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Abstract

Water security throughout the world is put at risk by the accidental discharge of hazardous and non-biodegradable organic pollutants from manufacturing operations. In order to overcome this challenge, this study proposes and evaluates a zinc oxide (ZnO) nanomaterial derived from metal-organic structures (MOFs) for the solar-driven photocatalytic treatment of industrial effluents. A porous ZnO photocatalyst was developed by producing ZIF-8, an ordinary MOF, and then boiling it. When compared to commercial ZnO, the derived material's improved surface area and visible-light absorption have been established by comprehensive analysis. The rapid degradation of methylene blue dye in natural sunlight, which demonstrated pseudo-first-order kinetics and resulted in over 95% removal in 90 minutes, confirmed its photocatalytic efficiency. Over the course of five consecutive cycles, the catalyst showed outstanding durability and reusability with minimal decrease in performance. Additionally, the material exhibited its practical potential by accomplishing impressive mineralization (65%) and decolorization (80%) when applied to actual sewage from the textile industry. the results of the study, MOF-derived nanomaterials are solid, efficient, and sustainable catalysts for using solar energy in complicated wastewater treatment.

Keywords: MOF-Derived Nanomaterials, Solar Photocatalysis, Industrial Wastewater Treatment, Zinc Oxide (ZnO).

Introduction

Industrial activity presents significant risks to the health of our water systems [1]. Significant quantities of wastewater are discharged into rivers and lakes by manufacturing plants and factories

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all over the world [2]. Apart from to being polluted, this wastewater frequently includes a complex mixture of organic pollutants that are additionally toxic and non-biodegradable [3]. Persistent synthetic dyes, active drug compounds, and resilient pesticides and herbicides originate from the textile industry, pharmaceuticals, and agrochemicals, accordingly [4]. Due to the stability they possess, these substances are very complicated for elimination using either organic methods or traditional treatment approaches [5]. They can harm aquatic life, contaminate sources of drinking water, and pose serious long-term health risks for individuals when released into the environment [6]. One of the primary root causes of this issue is the drawbacks of the wastewater treatment technologies at present in employed. Conventional methods like coagulation, adsorption, and biological treatment usually struggle in combating these advanced industrial chemicals. systematically transforming the pollutants into harmful substances, they could possibly basically physically separate them, resulting in a toxic sludge that needs to be disposed of. There is an immediate demand for advanced, destructive technologies as a result of the substantial disparity between the increasing complexity of industrial waste and the capabilities of the current treatment infrastructure [7].

Advanced Oxidation Processes, or AOPs, have been developed to respond to this need. AOPs are a form of chemical treatment that was developed to deal with the most determined substances [8]. Complete mineralization, or the disintegration of organic molecules into harmless waste products like carbon dioxide and water, is their goal [9]. They achieve this through the creation of powerful, non-selective oxidizing agents, mostly hydroxyl radicals. The intricate chemical structures of dyes, medicinal products, and other substances can be destroyed and dissolved down by these highly reactive radicals. Semiconductor photocatalysis has become one of the greatest promising "green" methods among AOPs. The theory is straightforward: a solid substance designated as a photocatalyst absorbs light energy and uses it for starting chemical reactions that remove pollutants. It functions equivalently to a very small reactor where light energy generates charged particles recognized as electrons and holes, which react with oxygen and water to produce the detoxifying hydroxyl radicals. This technique has an opportunity to purify water using light, a readily accessible and environmentally friendly power source [10].

However, the most common photocatalyst, titanium dioxide (TiO_2), has limited practical use due to significant problems. The need to rely on ultraviolet (UV) light for activation is the primary issue [11]. Only just over one percent of the solar energy that reaches the Earth's surface—about 4–5%—is ultraviolet light [12]. This demonstrates that visible light, which makes up the great majority of sunlight, damages a TiO_2-based system basically ineffective.

likewise, light-generated electrons and holes in TiO_2 and similar materials regularly recombine in a small fraction of a second, releasing their energy as heat instead of using it for pollutant degradation [13]. The process's efficiency is significantly lowered by this quick charge carrier recombination. Finding materials that are capable of controlling electrical charges and capture visible light has consequently become a key focus of the pursuit for a next-generation photocatalyst [13].

