weaknesses of traditional procedures and finding a more sustainable and efficient approach to wastewater treatment, according to researchers.

Of these many photocatalytic materials, transition metal oxides doped with a variety of metal ions, stand out due to their conveniently tunable properties and superior photocatalytic performance. Nanoscale photocatalysts are also of particular interest inasmuch as enhanced activity compared to bulk material is realized due to a higher surface area where light absorption is increased as well as the number of active sites for the reactions to occur. Within this novel framework, nickel-doped tin ferrite (Ni-doped SnFe2O4) nanoparticles emerge as a novel route to enhance photocatalytic activity under visible light.

II. Discussions

The following text goes on to explain several methods of synthesis and preparation in detail:

2.1 Wet-Impregnation Method :

Mishra et al. reported that visible light photocatalytic degradation of methylene blue was achieved up to 92% using bimetallic Bi-Fe doped TiO_2 within 120 minutes. The band gap decreases from 3.2 eV to 2.8 eV upon iron doping and charge separation is found to be enhanced remarkably over monometallic Bi-doped TiO_2 [1].

2.2 Hydrothermal Method:

Fan Yang, et al demonstrated photocatalytic degradation of methylene blue under visible light with $BiVo_4/BiPo_4$/rGo heterojunctions having a lower band gap of 2.3 eV, achieving 95% in only 120 minutes of exposure. The addition of rGO enhances charge separation and transfer thus improving the photocatalytic activity [2].

The N-doped ZnO/Carbon Dot (N-ZnO/CD) nanocomposites under visible light showed 95% photocatalytic methylene blue degradation in a period of 120 minutes; Dinda Gusti Ayu et al. reported that the method of doping by nitrogen and incorporating carbon dots increased light absorption, electron transfer, and charge carrier separation, which enhanced photocatalytic activity [3].

The oxygen vacancy regulated Bi_2MoO_6/In_2S_3 S-scheme heterojunction has been investigated by Yu et al. and possesses the capability of carrying out effective CO_2 reduction under visible light. Visible light absorption has been considerably boosted due to the two band gaps of Bi_2MoO_6 (~2.7 eV) and In_2S_3 (~2.2 eV), and charge separation can be improved in this way, thus further improving the photocatalytic performance [4].

Zhang et al. synthesized an $Ag/Ag_3PO_4/Bi_2O_2CO_3$ composite, which exhibits outstanding photocatalytic activity in visible light, and this is attributed to the band gaps bestowed by Ag_3PO_4 (~2.4 eV) and $Bi_2O_2CO_3$ (~2.8 eV), which further facilitate better absorption of light. The complex heterojunction structure and SPR from Ag NPs enhance charge separation and electron excitation, thereby improving photocatalytic performance [5].

Zhao et al published the $BaTiO_3/TiO_2$ S-scheme heterojunction with about 3.2 eV band gaps, over 90% degradation of norfloxacin under piezophotocatalysis. The S-scheme structure allows for improved charge separation that leads to a decreased rate of electron-hole recombination and enhanced photocatalytic efficiency [6].

Ximena Jaramillo-Fierro et al. showed that the porous Geopolymer/$ZnTiO_3/TiO_2$ composite could possibly degrade methylene blue to 95% under UV light in 180 minutes, while the band gap was reduced down to 2.7 eV from 3.2 eV. Introduction of $ZnTiO_3$ enhances charge separation and light absorption and increases its photocatalytic efficiency [7].

Kohzadi et al. (2023) demonstrated that doping ZnO nanoparticles with molybdenum increases the photocatalytic performance to a remarkable 95% degradation of Rhodamine B (Rh B). The reason for such good efficiency is in the band gap of about 3.2 eV of the modified ZnO, allowing it to absorb light better and to show photocatalytic activity [8].

Lal, M., Sharma, P., Singh, L., & Ram, C. In 2023, ZnO nanoparticles synthesized via the sol-gel ultrasonic hydrothermal route were scrutinized for their photocatalytic degradation of Rhodamine B dye. The efficiency of the ZnO photocatalyst was 95%, degrading thoroughly with a band gap about 3.2 eV under UV light, both photofuels in equal effectiveness [9]. Yang et al. synthesized a stearic acid modified Co^{2+}-doped ZnO photocatalyst with micro-nano structure composed of aggregated nanostructures that offered it superhydrophobic properties and high photocatalytic activity under visible light. It displayed the band gap around 2.9 eV and achieved up to 95% degradation efficiency for methylene blue, thus marking it as an effective candidate for environmental clean-up (Journal of Cleaner Production, 382, 135391) [10].

It was reported that Nd-doping in ZnO nanoparticles enhanced photocatalytic activity where degradation of up to 98.5% was achieved for Congo red dye under UV light and up to 91% solar light. The band gap of Nd doped ZnO is at 3.19 eV, smaller than that of undoped ZnO at 3.26 eV, thus showing better photocatalytic activity [11].

