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MORALITY BEFORE KNOWLEDGE

Green synthesis of ZnO-Silica composite from bamboo husk and its application for the photodegradation of direct blue 86 dye

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ABSTRACT
Background: The textile industry in Indonesia is rapidly growing, contributing to increasing synthetic dye waste, particularly Direct Blue 86 (DB-86), which is toxic and resistant to natural degradation. This study aims to develop an eco-friendly composite of ZnO-Silica through green synthesis using bamboo peel and *Ketapang* leaf extract for the photodegradation of DB-86. **Methods**: This study employs a literature review method to collect, analyze, and synthesize scientific data on the green synthesis of ZnO-silica composites from bamboo peel and their application in the photodegradation of Direct Blue 86 dye. Data were obtained from recent scholarly sources and analyzed through comparative synthesis and interpretation to evaluate the efficiency and potential of the materials in wastewater treatment. **Findings:** The findings of this study reveal that ZnO-silica composites synthesized via green synthesis using *Ketapang* leaf extract and bamboo peel-derived silica demonstrated high photocatalytic efficiency in degrading Direct Blue 86. Using the sol-gel method, the composite achieved a degradation efficiency of up to 99.10%. The optimal conditions included a catalyst dosage of 10 mg, dye concentration of 10 mg/L, and extended irradiation time. Compared to other catalysts like TiO_2 and MgO, the ZnO-silica composite showed competitive performance with lower required dosage and comparable degradation rates. **Conclusion**: The study concludes that bamboo peel, with its high silica content (98.31%), and ZnO derived from *Ketapang* leaves are effective and eco-friendly materials for the photodegradation of Direct Blue 86 dye, especially when synthesized using the sol-gel method with up to 99.10% efficiency. **Novelty/Originality of this article:** The novelty of this article lies in the innovative use of bamboo peel-derived silica and *Ketapang* leaf extract in a green synthesis approach to produce ZnO-silica composites for degrading Direct Blue 86 dye.

KEYWORDS: direct blue 86; environmental pollution; green synthesis; photocatalytic degradation; ZnO–silica.

1. Introduction

The textile industry in Indonesia has experienced rapid growth, with fluctuating increases in the number of workers, export prices, and local production costs. In March 2023, textile exports rose by 16.87% compared to the previous month (Purwanto, 2024). In addition to textiles, industries such as paper, printing, leather, pharmaceuticals, cosmetics, and food also utilize synthetic dyes, with approximately 10,000 types and over 800,000 tons produced globally each year. Therefore, research on effective and economical waste treatment methods has become essential in mitigating these impacts.

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Direct Blue 86 (DB-86) is a commonly detected dye in textile industry wastewater. It is toxic, carcinogenic, and capable of polluting aquatic ecosystems with its vivid color, even at low concentrations (<1 ppm). DB-86 is highly resistant to natural degradation, as it is an organic molecule that withstands heat, light, and aerobic digestion processes, thus requiring specific treatment methods (Hassaan et al., 2017). One effective approach is photodegradation, which utilizes photocatalytic processes to break down dye molecules into simpler, harmless components.

Zinc oxide (ZnO) composite is one of the substances that can be used to degrade the dye Direct Blue 86 (DB-86). ZnO exhibits excellent photocatalytic properties when exposed to UV light due to its high reactivity in breaking down complex organic compounds such as synthetic dyes. ZnO works by generating OH and O_2^- radicals that can break the azo bonds (–N=N–) in synthetic dyes, thereby decomposing DB-86 molecules into much simpler and non-toxic compounds such as CO_2 and H_2O. In addition, ZnO has semiconductor properties with a band gap energy of approximately 3.3 eV, allowing it to efficiently absorb UV light. The use of ZnO composites in degrading DB-86 dye can be enhanced by combining them with other materials such as silicon dioxide (SiO_2) to improve efficiency, stability, and reduce side effects during the photodegradation process. Silica serves as a support material to immobilize the ZnO catalyst. Due to its uniform distribution characteristics, silica enhances photocatalytic performance, and when combined with ZnO, it also increases the overall surface area.

Synthesis of ZnO–Silica composites has been widely conducted using various methods, including solvothermal, hydrothermal, precipitation, and sol-gel techniques (Truong et al., 2023). However, some of these methods have shown limitations such as the production of less stable and inefficient composites. Therefore, in this study, the authors propose the use of green synthesis in the hope of producing ZnO–Silica composites that are more stable and environmentally friendly.

Plant extracts offer an environmentally friendly alternative for composite synthesis through the green synthesis method, utilizing secondary metabolites as capping agents to produce composites with high stability, low toxicity, and excellent biocompatibility (Tjiang et al., 2019). Agricultural waste such as bamboo, rice husk, and sugarcane bagasse is often used due to its high carbon and silica content after combustion. In this study, bamboo husk is utilized as a precursor for silica synthesis based on a green synthesis approach (Kamboj et al., 2024). Additionally, *Ketapang* leaf extract (*Terminalia catappa*), which is rich in flavonoids and tannins, can act as both a reducing and stabilizing agent in ZnO synthesis. Mixing zinc-based solutions such as $Zn(NO_3)_2$ with *Ketapang* leaf extract followed by heating leads to the formation of ZnO (Hariani et al., 2024).

Based on this background, the present study focuses on the green synthesis of ZnO–Silica composites from bamboo husk and their application in the photodegradation of Direct Blue 86 dye. The synthesized composite materials will be characterized using instruments such as X-Ray Diffraction (XRD), Scanning Electron Microscope–Energy Dispersive X-Ray Spectrometry (SEM–EDX), Vibrating Sample Magnetometer (VSM), Ultraviolet–Visible Diffuse Reflectance Spectroscopy (UV–Vis DRS), and Fourier Transform Infrared Spectroscopy (FTIR). Several variables, including catalyst dosage, dye concentration, and irradiation time, will be analyzed to determine the optimal conditions for degradation, along with the evaluation of the degradation rate. The effectiveness of the ZnO/Silica composite in facilitating the photocatalytic degradation of Direct Blue 86 will be assessed using Total Organic Carbon (TOC) analysis.

