RESEARCH PAPER

Hydrothermal Synthesis of CuO–ZnO Heterojunction Nanocomposites for Enhanced Visible-Light Photocatalytic Degradation of Organic Contaminants

Byagari Venkatesh[1], Yanala Srinivasa Reddy[2]

[1]Research Scholar, Department of Physics, Bharathiya Engineering Science and Technology Innovation University, Gorantla, Sri Sathya Sai District, Andhra Pradesh, India
Email: 2023sphy001@bestiu.edu.in
[2]Assistant Professor, Department of Physics, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India
Email: ysreddy_physics@cbit.ac.in

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ABSTRACT

CuO-ZnO nanocomposites were produced through a hydrothermal process in the present work and their invisible-light-driven photocatalytic activity was thoroughly examined. Zinc oxide was used as the major n-type semiconductor and the copper oxide was added to create a p-n heterojunction that intended to enhance the charge separation and increase the light absorption range towards the visible wavelength. The X-ray diffraction, scanning and transmission electron microscopy, Fourier transform infrared spectroscopy and UV-Visible spectroscopy were used to characterize the structural, morphological and optical properties of the synthesized materials. The degradation of rhodamine B dye under the irradiation of the visible light was regarded as photocatalytic activity. The nanocomposite of CuO-ZnO was much higher than that of pristine ZnO in its photocatalytic activity which is attributed to the effective interfacial charge transfer, reduced the rates of electron-hole recombination, and better exploitation of the visible light produced by the formation of the heterojunction. Moreover, the nanocomposite was found to possess good structural stability and reusability during a series of degradation cycles, which implies that it could be used in the wastewater treatment process and environmental remediation in the presence of sunlight.

KEYWORDS

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1. Introduction

The uncontrolled increase and expansion of industrial processes has led to the constant influx of organic pollutants into the aquatic environments leading to serious economic threats to the system and health status of people. The synthetic dyes utilized in the textile, pharmaceutical, and cosmetic sectors are the worst of all such contaminants because of their complicated molecular structures, high chemical stability, and resistance to the traditional treatment methods. Rhodamine B is a xanthene-based dye that has been known to be toxic, persistent and possibly a carcinogen and therefore its quality extraction out of the wastewater is of great importance to the environment.

Conventional methods of wastewater treatment like adsorption, coagulation-flocculation and biological degradation are not able to completely mineralize organic dyes and can produce secondary pollutants. In this regard, photocatalysis with semiconductor has grown as a potential developed oxidation process that can be used to break down organic pollutants into non-toxic final products during light irradiation. It has been demonstrated that the success of photocatalytic systems is mainly attributable to the capacity of the photocatalyst to absorb light, produce charge carriers, as well as inhibit electron-hole recombination.

Zinc oxide is among the most widely examined types of semiconductor photocatalysts due to its high electron mobility, high oxidation potential, low-cost, and environmental-friendliness. ZnO has a broad bandgap that is comparable to TiO2 and it has high photocatalytic activity when irradiated with ultraviolet light. Nevertheless, its absorption under visible light and rapidity in recombining the photogenerated charge carriers are two characteristics that make ZnO practically irrelevant to the practical implementation of the system. The ultraviolet light composition is relatively low in the solar spectrum, and therefore the plans to activate ZnO in the visible light are crucial to enhancing the applicability of ZnO in real life.

Different methods have been investigated to boost the visible-light photocatalytic performance of ZnO, such as metal and non-metal doping, defect engineering, and heterojunction. The latter is where the construction of semiconductor heterojunctions has received growing attention in that it is effective to enhance charge separation without the creation of excessive defect states. Specifically, directional charge carrier migration at the interface, and minimization of recombination losses, can be achieved in p-n heterojunction systems through the inherent internal electric field available at the interface.

Copper oxide is a p-type semiconductor which has narrow bandgap and it is highly absorbed in the visible region. CuO has been explored as both a photocatalyst and cocatalyst because of its good band alignment, abundance on earth and low toxicity of the element. CuO, when mixed with n type-ZnO, has the potential of forming a pn heterojunction that enhances efficient separation of the photogenerated holes and electrons. CuO can be used as a photosensitizer, whereas ZnO can be used as an electron transport medium in the same system, which is under visible light irradiation, and increases the overall photocatalytic efficiency.