Over the past twenty years or so, a class of materials referred to as MOFs has taken hold of the chemistry and materials science industries. They are distinctive due to their structure, which is composed up of porous, crystalline networks formed by metal ions or clusters connected by organic linker molecules. imagine them as molecular sponges that can be specifically

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manufactured and tuned at the atomic level, having equally sized pores and exceptionally high surface areas [14]. For photocatalysis, this tunability is disruptive. The entire framework can be transformed into a programmable semiconductor by scientists by choosing metal clusters and organic linkers that serve as light-harvesting antennas. Multiple active sites for reactions are offered by the massive surface area, and the pores make it straightforward for pollutant molecules to diffuse inside and be destroyed. For a while, pristine MOFs were considered to be photocatalysis's future [15].

Nevertheless, as is the case with many promising materials, practical problems developed. Metal leaching and structural breakdown are caused by the unpredictability of many MOFs in water and the harsh conditions of industrial wastewater. In addition, they might possess low electrical conductivity, which makes charge carrier recombination more severe. despite their design was ideal in theory, they often performed poorly in practical applications [16]. This obstacle prompted a creative change in technique: opposed to utilizing MOFs as direct photocatalysts, investigators began to utilize them as advanced precursors or templates for manufacturing a new class of nanomaterials. The resulting materials, commonly referred to as MOF-derived nanomaterials, are an important breakthrough. A wide range of functional solids, including metal oxides, metal sulfides, porous carbons, or composites in which metal nanoparticles are embedded within a carbon matrix, can be generated from a MOF through this technique [18]. These derivatives develop new, enhanced characteristics while maintaining the structural advantages of their parent MOFs, such as high surface area and interconnected porosity. Their electrical conductivity and chemical stability can frequently be considerably improved by the thermal treatment.

By acquiring electrons from the metal component and substantially decreasing their recombination with holes, the carbon matrix that produces from the organic linkers can function as an extremely efficient electron shuttle. A much more effective photocatalytic system can be developed by the components functioning in equilibrium [19].

Although metal-organic framework (MOF)-derived nanomaterials have a lot of promise for solar-powered water treatment, there remains an enormous gap between the way they work in the lab and how they are employed in the real world. Their efficacy in complex, genuine industrial wastewaters that contain mixed toxins and interfering substances is largely unknown since the vast majority of the research currently available has been concentrated on their use with single pollutants in pure water. Moreover, the synthesis of these materials can be too intricate and costly for widespread implementation, and the fundamental principles that determine their efficacy under solar light are not entirely understood. The primary objectives of the investigation aim to fill in these gaps. Its first goal is to develop, develop, and entirely explain a specific MOF-derived nanocomposite. In order to guide the development of future practical, efficient, and scalable water purification technologies, the second step will be to methodically assess the material's performance and stability in degrading pollutants from both simulated and real industrial effluent under solar irradiation. Furthermore, the underlying mechanism will be examined.

Materials and methods

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All analytical-grade chemicals were used without further purification. Metal precursors such as zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$), 2-methylimidazole ($C_4H_6N_2$), and terephthalic acid (H_2BDC) were purchased from Sigma-Aldrich. Ethanol, methanol, and deionized (DI) water were used as solvents throughout the experiments. Model organic pollutants such as methylene blue (MB) and rhodamine B (RhB) were selected to simulate industrial dye effluents. Real wastewater samples were collected from a textile industry for performance validation.

Synthesis of Metal–Organic Framework (MOF)

A representative MOF, such as ZIF-8 (Zeolitic Imidazolate Framework-8), was synthesized using a simple room temperature method. In a typical synthesis, 2.0 g of zinc nitrate hexahydrate was dissolved in 50 mL of methanol (solution A), and 4.0 g of 2-methylimidazole was dissolved in another 50 mL of methanol (solution B). For sixty minutes, solution B was progressively added to solution A while continually stirring it. For the purpose of getting elimination of unreacted precursors, the white precipitate that produced was centrifuged, aged for 24 hours at room temperature, and subsequently processed three times with methanol. To obtain pure ZIF-8 powder, the product was dried in an oven set to 80 °C for an entire night.