The photodegradation process is an effective method for reducing organic pollutants such as dyes in wastewater. In this study, ZnO–Silica synthesized via green synthesis from bamboo husk was used to degrade the Direct Blue 86 dye. However, the degradation efficiency is influenced by several key factors, including catalyst dosage, dye concentration, and irradiation time. Therefore, research is needed to determine how variations in each parameter affect the efficiency of the photodegradation process. In addition, a literature-based analysis is essential to assess whether ZnO–Silica exhibits significant performance in degrading Direct Blue 86 compared to other similar catalysts. To address this issue, various catalyst dosages are tested to determine the optimal amount, a range of dye concentrations is applied to identify the threshold of effectiveness, and different irradiation times are used to determine the ideal duration for degradation. The experimental results are then compared with data from the literature to comprehensively evaluate the performance of the ZnO–Silica composite.

1.1 Green synthesis

Green synthesis is one of the widely used methods for synthesizing nanoparticles by utilizing natural materials, such as plant extracts (Kojong et al., 2018). Green synthesis can be carried out in various ways, one of which involves replacing hazardous reagents with natural sources to produce environmentally friendly nanoparticles. In nanoparticle production using plant extracts, the extract is mixed with a metal salt solution at room temperature, and the reaction typically occurs within a few minutes (Nabila et al., 2022). This method is considered environmentally friendly due to its ability to reduce or eliminate the reliance on toxic inorganic substances. Moreover, green synthesis is effective in minimizing the generation of toxic waste during the synthesis process, thereby providing a positive impact on the environment. The use of plant extracts in green synthesis is also highly economical, as it utilizes the secondary metabolites present in the extracts. These secondary metabolites function as both reducing agents and stabilizers during the synthesis process (Tjiang et al., 2019).

1.2 ZnO composite from Ketapang (Terminalia catappa)

A composite is defined as a combination formed between two or more materials that differ in shape, composition, and chemical properties. The constituent materials do not dissolve into one another, as they are separated into reinforcing materials and binding materials to maintain structural integrity (Pamungkas et al., 2021). One type of composite that is currently gaining attention due to its environmentally friendly nature, natural degradability, and low cost is the natural fiber-based composite. One such natural material that can be used as a fiber-based composite is *Ketapang* (*Terminalia catappa*) leaf. In addition to being eco-friendly, *Ketapang* leaves are also easily found in surrounding environments.

ZnO is a widely utilized material in various products and applications. ZnO nanoparticles are considered among the most promising materials in both industrial and scientific applications due to their wide band gap and high exciton binding energy. Advances in chemistry have led to the development of several environmentally friendly methods for ZnO synthesis, including the synthesis of ZnO nanoparticles using *Ketapang* leaf extract (Sari et al., 2023). This green synthesis method offers great potential for the development of optical biosensors. The superior optical properties of ZnO support efficient optical absorption and emission, photoluminescence, and chemiluminescence. ZnO stands out due to its high electron mobility, strong exciton binding energy, wide band gap, and high optical transmittance, making it highly suitable for sensor fabrication applications (Jayachandran et al., 2021).

1.3 Silica composite from bamboo (bambusa sp.)

Silica is a material commonly found in rocks and sand. It is generally used as a raw material in various industrial processes. In nature, silica exists in a crystalline structure, which, when synthesized, forms an amorphous structure. Silica can also be found in organic materials, such as bamboo leaves. The silica content in bamboo leaves ranges from approximately 75% to 90% (Martiana et al., 2022). The high silica content in bamboo makes it a potential source of biosilica through silica extraction. Several methods can be used to synthesize silica from bamboo leaves, including sol-gel, fusion, calcination, ultrasonic, and co-precipitation techniques. The sol-gel method has been reported to yield up to 87.02%

silica from bamboo leaves (Hamawi et al., 2023). The extraction of bamboo leaves results in a yellowish-brown solution containing sodium silicate (Na_2SiO_3). The reaction involving SiO_2 occurs due to the high electronegativity of oxygen atoms, making the silicon atoms more electropositive. This leads to the formation of an unstable intermediate compound, SiO_2OH^-. The dehydrogenation process and the bonding of hydroxyl ions with hydrogen produce water, while two nitronium ions are used to balance the negative charges that interact with SiO_3^{2-}, resulting in the formation of Na_2SiO_3 (Precelia et al., 2018).

1.4 Photodegradation and its applications

Photodegradation is a method capable of breaking down organic dye compounds using UV light and environmentally benign catalysts, resulting in simpler, non-toxic compounds. A photocatalyst is one type of catalyst used in the photodegradation process. Catalysts can accelerate chemical reactions with the assistance of UV light. Semiconductor materials are essential in the photodegradation process due to their ability to facilitate such reactions. Two main factors influence the activity of photocatalysts: band gap energy and the combination of electron–hole pairs. Photodegradation can be applied to treat liquid waste in the textile industry, offering a relatively new, effective, and efficient alternative for wastewater management (Zakinah et al., 2024). However, semiconductor photocatalysts also have limitations, such as low utilization of visible light, wide band gaps, and high electron recombination rates. Therefore, various elements—such as noble metals, transition metals, non-metals, and metalloids—are incorporated into photocatalysts to enhance photodegradation performance (Syoufian & Kurniawan, 2023).