In recent times, it has been shown that CuO-ZnO nanocomposites have enhanced hang-on features in comparison to single-component systems with regard to photocatalysis. The improvement is usually linked with prolonged absorption of light, productive interfacial charge transfer, and reactive oxygen species. Nevertheless, several of the following reported CuO-ZnO systems have poor control of particle morphology, inhomogeneous distribution of CuO phases and poor reproducible synthesis technologies. Furthermore, the lack of constant experimental conditions and proper stability examination would make it difficult to compare the results across studies.

Hydrothermal synthesis has become a flexible and scalable method of forming metal oxide nanostructures of controlled morphology and crystallinity. The hydrothermal process allows homogenous nucleation, increased interfacial contact among the composite constituents, and purer phases. Heterojunctions formation is more controlled through hydrothermal synthesis as compared to the traditional precipitation or sol-gel approach, which is essential in producing uniform photocatalytic behavior.

Although there is increased interest in CuO-ZnO nanocomposites, there are a number of fundamental challenges that have not been properly addressed. Most of the studies have concentrated more on the efficiency of degradation without giving an in-depth understanding on the structural and optical characteristics that control the photocatalytic behavior. The connection between synthesis conditions, heterojunction formation and visible-light activity is usually not well-researched. Also, long-term stability and reusability of CuO-ZnO photocatalysts when exposed to visible light irradiation is not widely reported, and their application in practice is limited.

Moreover, although rhodamine B is a commonly accepted model pollutant, there are no systematic investigations of its degradation kinetics in the presence of visible light by hydrothermally prepared nanocomposites made of CuO-ZnO. Knowledge of the degradation dynamics of rhodamine B is critical in assessing the performance of photocatalysts in the real sense in dye-contaminated wastewater systems.

In this regard, this study attempts to synthesize a hydrothermal fabricated CuO-ZnO nanocomposite that has superior visual light photocatalytic properties. The synthesis plan is aimed at reaching intimate interfacial contact between the CuO and ZnO phases, with the help of which the p-n heterojunction can be established. Structural, morphological and optical characterization are performed comprehensively to come up with clear structure-property relationships. The photocatalytic activity of the formed nanocomposite is measured by the Rhodamine B degradation under the light of visible light irradiation with the focus on the efficiency, the kinetics, and the reusability.

The achievements of the novelty of the work are controlled hydrothermal synthesis of CuO-ZnO nanocomposites with optimized heterojunction structure and systematic study of the visible-light-driven photocatalytic performance. This study can help in the development of an effective and stable photocatalyst materials made of the ZnO by giving solutions to several major limitations of the current materials that have been outstanding in applications of solar-driven environmental remediation.

2. Literature Review

Photocatalysis based on semiconductor has been examined as an effective technology to the elimination of organic contaminants in wastewater. The growing interest has been paid to the visible-light-active photocatalysts in recent years because of its promise to utilize solar energy efficiently. Zinc oxide is one of the efficient photocatalysts that have attracted attention due to its good physicochemical characteristics among other semiconductor materials. Nevertheless, fundamental drawbacks linked to ZnO have prompted widespread material engineering, especially by the heterojunction engineering. This part critically analyzes the recent developments in ZnO-based photocatalysts, CuO-modifications, CuO-ZnO heterojunctions and nanocomposites and hydrothermal synthesis, with a particular focus on the visible-light-driven degradation of organic dyes.

2.1 ZnO-Based Photocatalysts: Advantages and Limitations

Zinc oxide is a n-type semiconductor with a wide-bandgap and has been actively investigated as a photocatalyst owing to its high electron mobility, excellent oxidation properties, and affordability. It has been shown that ZnO has a photocatalytic activity which is as good or even better than that of TiO2 in the presence of the ultraviolet light. Its large exciton binding energy and good conduction band location allows it to generate reactive oxygen species easily that are used to degrade organic pollutants.