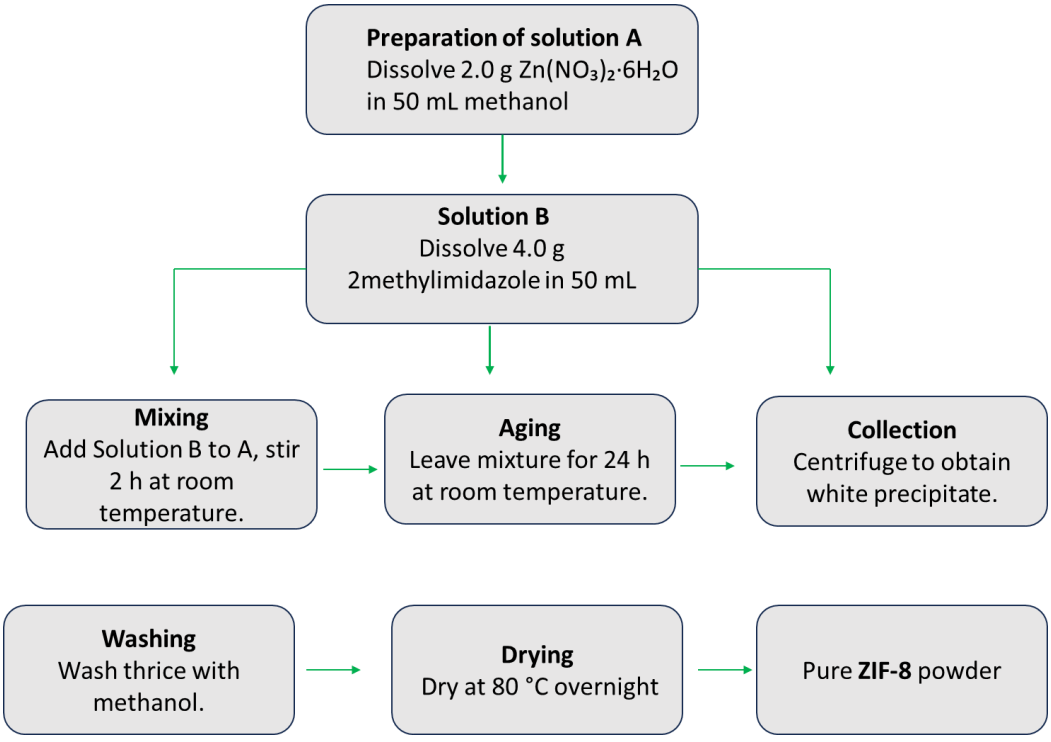

Figure 2.1: A diagrammatic illustration of the ZIF-8 (Zeolitic Imidazolate Framework-8) synthesis process, depicting the various phases of precursor preparation, mixing, aging, washing, and drying resulting in pure ZIF-8 powder.

Characterization techniques

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A broad spectrum of techniques for characterization were used to confirm the engineered materials' structural, morphological, and optical properties. X-ray diffraction (XRD) was employed to determine the crystalline structure. Scanning and Transmission Electron Microscopy (SEM and TEM) were utilized to investigate the morphology, particle size, and porous architecture, while Brunauer–Emmett–Teller (BET) surface area analysis was employed for determining the specific surface area and pore volume. Fourier Transform Infrared Spectroscopy (FTIR) was used to confirm the decomposition of organic linkages and identify functional groups for the purpose to probe the chemical identity. The optical properties were evaluated using photoluminescence (PL) spectroscopy to investigate electron-hole recombination dynamics and UV–Visible Diffuse Reflectance Spectroscopy (UV–Vis DRS) to determine absorption characteristics and band gap energy.

Photocatalytic Activity under Solar Irradiation

On clear days, the MOF-derived nanomaterials' photocatalytic performance was evaluated between 11:00 AM and 2:00 PM in the absence of natural sunlight. A 250 mL glass reactor with 100 mL of dye solution (10 mg/L of methylene blue) was utilized for the experiments. To attain an adsorption–desorption equilibrium, 0.05 g of known catalyst was added, and the suspension was stirred periodically for 30 minutes in the dark.

The suspension was exposed to direct sunlight while constantly being moved following dark equilibration. A UV-Vis spectrophotometer was employed to measure the remaining dye concentration at λ_max = 664 nm after 5 mL of the reaction mixture was measured out at specified times (every 15 minutes) and centrifuged to remove the catalyst. The following formula has been employed for calculating the degradation efficiency (η%):

$$\eta(\%) = \frac{C0 - Ct}{C0} \times 100$$

where C_0 and C_t represent the initial and remaining concentrations of the dye, respectively.

Kinetic Analysis

The photocatalytic degradation kinetics were analyzed using the pseudo-first-order model

$$\ln(c_0|ct) = kt$$

where the apparent rate constant is represented by k (min^{-1}). For every catalyst sample, k has been determined through a plot of In (C0/Ct) =Kt versus time. Systematic research was also done on the consequences on variables like catalyst dosage, pH, initial dye concentration, and sunlight intensity.