1.5 Direct blue 86 dye

Dyes, including Direct Blue 86, pose serious threats to human health and the environment due to their carcinogenic, mutagenic, and toxic properties. Direct Blue 86 is widely used in the textile industry, as well as in silk dyeing, paper, and plastics, with usage distribution of approximately 60% in textiles, 10% in paper, and 10% in plastics (Garg et al., 2019). This compound has the molecular formula $C_{32}H_{14}CuN_8Na_2O_6S_2$ and a molecular weight of 780.17 g/mol. It belongs to the azo dye group, which is difficult to degrade naturally due to the presence of azo bonds (–N=N–). Direct Blue 86 has a water solubility of 40 g/L at 60ºC and 80 g/L at 97ºC. It appears as a blue-colored dye with a minimum absorption wavelength of 594 nm and a color index number of 18820 (Hassaan et al., 2017). Due to its widespread use and environmental impact, Direct Blue 86 has become a major concern, highlighting the urgent need for effective wastewater treatment methods.

2. Methods

2.1 Research method

This scientific paper employs a literature review method to collect, analyze, and synthesize relevant information from various scientific sources related to the synthesis of ZnO–silica composites from bamboo husk and their application in the photodegradation of Direct Blue 86 dye. This approach aims to provide a comprehensive understanding of the potential use of green materials in industrial wastewater treatment. The primary focus of this study is to review the extraction process of silica from bamboo husk using environmentally friendly methods. In addition, the paper analyzes techniques for synthesizing ZnO–silica composites based on relevant literature and evaluates their efficiency in the photodegradation of Direct Blue 86 dye using available data. Furthermore, the discussion is directed toward exploring the potential applications of these materials in textile wastewater treatment.

2.2 Data collection

For data collection, this study relies on secondary data obtained from national and international journal articles published within the last 10 years, conference proceedings, textbooks, and research reports related to ZnO–silica synthesis and its application in photodegradation. These data were collected from various scientific databases, including Google Scholar, ScienceDirect, Springer, and ResearchGate. The data search was conducted using keywords such as: "ZnO–silica composites," "bamboo waste," "green synthesis," "Direct Blue 86 degradation," and "environmental photocatalysis." Data selection was based on relevance to the topic, clarity of methodology, and data recency.

2.3 Data analysis

Data analysis was carried out through several stages, including synthesizing information by comparing findings from different sources to identify similarities and differences in research methods and results. This was followed by interpreting the findings to draw conclusions about the efficiency, potential, and challenges of ZnO–silica composite applications in wastewater treatment. Thus, the results of this literature review are expected to provide a comprehensive overview of the synthesis of green materials derived from biomass waste. Moreover, the findings aim to inspire further research to develop eco-friendly materials and offer recommendations for the textile industry in adopting photocatalytic technology for liquid waste treatment.

3. Results and Discussion

3.1 The potential of green synthesis of bamboo husk as a silica source

Bamboo is a widely grown plant in Indonesia and offers various benefits. In addition to the stem, other parts of the bamboo plant, such as the leaves and husk, also hold significant potential. Bamboo husk contains several components, including silica, cellulose, and lignin, with the husk having a higher silica content compared to other parts of the bamboo. The silica contained in bamboo husk can be extracted and utilized for various applications (Heriyanto et al., 2021). Silica derived from bamboo husk holds great potential for use in green synthesis processes due to its high silica content. A study conducted by Hasri et al. (2020) showed that bamboo husk contains up to 98.31% silica. The synthesis process employs a hydrothermal method, which enables the production of nanosilica with good purity and particle distribution. Moreover, this method is environmentally friendly as it utilizes bamboo husk as the main raw material. A study by Pausa et al. (2015) on the silica content of oil palm shells revealed a silica percentage of 81.3%. Another study conducted by Bahtiar et al. (2021) analyzed the silica content in rice husks and rice straw, with results showing silica percentages of 79.85% and 84.83%, respectively.

Table 1. Comparative data of natural raw materials used

Types of natural raw materials	Silica content (%)
Bamboo husk	98.31%
Palm kernel shell	81.3%
Rice husk	79.85%
Rice straw	84.83%

Based on the table above, the silica content from various sources shows differing percentages. The highest silica percentage is found in bamboo husk, at 98.31%, while the lowest is found in rice husk. This indicates that bamboo husk, with its high purity level, is highly suitable for application in various industrial processes, one of which is dye photodegradation—such as in the degradation of Direct Blue 86. This dye is commonly used in the textile industry and can cause environmental pollution if not properly treated.

Therefore, the use of silica derived from bamboo husk in the photodegradation process presents a highly appropriate solution, as it not only provides effective results in reducing dye contamination but is also environmentally friendly and sustainable.

3.2 The potential of green synthesis of ketapang (Terminalia catappa) leaves as a ZnO source

Gonçalves et al. (2021) stated that green synthesis has become a major focus in the past decade due to the increasing depletion of natural resources. This approach offers a sustainable solution that minimizes negative environmental impacts through the production of nanomaterials and composites with wide-ranging applications across various sectors, including medicine, energy, industrial dye photodegradation, and food. In recent years, green synthesis has garnered significant attention for its ability to produce nanoparticles using environmentally friendly materials such as plant extracts, fruits, flowers, algae, yeast, bacteria, and fungi. Compared to other methods, the use of plant extracts has proven to be more efficient for nanoparticle synthesis, even on a large scale.

Semiconductor metal oxide nanostructures—particularly zinc oxide (ZnO) composites—play a vital role in various applications, especially in the photodegradation of organic compounds in industry. This is attributed to ZnO's unique properties, such as a high surface area-to-volume ratio, enhanced chemical reactivity, and superior electronic and physical characteristics. ZnO is an n-type semiconductor with a wide band gap (3.37 eV at 300 K), making it a versatile material for a wide range of critical applications due to its adjustable shape, size, and conductivity. Figure 1 summarizes the approaches and applications of ZnO green synthesis, highlighting the great potential of this method in producing environmentally friendly and efficient materials.