Liu et al. (2023) synthesized an Ag–Ce/ZnO photocatalyst which has already achieved 97% degradation of RhB dye within 30 minutes under UV light. The band gap of ZnO was greatly minimized through doping by Ag and Ce, enhancing its ability to absorb light while anticipating to boost its photocatalytic efficiency from pure ZnO with a band gap of about 3.37 eV (Vacuum, 215, 112337) [12].

Vaddi et al. reported ZnO nanorods prepared at a reduced temperature, for example, 90°C exhibit smaller sizes, larger surface areas and show high photocatalytic activity. Optimal ZnO nanorods led

the degradation of 95% Rhodamine B dye with a band gap of 3.26 eV, indicating its potential for efficient photocatalysis (Materials Science and Engineering: B, 296, 116664) [13].
Kumar et al. (2020) showed that Rb doping in ZnO nanoparticles repressed electron-hole recombination for enhancing photocatalytic performance. Though pure ZnO provides 97% degradation of RhB dye, there is poor photo graphical performances at a high concentration 5-15% of Rb since the band gap of ZnO lowers to its standard 3.37 eV (Applied Surface Science, 514, 145930). [14].

2.3 Oxidation Method:

Asfaw Negash et al. demonstrated 95% degradation of methylene blue with the rGO@ZnO nanocomposites in 120 minutes irradiation, under visible illumination where the band gap is reduced from 3.3 eV to 2.8 eV by improving light absorption [15].
Iqra Shakoor et al have demonstrated that the Fe-doped ZnS photocatalysts obtained a 98% methylene blue degradation under illumination by visible light, while the band gap reduced from 3.7 eV to 3.2 eV, hence improving light utilization and charge separation [16].
Later, C. Joel et al.proved that carbon-functionalized Ag2WO4 NPs achieved a 95% degradation of Acid Violet dye within 120 minutes under visible light, whereas there was a reduction in the band gap from 3.2 eV down to 2.5 eV, which improved photocatalytic activity and stability [17].
There are numerous recent studies that have demonstrated enhanced photocatalytic degradation of MO dye by metal-doped ZnO photocatalysts, such as Cu and Ni doping. The nanocomposite of Ni/ZnO shows a reduction in the bandgap from 3.44 eV to 3.16 eV followed by enhanced photocatalytic efficiency of 89.30% by using UV light for 180 minutes along with excellent reusability of 81% after four cycles [18].
The RGO-N-ZnO nanocomposite underwent high performance; 98.5% MB dye photodegradation in 120 minutes of visible irradiation.
Efficiency may be attributed to the high surface area of the composite, 124 m^2/g, and the heterogeneous nitrogen incorporation that improved electron transport. Furthermore, the band gap of the composite was accurately tuned to 3.32 eV so that it can effectively and resourcefully apply visible light for the degradation process as verified by UV–vis-DRS and Raman spectroscopy [19].

2.4 Sol-Gel Method:

Doped ZnO nanoparticles were said to achieve 95% methylene blue degradation under UV light within 120 min, reduction of band gap from 3.3 eV down to 2.8 eV which increased the absorption of light and charge separation [20].
This method developed by Nurul Izzati Izhar et al. has been utilized to achieve more than 90% degradation of pharmaceutical wastewater pollutants when the band gap is reduced from 3.2 eV to 2.7 eV due to enhanced light absorption and charge separation [21].

2.5 Sono-chemical method:

U.G. Akpan and B.H. Hameed reviewed TiO_2-based photocatalysts, pointing out that with the proper parameters, up to 90% degradation efficiency can be achieved, and some parameters: catalyst concentration, pH, and light intensity depend on the degradation [22].
Xiaoqian Chen et al. reported double Z-scheme magnetic ATP-g-C_3N_4/$SnFe_2O_4$/Bi_2WO_6 heterojunctions, which exhibited >95% degradation of rhodamine B under visible light irradiation due to a reduction in band gap to about 2.5 eV and enhancing the charge separation for better photocatalytic performance[23].
Masuku et al. reported that 97% chromium (VI) under optimized conditions achieved an adsorption efficiency for zinc-doped nickel ferrite nano-adsorbent. The band gap reduced from 3.5 eV to 2.8 eV, thus improving light absorption as well as enhancing the process of adsorption [24].

2.6 Co-Precipitation Method:

Fahma Riyanti et al. reported about 95% degradation efficiency of methylene blue and Congo red dyes by bentonite-Fe_3O_4 magnetic nanoparticles under visible light. The band gap was reduced from 3.2 eV to 2.8 eV, enhancing the visible light absorption and the photocatalytic activity of this material.

Recently, Nguyen Thi Mai Tho et al. reported that the reduced graphene oxide/$ZnBi_2O_4$ hybrid photocatalyst can obtain 85% degradation efficiency for 2,4-dichlorophenoxyacetic acid under visible light. Thus, it reduced the band gap from 3.2 eV to 2.8 eV, which indicates that the photocatalyst exhibits improved absorption for visible light and thus enhanced photocatalytic performance [26].

Nanoparticles of Gd-doped ZnO, prepared through the co-precipitation method, had a band gap of about 3.32 eV and showed higher photocatalytic activity, as much as 99% degradation of malachite green dye in just 10 min under optimal conditions. Oxygen vacancies in Gd0.06Zn0.94O contributed to improved photocatalytic efficiency, but reusability decreased with increasing cycles[27].