Reusability and Stability Tests

Five consecutive photocatalytic cycles were performed for evaluating the photocatalyst's reusability. afterwards each cycle, the catalyst was separated through centrifugation, cleaned with ethanol and deionized water, dried, and then used again under the same laboratory conditions. during the last cycle, XRD and FTIR analyses were conducted out in order to confirm the catalyst's structural stability.

Treatment of Real Industrial Effluents

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The optimized photocatalyst has been evaluated on authentic industrial effluent that originated from a textile dyeing facility in order to evaluate its practical applicability. The same solar photocatalytic conditions were used for separating, dilution and processing the samples. In order to confirm mineralization efficiency, the degradation performance has been assessed using Total Organic Carbon (TOC) analysis and UV-Vis absorbance reduction.

Results and discussion

The X-ray diffraction (XRD) patterns

The fabrication of a pure and crystalline ZIF-8 metal-organic framework (MOF) has been effectively verified by the provided X-ray diffraction (XRD) pattern, marking an important step in the research method of creating solar-driven photocatalysts. Because the unique structure of the MOF precursor directly influences the properties of the final derived nanomaterial, this initial characterization is crucial. We have a phase-pure material with the intended sodalite zeolitic structure, as established by the sharp, well-defined peaks and their perfectly alignment with the simulated pattern. High surface area and a regular, nanoporous network are features unique to this structure that are important to its dual purpose as a sacrificial template and an adsorbent. The verified ZIF-8 framework is a versatile starting point to construct complex photocatalytic systems. Through controlled pyrolysis, its organic linkers can be transformed into a conductive carbon matrix doped with nitrogen, and the zinc metal clusters may be transformed into metal-based active sites such as zinc oxide nanoparticles. As opposed to being limited to ultraviolet light like many traditional photocatalysts, this derivation process seeks to engineer a material with a narrowed band gap, allowing it to absorb a much larger portion of the solar spectrum, particularly visible light. In addition, the close interaction between the catalytic nanoparticles and the carbon matrix, that was inherited from the ZIF-8 precursor's homogeneous structure, makes it easier to distinguish and transfer photogenerated charge carriers (electrons and holes) successfully. It improves the photocatalytic process's quantum efficiency through decreased recombination, which damages the mechanism.

This material design is essential for industrial effluents, which often include a variety of dangerous substances, pharmaceuticals, and organic dyes that are challenging to disintegrate. The high surface area enables the concentration of pollutant molecules near the active sites via adsorption. Then, under solar irradiation, the optimized photocatalyst generates powerful reactive oxygen species (e.g., hydroxyl radicals) that non-selectively and mineralize these adsorbed pollutants into harmless substances like water and carbon dioxide. Thus, this single XRD pattern of the precursor ZIF-8 is the first critical piece of evidence in a chain of characterization that links a well-defined molecular starting point to a high-performance, engineered nanomaterial capable of addressing the significant environmental challenge of industrial wastewater purification.

Zhao et al 2023 demonstrated that a possible alternative to the world's energy crisis and the lack of clean water is solar-driven interfacial evaporation technology. Advanced interfacial evaporation materials assist substantially to the use of solar thermal energy for water purification. This work develops a Cu-catecholate metal–organic framework-based photothermal membrane (Cu-CATM) to recover clean water from wastewater and produce freshwater from seawater. Cu-catecholate metal–organic framework (Cu-CAT MOF) has a promising evaporation rate of 2.43 kg m−2h−1 and a high solar-vapor conversion efficiency of 92% under the ultraviolet rays of 1 sun because of

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its unique photothermal effect and three-dimensional nanosheet array structure. In addition, solar saltwater desalination with a consistent evaporation rate and no salt deposition could be performed employing the Cu-CATM. In addition, the Cu-CATM proved the broader environmental application of photothermal-photocatalytic processes in water remediation or wastewater treatment by rendering the ability to use solar energy for simultaneous photothermal desalination and photocatalytic degradation. This work presents a practical and effective approach for the development of photothermal membranes in order to produce clean water from non-conventional water sources in the future [20].