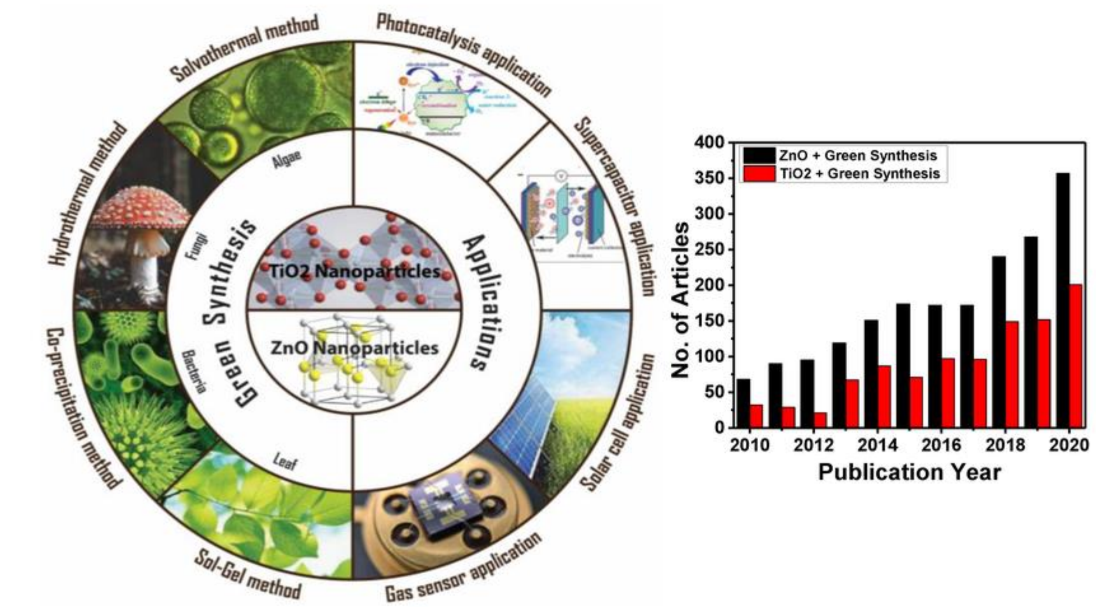

Fig. 1. Schematic illustration of the green synthesis approach for ZnO and TiO_2 nanoparticles (NPs) and their applications

In this study, Terminalia catappa *(Ketapang*) leaf extract will be used as a source for synthesizing ZnO nanoparticles. Terminalia catappa leaves have significant potential as a source for ZnO (zinc oxide) nanoparticle synthesis. In a study by Davadiga et al. (2017), *T. catappa* leaves were utilized to synthesize silver nanoparticles, and the results indicated that these leaves are rich in secondary metabolites such as flavonoids, saponins, tannins, and other phenolic compounds with strong antioxidant activity. These bioactive compounds enable the leaves to function as effective bioreductants in reducing metal ions into nanoparticles, as well as stabilizing agents that support the formation of nanoparticles with well-distributed particle sizes. Moreover, research has shown that *T. catappa* leaf extract can be used to produce nanoparticles with small sizes and specific morphological characteristics. In photocatalytic applications, for instance, ZnO-based nanoparticles synthesized from *T. catappa* leaves have demonstrated potential for degrading dyes such as Direct Blue 86. This effectiveness is attributed to the high surface area of ZnO, which enhances its chemical reactivity and photocatalytic performance.

3.3 Green synthesis process of ZnO/silica composite

The synthesis of ZnO/Silica composites has been widely investigated due to their potential as photocatalysts in the degradation of organic pollutants and liquid waste. This potential makes ZnO/Silica a highly promising material for wastewater treatment applications, particularly in addressing water pollution caused by hazardous organic compounds. Among the commonly used methods for synthesizing ZnO/Silica composites are the sol-gel and precipitation methods. Silica is one of the most commonly synthesized materials at the nanoscale due to its favorable properties for various applications, such as the fabrication of ZnO/Silica nanocomposites. The sol-gel method for silica synthesis is considered relatively simple and efficient. This method operates at low temperatures and produces silica gel with higher purity compared to conventional methods (Budiharti & Supardi, 2015).

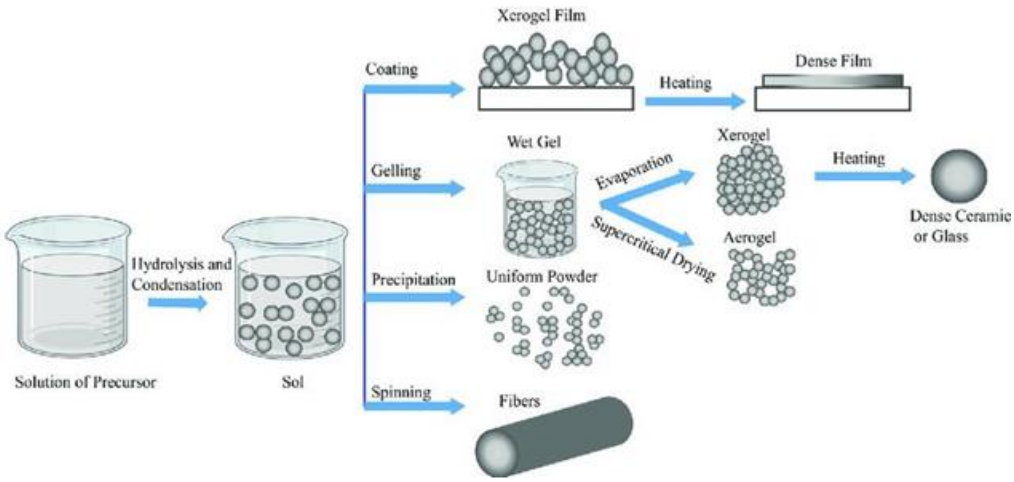

Fig. 2. Schematic diagram of the sol-gel method
(Aboualigaledari & Rahmani, 2021)