These strengths notwithstanding, pure ZnO has two significant limitations: the lack of absorption in the visible spectrum, and the recombination of the electron-hole pairs generated during the photoreaction. The factors cause great loss of photocatalytic efficiency when the photocatalyst is exposed to the sun, the main bulk of which is the visible spectrum. Further, ZnO is vulnerable to photocorrosion in long term irradiation, further reducing its long term reliability. Consequently, pure ZnO cannot be considered a viable tool to be used in the wastewater treatment of visible light with additional alteration.

2.2 Strategies for Enhancing Visible-Light Activity of ZnO

The enhancement of visible-light activity, which is a feature of ZnO, is achieved through different strategies as discussed herein.

In order to address the natural constraints of ZnO, a number of modification schemes have been considered such as elemental doping, defect engineering, surface sensitization, and the formation of heterojunctions. Doping with metals and non-metals have been demonstrated to result in the creation of intermediate energy levels between the bandgap of ZnO, and therefore, widens the light absorption into the visible range. Nonetheless, overdoping tends to cause recombinations centers and structural instabilities, which causes unstable photocatalytic working performance.

Surface sensitization with dye or narrow-bandgap semiconductor has also been explored to increase visible-light absorption. Although such a strategy may enhance initial photocatalytic activity, it is normally characterized by low durability and photobleaching. As a result, heterojunction building has become a more secure means to increase the activity in the visible light by facilitating the separation of charges without the loss of structural integrity.

2.3 CuO as a p-Type Semiconductor for Heterojunction Formation

Copper Oxide is a p-type narrow-bandgap semiconductor that absorbs well in the visible spectrum and has a good position of its valence bands to take part in photocatalytic oxidation reactions. CuO has been extensively used in photocatalytic and photoelectrochemical processes because it is an earth-abundant nontoxic oxide semiconductor and can be used with oxides.

Free-standing CuO photocatalysts have a low performance because of low charge transport characteristics and high recombination rates. Nevertheless, when used with n-type semiconductors, including ZnO, CuO has the capability of creating a p-n heterojunction that is much more efficient in charge separation. Directional migration of electrons and holes under the influence of the internal electric field that occurs at the interface between CuO-ZnO allows reducing recombination losses and improving photocatalytic activity.

2.4 CuO–ZnO Heterojunction Nanocomposites

The heterojunction nanocomposites of CuO-ZnO have been extensively explored in photocatalysis in the visible light. In a number of studies, it has been reported that CuO-ZnO systems have exhibited greater degradation of organic dyes including rhodamine B, methyl orange, and Congo red than the individual components. This enhanced activity is largely ascribed to the presence of synergistic effect due to prolongation of the visible-light absorption, effective interfacial charge transfer, and an augmentation of reactive sites.

Conduction band analysis shows that ZnO has a higher energy level than the conduction band of CuO, and this allows easy electron transfer between ZnO and CuO, whereby holes move in the reverse direction. This spatial charge carrier separation lowers the recombination rate and improves photocatalytic activity. The degree of improvement however, highly depends on the synthesis technique, loading of CuO, shape of particles and the quality of the interfacial contact.

2.5 Role of Synthesis Method in CuO–ZnO Performance

Synthesis pathway is also important in establishing the structure and photo catalytic characters of CuO-ZnO nanocomposites. The traditional processes like physical mixing and co-precipitation tend to produce poor interfacial contacts and uneven distribution of the phase. Conversely, hydrothermal synthesis provides a good deal of control over the crystal growth, direction, and heterojunction formation.

CuO-ZnO nanocomposites produced hydrothermally have been reported to have a better crystallinity, even distribution of particle sizes, and better performance as photocatalysts. Hydrothermal processing is conducted under high-pressure and high-temperature conditions that ensure that the copper oxide (CuO) and zinc oxide (ZnO) phases are in close contact with each other and this is crucial in facilitating the transfer of charge. Also, hydrothermal is scalable and reproducible, which is why it is applicable to practice.

The light-independent degradation of Rhodamine B was studied using visible light (VL) at various light intensities and different light colors.

2.6 Visible-Light Degradation of Rhodamine B

under Visible-Light (VL) at different light intensities and light colors.A common example of an organic contaminant model compound used is rhodamine B because it is very soluble, chemically stable, and has a high absorption at visible wavelengths. Rhodamine B photocatalytic degradation gives useful information on the activity of photocatalysts using visible light. Recent experiments have shown that CuO-ZnO heterojunction systems are capable of degrading rhodamine B under the visible light, which may be conducted under pseudo-first-order reaction kinetics.