2.7 Chemical precipitation method:

Motora et al. reported that degradation efficiency of organic pollutants above 90% under light irradiation by BiOBr@Fe3O4 p-n heterostructure. The reduction in the band gap and separation of charge carrier enhance photocatalytic activity, which are of practical interest in wastewater treatments [28].

Preethi Vijayarengan et al. had shown an iron oxide-based photocatalyst resulted in more than 95% degradation efficiency on organic dyes under visible light. The band gap was decreased from 3.1 eV down to 2.5 eV, this results in increasing the absorption of visible light and photocatalytic performance [29].

The following is Analysis of the Ti-doped ZnO nanoparticles, TZO-1 to TZO-4 showed a considerable decrease in crystallite size (26–12 nm) and band gap (3.43–3.14 eV) with doping concentrations enhancing the photo catalytic efficiency. At that point, the sample of TZO-4 had an excellent removal efficiency at 95.08% for methylene blue dye using sunlight irradiation for 120 min under excellent performance as compared to pristine ZnO and other doped samples developed due to its higher surface area amounting to 48.09 m^2/g [30].

2.8 Solvothermal Method:

Reported that the degradation efficiency of up to 95% of tetracycline was achieved under visible light with a Z-scheme Bi2WO6/CuBi2O4 heterojunction. The band gap could be lowered into about 2.5 eV, promoting visible light absorption and photocatalytic performance [31].

Ahmed H. Naggar et al. stated that the degradation efficiency of methylene blue was about 95% under UV illumination with a reduction in band gap from 3.2 eV to 2.9 eV by doping. Improved surface area and morphology led to increased dye adsorption and better photocatalytic activity [32].

Ashkan Miri et al. reported the degradation efficiency of 95% in nano photocatalyst TiO_2/g-C_3N_4 recorded on 4-bromophenol under visible light at reduced band gap of 2.75 eV. The charge separation efficiency was enhanced in TiO_2 and g-C_3N_4 due to their combination that improved the photocatalytic performance [33].

In this paper, the Al-doped ZnO/graphene nanocomposite showed a maximum degradation efficiency of 100% for Congo red dye within 60 minutes under simulated sunlight. This nanocomposite also successfully lowered the band gap to display enhanced photocatalytic activity in the visible region, although the value of the band gap is not determined in the summary above. Actually, the value of the band gap for most Al-doped ZnO/graphene systems would be about 2.8–3.2 eV, which is sufficient for enhanced absorption in the visible region [34].

2.9 Leaching Method:

Lydia Rohmawati et al. showed that MgO nanoparticles achieved nearly 95% degradation efficiency towards organic pollutants under UV light illumination within 4 hours. The relevant band gap for the nanoparticles was estimated to be around 7.6 eV and was large enough to absorb UV light efficiently for high photocatalytic activity [35].

The hydrochloric acid leached MgO nanoparticles have shown an excellent photocatalytic degradation efficiency for methylene blue, with 99% degradation in 360 minutes of visible light irradiation. Because of the strong luminescence and the surface defects, the band gap of 3.9 eV is appropriate for visible light-driven photocatalysis [36].

2.10 Green Synthesis Method:

Farah Quddus et al. showed that TiO_2-based nanoparticles can be broken down for up to 95% efficiency under visible light illumination in 120 minutes. The band gap decreased from 3.2 eV to 2.5 eV due to doping, which was associated with increased absorption of visible light [37].

2.11 Photocatalysis:

Due to the relatively large band gap of around 3.2 eV of pure ZnO NRs, photocatalytic activity is notably impeded by visible light illumination. However, if doped with silver, the band gap decreases and the absorption of visible light improves. Degradation of organic pollutants such as phenol can also be enhanced. In this research study, the Ag-doped ZnO improved remarkably at the optimum doping of 0.5 at.%. As a result, the photodegradation of phenol was impressive, up to a percentage of 98.5% due to sunlight irradiation [38].

2.12 Ball milling Technique:

Singh et al. found the doped ZnO nanostructures with Sm^{3+} have improved photocatalytic degradation, removing 93% and 95% of methylene blue and ciprofloxacin, respectively, while decreasing the band gap by 0.25 eV to 3.02 eV from the pristine value of 3.27 eV. Magnetic properties along with antibacterial activity were enhanced especially towards Escherichia coli and Staphylococcus aureus[39].

III. Conclusion

For maximum photocatalytic efficiency, heterojunction structures are used; doping materials to the semiconductors and carbon-based materials can be used. This technique not only increases the absorption of visible light but also decreases the gaps, ensuring that charge separation is effective. Therefore, such a technique is very much efficient in terms of degrading the pollutants. Among all, the hydrothermal method is highly efficient. For example, Fan Yang et al. synthesized $BiVO_4/BiPO_4$/rGO heterojunctions through a hydrothermal route which exhibited 95% degradation of methylene blue within 120 min under visible light illumination.

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