Nainggolan et al. (2023) conducted a study on the synthesis of ZnO/Silica photocatalysts using the sol-gel method, applied to the photodegradation of Rhodamine B dye. Characterization using X-ray diffraction (XRD) revealed that the synthesized material had crystal sizes ranging from 15.51 to 82.71 nm with a wurtzite or hexagonal structure, which is a typical crystalline form of ZnO. Optimal photodegradation occurred at pH 6 with an irradiation time of 3 hours, achieving a degradation efficiency of 99.10%. This study demonstrates that the synthesized ZnO/Silica composite possesses excellent potential in photocatalytic applications for dye degradation and plays an important role in the treatment of textile industrial wastewater. The precipitation method is also widely employed in the synthesis of ZnO/Silica composites for photocatalytic applications. This method is favored for its ability to produce materials with small particle sizes and uniform particle size distribution, which are key factors in enhancing photocatalytic efficiency. In the precipitation method, precursor compounds containing key elements, such as silica (SiO_2), are dissolved in suitable solvents and subsequently processed under specific conditions—such as changes in pH, temperature, and concentration—to precipitate the desired material.

A study conducted by Sunardi and Silviana (2022) focused on the synthesis of ZnO–Silica nanocomposites and their application for the photodegradation of Rhodamine B dye.

The results showed that the resulting ZnO–Silica nanocomposite achieved a very high degradation efficiency of up to 95.8690%. This value indicates that the composite is highly effective in reducing contaminant concentrations in wastewater. The high degradation efficiency makes ZnO–Silica nanocomposites highly promising for application in industrial wastewater treatment, particularly in the textile industry, which frequently generates dye-laden and chemically hazardous effluents.

Table 2. Efficiency comparison between sol-gel and precipitation methods

Method	Degradation percentage
Sol gel	99.10%
Precipitation	95.8690%

The table above presents a comparison of degradation efficiency levels using two synthesis methods: the sol-gel method and the precipitation method, applied to ZnO–Silica composites. The sol-gel method achieved a degradation efficiency of 99.10%, while the precipitation method resulted in an efficiency of 95.8690%. Based on this analysis, it can be concluded that both methods—sol-gel and precipitation—are highly suitable and efficient for use in green synthesis processes, as they employ environmentally friendly materials and produce high degradation efficiencies. These results support the principles of sustainability in the treatment of textile industrial wastewater.

3.4 Application of ZnO–silica composite in the photodegradation of direct blue 86 dye

According to a study conducted by Hassaan et al. (2017), ZnO–Silica composites synthesized through green synthesis methods show great potential in degrading azo compounds such as Direct Blue 86 via photocatalysis. The study demonstrated that ozonation, particularly when combined with UV radiation, could degrade up to 98% of Direct Blue 86 within 35 minutes at pH 11 and an initial concentration of 100 ppm. This successful degradation indicates that azo dye molecules can be effectively broken down through advanced oxidation processes that generate hydroxyl radicals with high oxidative potential. In the context of ZnO–Silica composites, silica acts as a support material to reduce the agglomeration of ZnO nanoparticles, thereby enhancing the stability of the material. Research by Agustina et al. (2022) showed that the use of ZnO–silica aerogels as photocatalysts achieved degradation efficiencies of up to 96% for methylene blue, providing strong evidence that the combination of ZnO and silica offers a synergistic effect in photocatalytic applications. Other studies have also noted that the degradation process of azo dyes such as Direct Blue 86 can be further optimized by adjusting pH, catalyst dosage, irradiation time, and initial dye concentration.

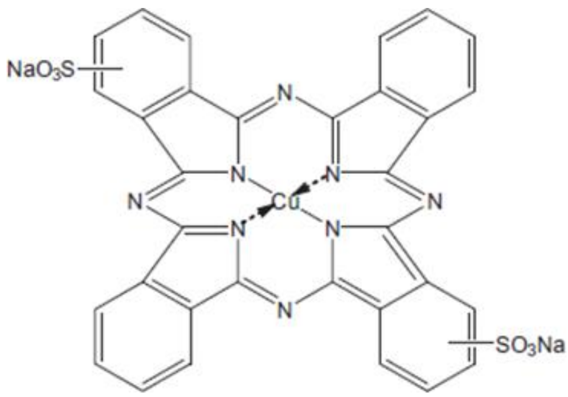

Fig. 3. Chemical structure of direct blue 86 dye

The effectiveness of photocatalysts is influenced by several key parameters, including pH, irradiation duration, catalyst dosage, and the initial dye concentration. This study will evaluate various literature sources that examine the impact of these parameters in order to identify the most effective composite for degrading Direct Blue 86. During the photodegradation process of Direct Blue 86 into simpler compounds, specific mechanisms are involved. Furthermore, the efficiency of the photocatalytic degradation of Direct Blue 86 is also determined by several key parameters that encompass the overall reaction conditions.

3.4.1 Photodegradation mechanism

First, the mechanism of photodegradation. Photodegradation is a process by which compounds, such as organic substances, are broken down with the assistance of light or photons. Photocatalysis is a preferred method due to its environmentally friendly nature. In its reaction, photocatalysis involves hydrogen as a catalyst that absorbs light and interacts with the reactants in either the liquid or gas phase (Chiu et al., 2019).