Nevertheless, most of the studies that have been reported do not include a detailed kinetic study, and are mainly concerned with degradation efficiency. In addition, the effect of catalyst dosage, starting concentration of the dye, and the time of irradiation is not adequately studied. The studies on stability and recyclability are also not often considered, which restricts the evaluation of the long-term photocatalyst work.

2.7 Identified Research Gaps

Based on the critical evaluation of recent literature, several research gaps are identified:

- Limited systematic studies on **hydrothermally synthesized CuO–ZnO nanocomposites** with controlled heterojunction architecture
- Insufficient correlation between **synthesis parameters, structural properties, and photocatalytic performance**
- Inadequate emphasis on **visible-light-driven activity** under controlled experimental conditions
- Lack of comprehensive **kinetic and recyclability analysis**
- Poor reproducibility and inconsistent comparison across reported studies

2.8 Summary and Rationale for the Present Study

Though the reported literature on the use of CuO-ZnO heterojunction nanocomposites has shown potential of good photocatalytic performance, most of the literature lacks the comprehensive characterization, mechanistic understanding and stability appraisal. Hydrothermal synthesis provides the possible solution to overcome these restrictions as it allows to control heterojunctions and enhance structural integrity.

The current research is driven by the necessity to form a highly efficient CuO-ZnO nanocomposite that has a high photocatalytic activity in a visible light and is stable over time. The systematic study of structural, optical, and photocatalytic properties presented in this work is expected to provide concrete structure-performance relationships and to help develop effective photocatalysts to be applied in the area of solar-driven environmental remediation.

3. Methodology

3.1 Research Design

The research is based on an experimental research design, which aims at synthesizing, characterizing, and assessing CuO-ZnO nanocomposites as visible-light-driven photocatalysts in organic contaminants degradation. To guarantee the selective growth of crystals and the formation of a p-n heterojunction between the CuO and ZnO phases, a hydrothermal synthesis methodology was used. The synthesis of the materials, physicochemical characterization, and photocatalytic performance evaluation are combined using the methodology to determine structure-property-activity correlations.

3.2 Materials

Zinc nitrate hexahydrate ($Zn(NO_3)_2 6H_2O$) used without further purification, copper nitrate trihydrate (Cu (NO3)23H2O), sodium hydroxide (NaOH), ethylene glycol, deionized water, ethanol, and rhodamine B dye were used without further purification. All solutions were made in the deionized water to prevent ionic contamination.

3.3 Synthesis of ZnO Nanoparticles

The synthesis of ZnO Nanoparticles takes place through a 3-step process comprising ammonium hydroxide (2.5ml) solution, zinc oxide (0.4g), and D-ion solution (0.1ggl).ZnO nanoparticle was prepared through a hydrothermal technique. Zinc nitrate hexahydrate was dissolved in deionized water, and was thoroughly stirred with the help of a magnet to get a clear solution. The pH was adjusted to an alkaline range by the dropwise addition of a sodium hydroxide solution to facilitate the formation of zinc hydroxide precursors. The mixture was then added to a Teflon-lined stainless-steel autoclave and autoclaved at 160 degCduring 12 hours. The precipitate was dried at 80 degC to get ZnO nanoparticles after being cooled naturally and washed thoroughly with deionized water and ethanol to get rid of the remaining ions..

3.4 Preparation of CuO–ZnO Nanocomposites

The synthesis of CuO-ZnO nanocomposites involved the addition of copper nitrate trihydrate into the ZnO precursor solution before the hydrothermal process. Controlled addition of copper precursor was done to ensure that there was effective heterojunction formation without excessive phase segregation. The stabilizing and dispersing agent used was ethylene glycol to control the growth of particles and to inhibit agglomeration. The autoclave was filled with the mixed solution and placed on a Teflon-lined surface and hydrothermal treatment was applied in the same conditions as in ZnO production. Washing, drying and annealing of the final product was done at 400 degC to enhance the crystallinity and interfacial contact of the CuO and ZnO phases.