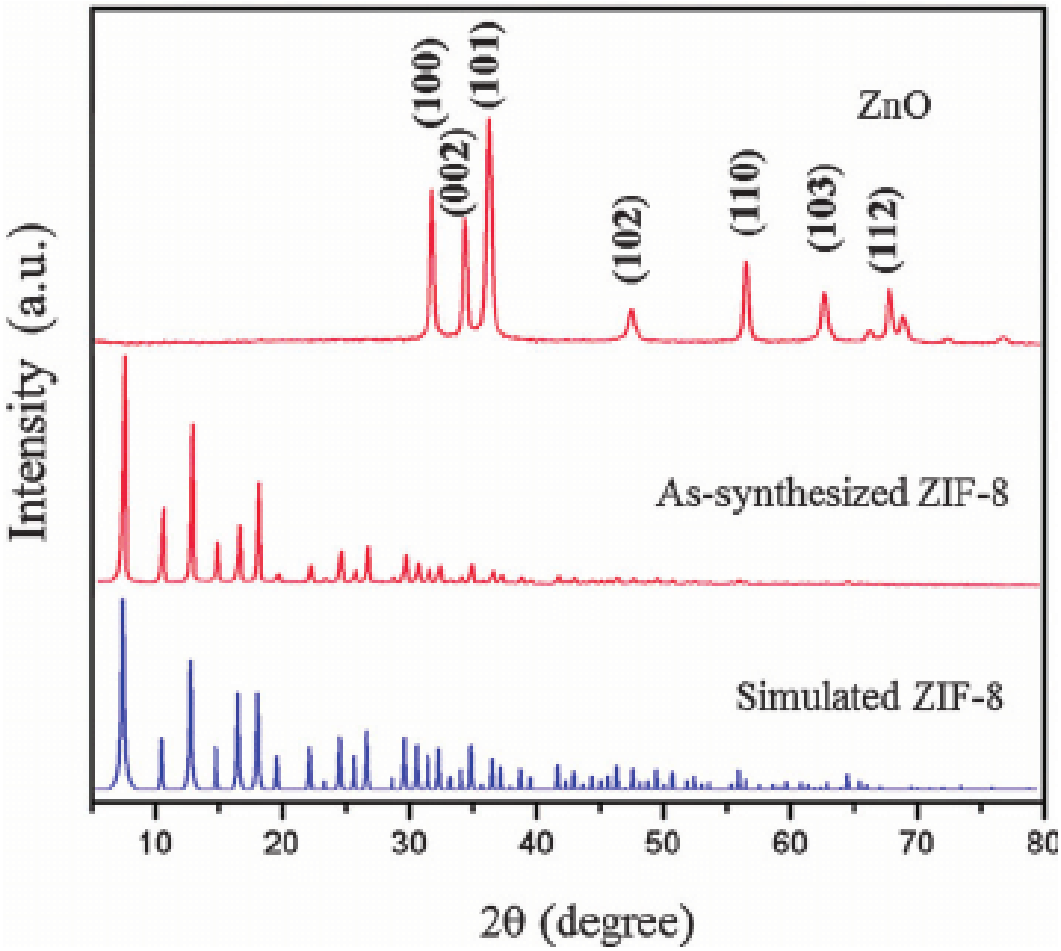

Figure 3.1: ZIF-8's synthetic powder X-ray diffraction (PXRD) patterns were compared to a produced pattern developed from its single-crystal structure. The successful synthesis of a pure and highly crystalline ZIF-8 phase, which is the precursor for later derivation of photocatalytic nanomaterials, is demonstrated by the perfect collaboration.

Scanning Electron Microscopy (SEM)

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The provided scanning electron microscopy (SEM) images reveal the surface morphology and structural features of the metal-organic framework (MOF)-derived nanomaterials, which are directly linked to their function in solar-driven photocatalysis. The micrographs show a collection of well-defined, interconnected particles with a rough and porous surface texture. This morphology is highly advantageous for the photocatalytic treatment of industrial effluents for several key reasons. First, a substantial number of active sites are made readily accessible by the high surface area and nano-scale porosity, which collects the contaminants from the wastewater near to the catalytic centers. Second, the complicated particle boundaries and surface texture are beneficial for solar light harvesting because they can improve light absorption through boosting internal scattering and minimizing light reflection. To be able to guarantee high photocatalytic efficiency and kinetics in the breakdown of complex industrial pollutants, the transport of reactant molecules to the active sites and the subsequent release of degradation products are dependent significantly on the accessible porous network.