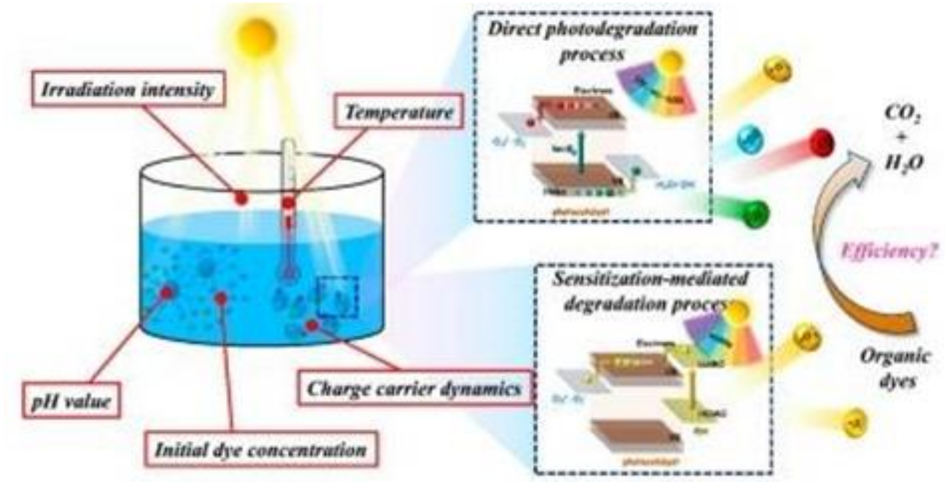

Fig. 4. Photodegradation process of organic dyes using semiconductor photocatalysts

Photocatalysis occurs through the activation of oxide catalysts by photons with energy equal to or greater than the band-gap energy of the catalyst. This process leads to charge separation, in which electrons from the valence band are excited to the conduction band, leaving behind positive holes (H^+) in the valence band. The excited electrons can either reduce dye molecules or react with adsorbed oxygen to form superoxide radical anions (O_2^-). Meanwhile, the holes can generate hydroxyl radicals (OH) through reactions with water or hydroxide ions (OH^-). These resulting reactive species are highly potent and capable of decomposing dye molecules (Sugiyana & Notodarmojo, 2015).

3.4.2 Photodegradation efficiency of direct blue 86

The photodegradation of Direct Blue 86 is a process that involves the degradation of organic compounds using a photocatalyst under specific light exposure, such as UV or visible light. The efficiency of this process is influenced by several factors, including the solution pH, catalyst dosage, irradiation time, and initial dye concentration. Evaluating photodegradation efficiency aims to determine the optimal conditions that yield the highest degradation rate. These parameters not only play a key role in enhancing the performance of the photocatalyst but also ensure that the degradation process is efficient and environmentally friendly. The following is a summary of photodegradation efficiency data for Direct Blue 86 based on various studied parameters. According to the study conducted by Davar et al. (2015), the photodegradation efficiency of Direct Blue 86 can be determined by calculating the percentage of photocatalytic degradation performed by the ZnO–Silica composite against the Direct Blue 86 dye, as follows:

$$Degradation\ (\%) = \frac{C_0 - C_t}{C_0} x100\% = \frac{A_0 - A_t}{A_0} x100\% \quad \text{(Eq. 1)}$$

where C_0 is the initial dye concentration, C_t is the dye concentration at a given reaction time (t), A_0 is the initial absorbance of the dye solution, and A_t is the absorbance at a specific reaction time. Based on this formulation, it can be concluded that the key factors influencing photodegradation are dye concentration, irradiation time, and catalyst dosage. From the literature review conducted, experimental data were obtained regarding catalyst dosage, dye concentration, and irradiation time tested on various catalysts, including those doped with SiO_2 (silica). In addition, differences in the reaction rate constant (k), expressed in min^{-1}, were observed among the different catalysts. These data will be used as a comparative basis to evaluate the photodegradation efficiency of Direct Blue 86 dye.

Table 3. Comparative data of catalysts used in the photodegradation efficiency of direct blue 86

Catalyst Doping/ SiO_2	Catalyst Dose (grams)	Dye Concentra -tion (g/L)	Irradi-ation Time	% Degradation Efficiency	k (min^{-1})	Notes
TiO_2	0,3 g	10 g/L	90 minutes	(50-87,7)%	0,94 min^{-1}	Dong et al. (2015) stated in their study that the TiO_2/SiO_2 nanoparticle composite with the best performance in degrading dyes was the $80TiO_2$–$20SiO_2$-900 formulation.
ZnO	0,406 g	10 g/L	90 minutes	55,43%	0,00856 min^{-1}	Sutanto et al. (2015) conducted a study using a double-layer ZnO catalyst doped with varying concentrations of silver (Ag) at 2%, 4%, 6%, and 8%. The 6% Ag doping showed a relatively high degradation efficiency in degrading dye compounds.
MgO	10 mg	100 mg/L	90 minutes	99,83%	0.0286	Zheng et al. (2019) employed MgO nanoparticles to degrade dyes, with dye concentrations ranging from 25, 50, 100, 200, to 500 mg/L. The study found that the higher the dye concentration, the lower the degradation efficiency.

Dong et al. (2015) conducted a study on the degradation of several cationic and anionic dyes using nanoparticle composites derived from TiO_2 doped with SiO_2. In this research, both the types of dyes and the compositions of the composites were varied. The dyes used included Methylene Blue (MB), Safranin O (SO), Crystal Violet (CV), Brilliant Green (BG), Basic Fuchsin (BF), Rhodamine-6G (Rh6G), Acid Fuchsin (AF), Orange II (OII), and Acid Red 1 (AR1). The composite variations employed in the study included TiO_2/SiO_2, $80TiO_2$–$20SiO_2$-900, and SiO_2-600.