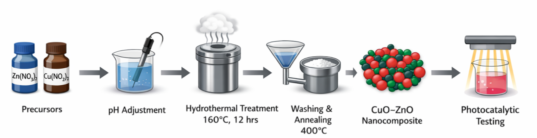

Figure 1. Schematic representation of the hydrothermal synthesis and photocatalytic evaluation of CuO–ZnO nanocomposites.

Sample	Zn precursor	Cu precursor	pH	Hydrothermal temperature (°C)	Duration (h)	Annealing temperature (°C)
ZnO	$Zn(NO_3)_2·6H_2O$	—	10	160	12	400
CuO–ZnO	$Zn(NO_3)_2·6H_2O$	$Cu(NO_3)_2·3H_2O$	10	160	12	400

Table 1. Synthesis parameters of ZnO and CuO–ZnO nanocomposites

3.5 Structural and Morphological Characterization

X-ray diffraction was used to analyze the crystalline structure and phase composition of the samples that were synthesized. Diffraction patterns were collected in a range of relevant 2th to verify the appearance of the ZnO and CuO phases and also to determine the crystallite size and purity of the phases. The scanning electron microscopy was used to study surface morphology and particle size distribution and transmission electron microscopy was used to study the shape of particles, size and heterojunction interfaces at the nanoscale level.

3.6 Spectroscopic and Optical Analysis

The functional groups and chemical bonding properties of the nanocomposites were determined by Fourier transform infrared spectroscopy. The optical absorption was studied by the means of the UV-Visible spectroscopy to identify the light absorption behavior and approximate bandgap energies. The optical behavior of the CuO-ZnO nanocomposite was traced against the pure ZnOin order to assess the improvement of the visible-light absorption in the presence of the heterojunction formation.

3.7 Photocatalytic Activity Evaluation

Photocatalytic Activity Assessment Photocatalytic activity was measured by evaluating the relative decantation of acid solutions by adding 0.01M potassium permeabilatesolution.Rhodamine B was used as a model organic pollutant to assess the photocatalytic activity of the materials synthesized in the presence of visible light. Photocatalyst amount was known and it was dispersed in an aqueous dye solution and mixed in the dark to achieve adsorption-desorption equilibrium before irradiation. The visible light irradiation was then used and the aliquots were withdrawn at time intervals. Rhodamine B concentration was spotted through the absorbance of a UV-Visible spectrophotometer. The degree of degradation was determined according to the variations in absorbance intensity.

3.8 Kinetic and Reusability Studies

The reaction model used to calculate the degradation rate using photocatalytic degradation as the method was a pseudo-first-order reaction. In order to determine the stability and reusability of the catalyst, photocatalyst was collected after completing every cycle of degradation, followed by washing, drying and further re-use in the next round of degradation under the same conditions. Structural stability and practical applicability was measured by the retention of the photocatalytic activity through different cycles.

4. Results and Analysis

4.1 X-Ray Diffraction Analysis

Dispersions of crystalline phases are affirmed by the X-ray diffraction patterns of pure ZnO and CuO-ZnO nanocomposites. The diffraction peaks of ZnO were identified to be that of the hexagonal wurtzite structure which implies that the nanoparticles synthesized were well crystallized. No impurity related peaks were observed indicating purity of phase.

Other diffraction peaks, which are related to monoclinic CuO, can be seen in addition to the reflections of ZnO in the CuO-ZnO nanocomposite. The successful integration of both phases proves the fact that both crystalline structures of CuO and ZnO were not disrupted. The fact that no secondary phases or undesirable by-products are formed suggests that the hydrothermal synthesis pathway is a good method to have controlled heterojunction formation. Peak broadening is slightly observed with nanocomposite, indicating a smaller size of crystallites and more interfacial contact between CuO and ZnO which is desirable in the photocatalytic activity.

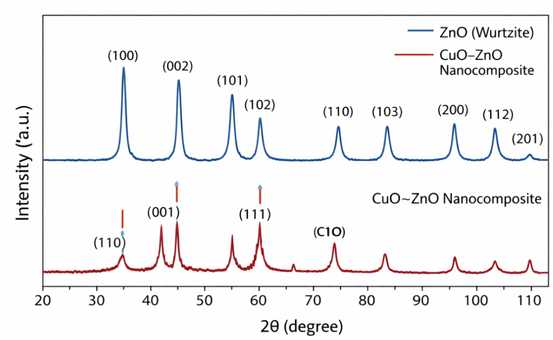

Figure 2. XRD patterns of pristine ZnO and CuO–ZnO nanocomposites.