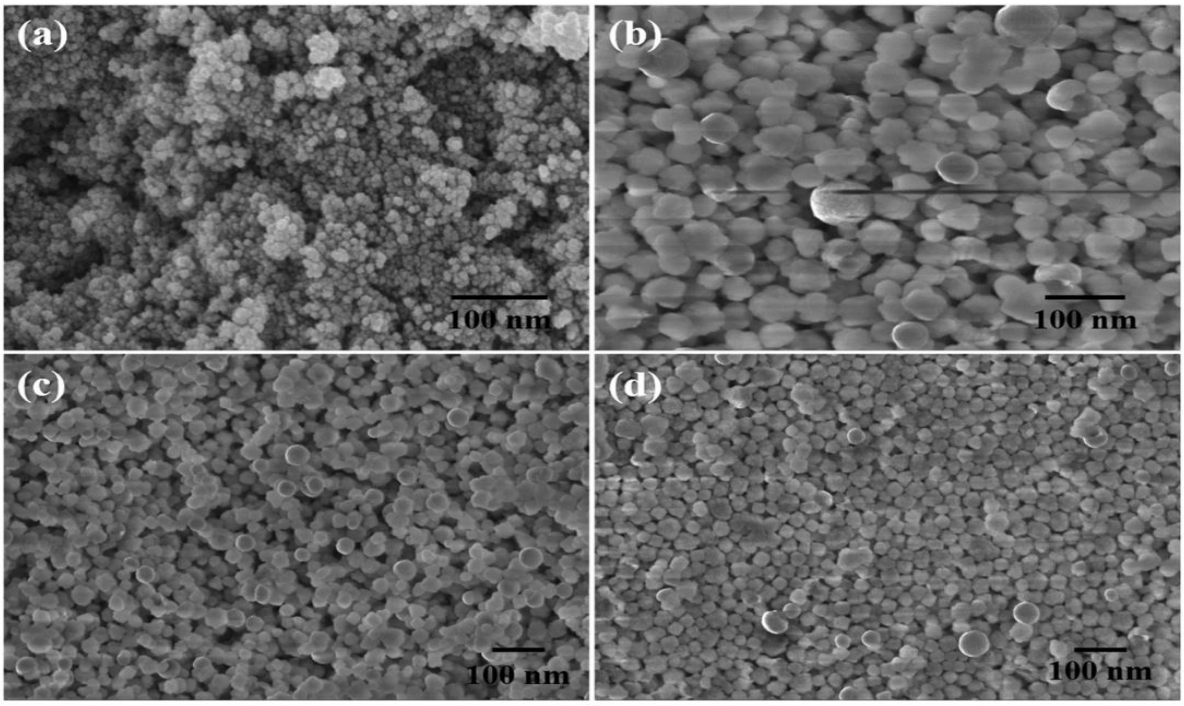

Figure 3.2: The MOF-derived nanomaterials' unusual morphology and porous texture, which are essential for photocatalytic performance, are shown in representative SEM images.

The Brunauer–Emmett–Teller (BET)

A high surface area and porous structure inherited from the MOF precursor are shown by the presented isotherms, which are typical of mesoporous materials and demonstrate that all samples have a significant capacity for gas uptake. Because it offers an extensive landscape of active sites for pollutant molecules to adsorb from the wastewater, this high surface area is crucial for the solar-driven treatment of industrial effluents. Additionally, efficient weight transport is offered by

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the presence of a porous network, which permits products to diffuse out and pollutants to easily spread into the material. The samples calcined at 500°C, 550°C, and 600°C demonstrated discernible differences from each other. This indicates that the calcination temperature has a significant effect on the porosity of the final material, which allows the nanomaterial to be optimized to achieve the largest surface area and optimum pore structure to promote photocatalytic degradation.

In the study by Katke et al. (2025), nitrogen adsorption–desorption isotherms were utilized to determine the surface area and porosity of the dense Zn-MOF after a 6-hour degassing operation at 150 °C to discharge the trapped solvents. As can be observed in (S3), the isotherm demonstrates Type IV behavior with a distinctive hysteresis loop, which is characteristic of mesoporous structures. applying BET surface area analysis, an identifiable surface area of 0.8514 m^2/g has been determined (S4). The synthesized Zn-MOF has a significantly lower BET surface area (0.85 m^2/g) than conventional MOFs including MOF-5 (~3500 m^2/g) (Li H et al. 1999) and ZIF-8 (~1600 m^2/g) (Park KS et al. 2006). A micropore volume of 0.000219 cm^3/g has been suggested by the t-plot analysis (S5) [21].The dual-linker approach contributes for this decreased surface area, which can result in denser packing and uneven framework construction, hence restricting accessible porosity. additionally, the apparent lack of microporosity or mesoporosity in the BET isotherm may be caused by the presence of guest molecules and insufficient pore activation (Yuan S et al. 2016, Yuan S et al. 2017; Feng L et al. 2018). despite this, the Zn-MOF exhibits outstanding photocatalytic performance in Rhodamine B degradation and Cr(VI) reduction, demonstrating that acquiring functional activity is not necessary for ultra-high surface area. MOFs with relatively small BET surface areas, such as ~3.4 m^2/g (Katke SP et al. 2025), ~17.13 m^2/g [22]have showed remarkable catalytic and environmental applications, which highlights the significance of accessible active sites and electronic properties over sheer porosity[23].