During the reaction, SiO_2 nanoparticles play a crucial role in adsorbing dye molecules from the solution. This adsorption occurs through electrostatic interactions between the surface Si–O$^-$ groups on the nanoparticles and the positively charged parts of the dye molecules. Once adsorbed, the dye molecules rapidly diffuse into the mesoporous surface, making the SiO_2 nanoparticles rich in dye content. Meanwhile, hydroxyl radicals (OH) generated by the TiO_2 nanocrystals begin attacking the adsorbed dye molecules. These attacks occur from various directions, leading to the breakdown of the dye molecules into smaller fragments, which are then converted into end products such as CO_2, H_2O, and other compounds. These degradation products subsequently diffuse out from the pores into the solution.

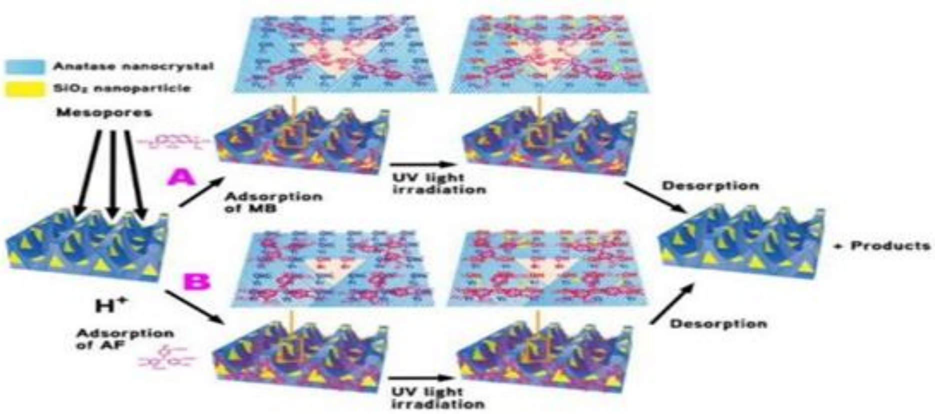

Fig. 5. Schematic of TiO_2/SiO_2 composite in dye degradation

In the TiO_2/SiO_2 mesoporous composites, the SiO_2 nanoparticles possess the ability to regenerate their adsorption capacity automatically, thanks to the synergistic interaction with surrounding TiO_2 nanocrystals. SiO_2 immediately re-adsorbs dye molecules from the solution, while the TiO_2 nanocrystals oxidize the adsorbed dyes. This synergistic process continues cyclically, significantly enhancing the utilization efficiency of the •OH radicals. As a result, the photocatalytic activity of the composite exhibits excellent performance. The mesoporous $80TiO_2$–$20SiO_2$-900 composite demonstrated outstanding performance with a degradation efficiency ranging from 50% to 80% against all types of cationic dyes. This advantage is attributed to the synergy between the integrated adsorption process and photocatalytic oxidation.

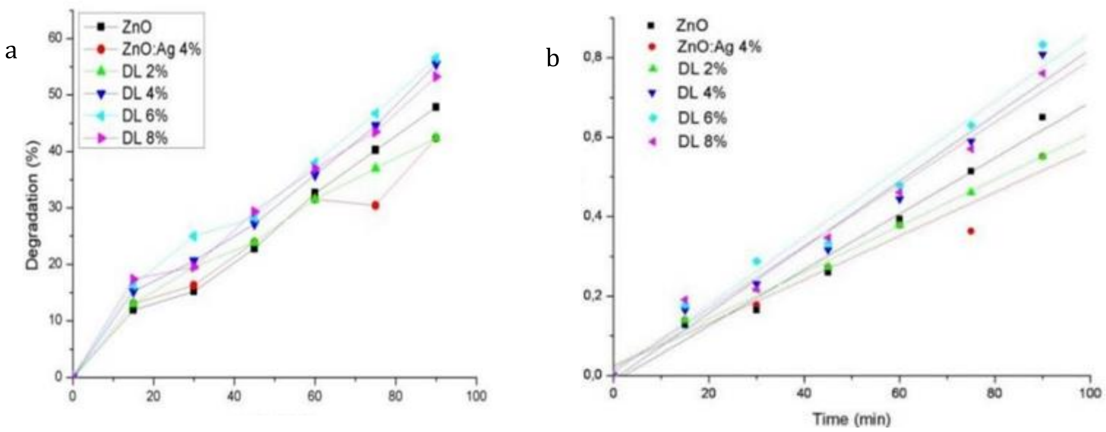

Fig. 6. (a) Photocatalytic degradation of ZnO/ZnO in dye removal, (b) Reaction rate of ZnO composite in dye degradation

Sutanto et al. (2015), in their study, utilized a double-layer composite consisting of ZnO. The ZnO was doped with silver (Ag) and varied with different doping concentrations, namely 2%, 4%, 6%, and 8%. With each increase in the doping level, the composite dosage also increased, resulting in enhanced performance of the composite in degrading dye compounds. This was evidenced by the highest degradation efficiency obtained at the 6% Ag-doped ZnO composite, which achieved a degradation rate of more than 50%.

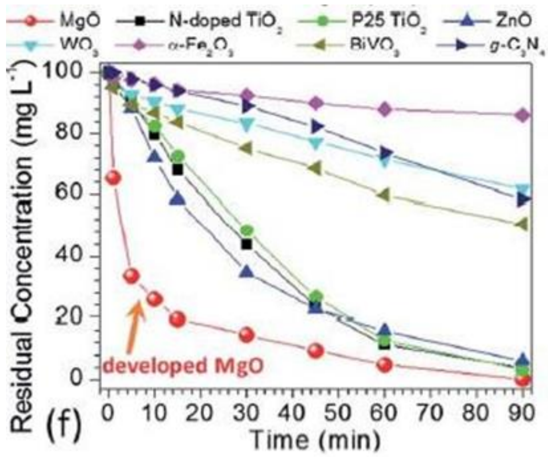

Fig. 7. Dye degradation at dye concentration of 100 g/L
(Zheng et al., 2019)