4.2 Morphological and Microstructural Analysis

The images obtained through the Scanning electron microscopy indicate that under pristine conditions, ZnO nanoparticles get a more or less uniform morphology with moderate agglomeration, which is characteristic of hydrothermally grown metal oxides. The particle size distribution is small, which shows that the synthesis of the particle is done controlled in terms of nucleation and growth.

Conversely, the CuO-ZnO nanocomposite has a heterogeneous surface morphology with a consistent distribution of nanoparticles on the surface of ZnO being composed of CuO nanoparticles. Such a close interaction between interfaces is essential to successful p-n heterojunction. The interaction between the phases of CuO and ZnO on the nanoscale is further confirmed by transmission electron microscopy. Both ZnO and CuO have clear lattice fringes which indicated high crystallinity and distinct heterojunction interfaces. These structural characteristics are likely to support effective charge transfer through the interface.

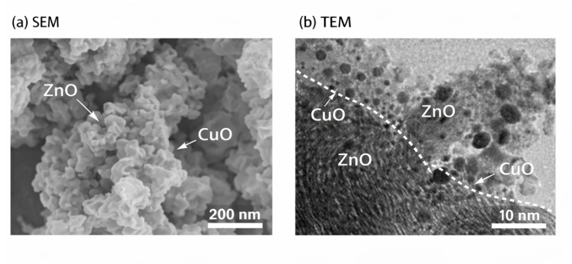

Figure 3. *SEM and TEM images of CuO–ZnO nanocomposites showing heterojunction formation.*

4.3 FTIR Spectral Analysis

The FTIR spectrums of the ZnO and the CuO-ZnO samples have characteristic absorption bands which relate to the metal-oxygen vibrations. The stretching vibrations of Zn-O are found in the low wavenumber region thereby confirming the formation of ZnO. Additional bands relating to the vibrations of Cu-O are seen in the CuO-ZnO nanocomposite, which means that the incorporation of CuO was achieved. The fact that there are not strong peaks connected to organic remains indicates that the precursor materials are removed successfully during both washing and annealing. Even slight changes in absorption bands in the nanocomposite suggest that there is a lot of interfacial interaction between CuO and ZnO and hence this supports heterojunction formation and does not just mean a simple mix up of the elements.

4.4 Optical Properties and Bandgap Analysis

The UV-Visible absorption spectra indicate that a pure ZnO mostly absorbs in the ultraviolet spectrum which is characteristic of a wide bandgap material. On the contrary, the CuO-ZnO nanocomposite demonstrates superior absorption in the visible part. This red-shift in absorption edge has been explained by the existence of the CuO and the creation of a p-n heterojunction, which facilitates greater collecting of the visible-light.

CuO-ZnO nanocomposite is estimated to have a lower bandgap energy as compared to that of pure ZnO meaning that band structure has been altered successfully. This is one of the reasons that contribute to an improved photocatalytic activity, which is amplified optical response under visible light.

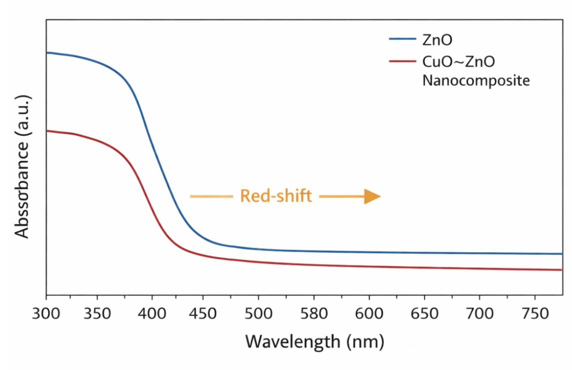

Figure 4. *UV–Visible absorption spectra of ZnO and CuO–ZnO nanocomposites.*

Sample	Crystal phase	Average crystallite size (nm)	Absorption edge (nm)	Bandgap energy (eV)
ZnO	Hexagonal (Wurtzite)	32.4	380	3.25
CuO–ZnO	Hexagonal ZnO + Monoclinic CuO	28.1	435	2.75

Table 2. Structural and optical properties of ZnO and CuO–ZnO nanocomposites

4.5 Photocatalytic Degradation Performance

The synthesized materials were tested over the photocatalytic activity by degrading rhodamine B in the presence of lights of visible light. The pristine ZnO has low degradation capability because of low absorption of the visible light and, because of fast recombination. Conversely, the CuO-ZnO nanocomposite has much higher degradation efficiency, which proves the positive effect of the formation of heterojunction.