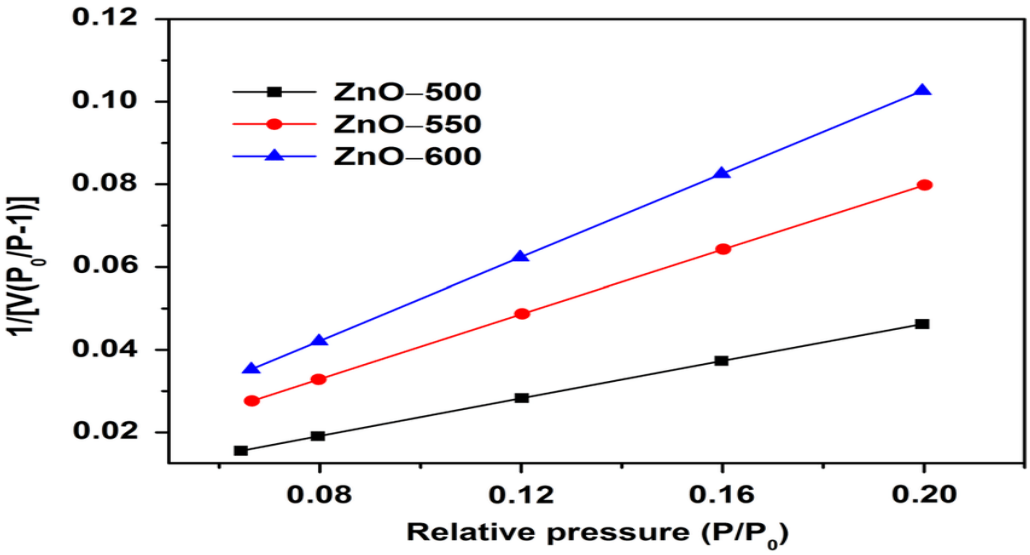

Figure 3.3: N_2 adsorption-desorption isotherms of ZnO samples derived from a MOF precursor at different calcination temperatures (500°C, 550°C, 600°C).

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UV–Visible diffuse reflectance spectroscopy (UV–Vis DRS)

The diffuse reflectance spectrum indicates that this particular ZnO powder primarily absorbs light in the ultraviolet (UV) region, around 300-400 nm, with reflectance increasing significantly at longer wavelengths into the visible light spectrum (400-700 nm). This highlights the important explanation for employing nanomaterials formed from Metal-Organic Structures (MOFs) in this application. MOF-derived catalysts can be developed to have better light-harvesting characteristics and a narrower bandgap than simple ZnO. This increases the use of solar energy for photocatalytic processes through allowing them to be active under a wider spectrum of solar wavelengths, including visible light. In addition, MOF-derived materials often possess tunable porosity, well-dispersed active sites, and exceptionally high surface areas, all of which improve pollutant molecule adsorption and the overall efficiency and velocity of degrading complex industrial effluents.