Zheng et al. (2019), in their study, utilized MgO nanoparticle composites to degrade dye compounds. The dye concentrations used varied at 25, 50, 100, 200, and 500 ppm. The research focused on investigating the effect of dye concentration on photocatalytic degradation using MgO composites, while keeping the composite dosage constant at 10 mg. The study successfully demonstrated that as the dye concentration increases while maintaining a constant composite dosage, the degradation efficiency decreases. However, when both the composite dosage and irradiation time are increased, the degradation efficiency improves accordingly. This finding is supported by the following data:

Table 4. Degradation efficiency data of MgO composites

Concentration (mg $^{L-1}$)	*Kf* (min^{-1})	$T_{1/2}$(min)	R^2	Degradation efficiency (%)
25	0.2000	3.47	0.9639	100.00
50	0.1001	6.92	0.9465	100.00
100	0.0286	24.24	0.9501	99.83
200	0.0115	60.27	0.9670	68.35
500	0.0022	315.07	0.9368	18.74

(Zheng et al., 2019)

ZnO exhibits a relatively high reaction rate and photodegradation efficiency even when used in small doses, approximately 0.4 grams. In comparison, MgO requires a significantly larger dose—around 10 grams—to achieve comparable efficiency in dye degradation. Therefore, increasing the ZnO dosage beyond its initial amount is expected to significantly enhance its degradation efficiency. Furthermore, based on previous studies, silica plays an important role as an effective dye adsorbent. This was demonstrated in a study by Dong et al. (2015), which reported that doping TiO_2 with silica resulted in high degradation efficiency, highlighting the synergistic effect between photocatalysis and adsorption in enhancing pollutant removal performance.

First, the effect of irradiation time. Determining the optimal irradiation time aims to identify the duration required for a composite to effectively degrade a large amount of dye (Suprihatin et al., 2021). Generally, the longer the irradiation time, the more molecules are decomposed by photon energy. This process excites electrons from the valence band to the conduction band, generating hydroxyl radicals (OH). The greater the number of hydroxyl radicals, the more dye molecules can be degraded (Sari et al., 2023). Based on table 3, irradiation time significantly influences the efficiency of the photodegradation process of Direct Blue 86 using ZnO-Silica composites. Longer irradiation duration tends to increase degradation efficiency, as it allows sufficient time for the formation of reactive radicals and their interaction with dye molecules. However, this efficiency is also influenced by other factors, such as catalyst dosage and initial dye concentration. Under optimal conditions, extended irradiation enables more complete degradation, resulting in a greater reduction in dye concentration. On the other hand, excessively long irradiation may increase the risk of radical recombination, which can reduce the degradation efficiency. Therefore, determining the optimal irradiation time for each type of catalyst and reaction condition is essential.

Second, the effect of ZnO-Silica composite dosage. The determination of the effect of ZnO-Silica dosage aims to evaluate the impact of varying doses of the composite on dye degradation (Raksun et al., 2020). Increasing the dosage of ZnO-Silica with an adequate concentration can accelerate the breakdown of dye molecules (Paramitha et al., 2023). According to the data presented in table 3, the optimum dosage of ZnO-Silica composite for degrading Direct Blue 86 was found to be 10 mg. A dosage lower than this optimal amount may slow down the degradation performance of the composite. Conversely, an excessive dosage may cause saturation, which can hinder degradation efficiency due to insufficient light to activate all photocatalyst particles. Moreover, an excess of catalyst can block light penetration, reducing light intensity at deeper layers. Hence, precise dosage determination is crucial to optimize dye degradation outcomes.

Third, the effect of dye concentration. The concentration of dye used in the degradation process significantly affects the overall efficiency. A higher dye concentration can reduce the photocatalyst's adsorption capacity, leading to a decrease in the photocatalytic reaction rate (Nainggolan et al., 2023). Therefore, selecting an appropriate dye concentration is essential to achieve optimal degradation performance. Based on table 3, the comparison of dye concentrations illustrates the impact on photodegradation efficiency. Lower dye concentrations tend to result in faster and more efficient degradation. This is because dye molecules are more likely to interact with the photocatalyst surface, and the available reactive radicals are sufficient to decompose the dye molecules in a shorter time, thereby enhancing the overall degradation process.

4. Conclusions

Based on the explanation above, it can be concluded that the silica content found in bamboo husk can be utilized in various sectors. Bamboo contains 98.31% silica, indicating a high level of purity, making bamboo husk highly suitable for use in various industrial applications, including the photodegradation of dyes such as Direct Blue 86. Green synthesis is considered an appropriate method for degrading hazardous organic dyes due to its environmentally friendly nature. ZnO-based nanoparticles derived from *Ketapang* leaves have demonstrated the ability to degrade Direct Blue 86 dye. This is attributed to the large surface area of ZnO, which enhances its chemical activity and photocatalytic capabilities. The synthesis of silica can be performed using two methods: the sol-gel method and the precipitation method. The sol-gel method is widely used because it can produce silica gel with higher purity. The degradation efficiency obtained using the sol-gel method reached up to 99.10%.

Several factors influence the photodegradation process, including dye concentration, irradiation time, and the catalyst dosage used. Dye concentration affects the photodegradation process because higher concentrations of dye can reduce the adsorption capacity of the photocatalyst, resulting in a lower rate of photocatalytic reaction. Irradiation time also plays a role in photodegradation; the longer the exposure time, the more molecules are decomposed by photon energy. The final factor is catalyst dosage, where a higher and adequate dose is recommended to accelerate the degradation of dye compounds. Therefore, for the photodegradation of Direct Blue 86, it is advisable to use a dye concentration of around 10 mg/L, with optimal irradiation time and an appropriate composite dosage of approximately 10 mg.

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