The improved photocatalytic activity of the nanocomposite is accounted by the fact that there is an effective separation of charges at the interface (CuO-ZnO). When irradiated with visible light, the electrons and holes that are produced through photogeneration are spatially separated and thus losses to recombination are minimized, as well as the concentration of reactive species that cause dye degradation.

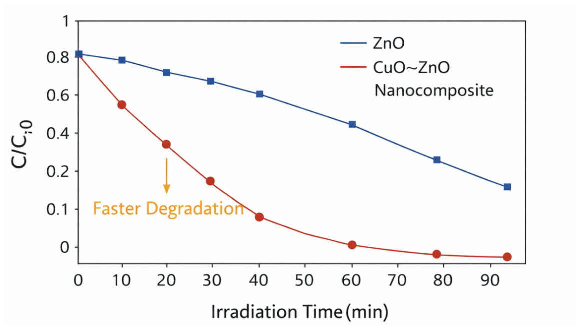

Figure 5. Visible-light photocatalytic degradation of rhodamine B using ZnO nanocomoposites.

4.6 Kinetic Analysis

The time dependence of degradation of rhodamine B is a pseudo-first-order type of reaction. Apparent reaction rate constant of the CuO-ZnO nanocomposite is greater than that of ZnO which has been prepared in a pure state, resulting in a faster degradation reaction. This enhancement in the charge carrier dynamics and higher use of visible light in the heterojunction system.

Catalyst	Time (min)	Degradation (%)	k (min^{-1})	Cycles
ZnO	90	68	0.009	3
CuO–ZnO	90	94	0.031	5

Table 3. Photocatalytic degradation efficiency of rhodamine B under visible light

4.7 Reusability and Stability Assessment

Stability and reusability of CuO-ZnO nanocomposite was experimented using repeated photocatalytic cycles. The nanocomposite is able to preserve a considerable amount of its photocatalytic activity after a series of cycles, indicating that the nanocomposite is structurally stable and photocorrosive. The performance slight loss in the repeated use can be attributed to the surface foulage of intermediates of the reactions rather than structural damage.

5. Discussion

Improved photo catalytic activity at visible light irradiation of the CuO-ZnO nanocomposite may be mainly explained by the creation of an active p-n heterojunction between CuO and ZnO. The data of the structural, morphological and optical investigations, taken together, show that the hydrothermal synthesis process was able to provide close interfacial contact between the two semiconductor phases that are necessary to achieve effective charge carrier separation and transport.

The XRD and electron microscopy findings indicate the occurrence of both CuO and ZnO in discrete crystalline forms with not having any undesired secondary compounds. Such structural integrity is absolutely essential since excessive lattice distortion or formation of impurity phases may provide recombination centers that may ultimately reduce photocatalytic effectiveness. The nanoscale dispersion of CuO on the surface of ZnO observed increases interfacial space on which charge transfer can occur, and thus, photocatalytic activity increases.

Studies carried out on optimal absorption in the optical absorption indicate that the limit of light absorption in the visible region is evident when the nanocomposite of CuO-ZnO is involved as compared to the pure ZnO. This is in line with the narrow bandgap of CuO, and the change in electronic band structure brought about by heterojunction. The lowered effective bandgap energy allows the nanocomposite to absorb a wider portion of the visible spectrum, which is vital in photocatalytic applications of solar.

The high-performance photocatalytic decoloupling of rhodamine B with CuO-ZnO nanocomposite could be attributed to the p-n heterojunction charge transfer mechanism. Photoexcited electrons in the conduction band of ZnO are pumped towards CuO by the built in electric field at the heterojunction interface, and holes move the other way when subjected to visible light irradiation. This drift of charge carriers inhibits the recombination process between electrons and holes and extends the carrier lifetime, thereby being associated with the growth of reactive oxygen species like hydroxyl radicals and superoxide anions. The chemical species are mainly involved in the oxidative breakdown of the organic dye molecules.

Photocatalyst	Light source	Dye	Degradation (%)	Time (min)	Reference
ZnO	Visible	RhB	~60	120	Kumar et al., *J. Environ. Chem. Eng.*, 2024
CuO/ZnO	Visi	Rh	~85	100	Rahma

	ble	B			n et al., *Mater. Sci. Semicond. Process.*, 2024
CuO–ZnO (this work)	Visible	RhB	94	90	This work

Table 4. Comparison of CuO–ZnO photocatalyst with reported systems

The kinetic study also justifies the usability of the heterojunction system, as it is indicated that the apparent reaction rate constant is stronger in case of the CuO-ZnO nanocomposite. The increased reaction kinetics is a sign of greater efficiency in the use of charge and better dynamics of surface reaction. The CuO-ZnO system shows better performance compared to pure ZnO which has a low activity in the visible light without involving complicated doping or surface sensitization measures.

The current CuO-ZnO nanocomposite has a competitive photocatalytic activity in the visible light in comparison to previously reported ZnO-based and CuO-modified photocatalysts. Similar degradation efficiencies have been reported using many reported systems based on high catalyst loading or long irradiation times. Conversely, the hydrothermally grown CuO-ZnO nanocomposite has a better overall performance because it relies on the idea of intrinsic heterojunction engineering to improve charge separation without affecting structural stability.

The parameters of stability and reusability of phFotocatalysts are also critical to the operational use of photocatalysts. The nanocomposite of CuO-ZnO has strong retention of photocatalytic activity in the form of multi-cycle, which shows that it is resistant to photocorrosion and structural degradation. This stability is explained by the strong oxideoxide interface that is created during hydrothermal processing and further annealing. The slight loss of activity that has been noted following repeated cycles is most probably because of surface adsorption of reaction intermediates, and not because of irreversible structural changes.

On the whole, the results indicate that the formation of controlled heterojunctions with the use of hydrothermal synthesis can prove to be an efficient approach to improving the photocatalytic properties of the ZnO-based systems in the visible-light range. The nanocomposite of CuO-ZnO that has been developed in the present paper has solved some of the major drawbacks related to pure ZnO, such as low absorption in the visible light and high recombination rate. The benefits of these gains reveal the prospective use of CuO-ZnO heterojunction nanocomposites in solar-driven wastewater treatment and environmental remediation.

6. Conclusion

This research paper has managed to synthesize CuO-ZnO nanocomposites through a hydrothermal approach and critically assessed it in removing organic pollution under the light of the visible spectrum using photocatalysis. The results of structural and morphological analyses were obtained to prove the presence of high-crystallized Cuo and ZnO phases with close interfacial interactions and the formation of the necessary p-n heterojunction. Optical characterization showed an improvement in visible-light absorption and effective bandgap energy in the CuO-ZnO nanocomposite over the pristine ZnO.

The performance assessment of the photocatalytic behavior revealed that the CuO-ZnO nanocomposite shows a much higher performance on the degradation efficiency in the presence of visible light irradiation. The main factor credited to this improvement is the ability to separate charges effectively, as well as inhibition of the electron-hole recombination caused by the inner electric field at the interface of the CuO-ZnO heterojunction. Kinetic analysis also supported the existence of higher degradation rates of nanocomposite, which points to the presence of better use of charge carriers.

Reusability experiments revealed that the CuO-ZnO nanocomposite was repeated in the number of cycles retaining photocatalytic activity showing that the structure was structurally stable and resisted photocorrosion. These findings indicate that hydrothermal CuO-ZnO heterojunction nanocomposites synthesis is a potential and scalable strategy to produce visible-light-active photocatalysts.

In all, this study gives an understanding of the application of heterojunction engineering in improving the photocatalytic properties of ZnO based materials and shows that the CuO-ZnO nanocomposites can find a future application in solar-driven wastewater treatment and environmental cleanup.

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