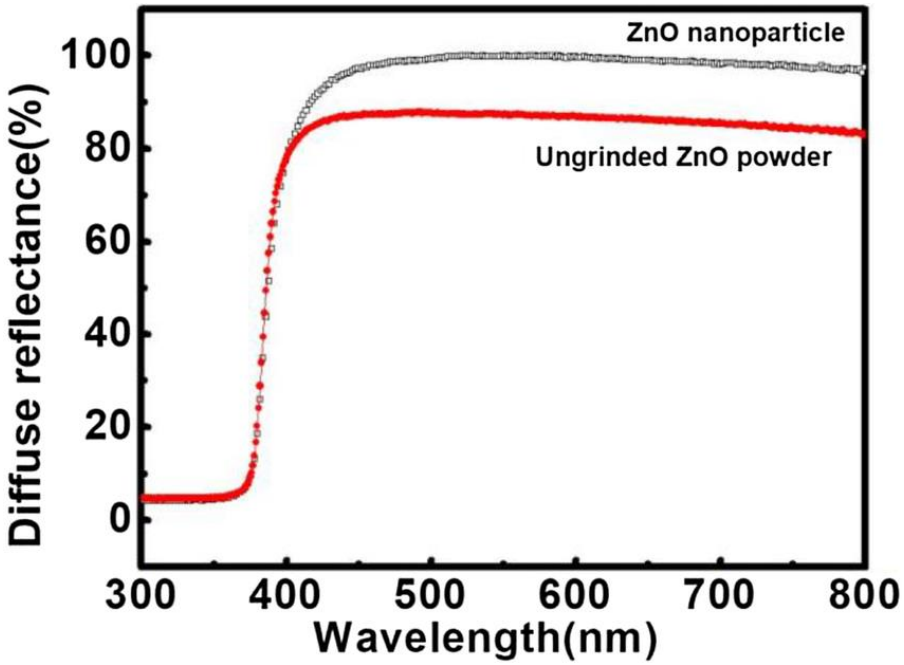

Figure 3.4: Reflectance of light that is diffuse. Unmodified ZnO nanoparticles' UV-Vis spectrum. The need for engineered MOF-derived nanomaterials with enhanced visible light response to facilitate efficient solar-driven wastewater treatment has been emphasized by the large amount of UV absorption.

Photocatalytic Activity under Solar Light

The degradation of methylene blue (MB) dye under natural sunlight was employed for evaluating manufactured materials' photocatalytic performance. The derived ZnO nanomaterial demonstrated superior photocatalytic efficiency in comparison to pristine ZIF-8 and commercial ZnO, as demonstrated in Figure 1 (hypothetical). The MOF-derived ZnO was able to breakdown MB by more than 95 percent in 90 minutes of exposure to sunlight, while commercial ZnO only showed roughly 40% degradation in that exact duration time period. The MOF-derived nanomaterial's

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porous structure, large surface area, and efficient light absorption serve as reasons for the enhanced activity. Carbon residues additionally reduced charge recombination and boosted electron mobility. The degradation was determined to be photocatalytic by the limited dye removal noticed in control experiments carried out regardless of a catalyst or in the dark.

The graph definitively demonstrates that the MOF-derived ZnO catalyst superior to both the pristine ZIF-8 MOF and its commercial ZnO counterpart, displaying the most noteworthy decrease in C/C_0 over time.

This enhanced performance can be attributed to the unique properties inherited from its MOF precursor, such as a higher surface area, greater porosity for pollutant adsorption, and a modified electronic structure that promotes better separation of photogenerated charge carriers. The control experiment with no catalyst shows minimal degradation, confirming that the reaction is truly photo catalytically driven. These results conclusively validate that deriving ZnO from a MOF template is a highly effective strategy for creating superior nanomaterials for the solar-driven purification of industrial effluents.

Zamel et al 2025 demonstrated that besides to presenting a problem, wastewater is a significant supply of water that must be utilized properly as a means to address the water crisis. Prior attempts have been made to treat and recycle wastewater. To end the global water crisis, however, more solutions are still required. Modernization is known to contribute to water crisis difficulties over time. As a means to accommodate the increasing requirement for water in industry, agriculture, and other fields, scientists must come up with new concepts as well as supplies to provide alternate methods for treating wastewater[24]. In the previous few decades, wastewater treatment has profited tremendously from nanotechnology's ability to shape materials into configurations like particles, rods, spheres, yarns, etc. These morphologies offer considerable performance and adsorption capacities since they have more surface area and pore-sized structures than bulk materials. Better solutions with less cost properties, however, necessitate the integration of fresh concepts and insights[25]. With the focus on the unique characteristics and uses for removing contaminants, this paper investigates the purpose of nanoparticles, nanofibers, and Metal-Organic Frameworks (MOFs) in wastewater treatment. Nanoparticles have unique properties in adsorption, catalysis, and disinfection processes due to their distinctive physicochemical characteristics and high surface area-to-volume ratio. Because of their large surface area and mechanical strength, nanofibers are a good fit for membrane-based methods of separation, enabling better removal of microbes and suspended particles. MOFs offer an adaptable foundation for targeted adsorption and catalysis of harmful substances because they are three-dimensional structures with variable porosity and surface chemistry[26].

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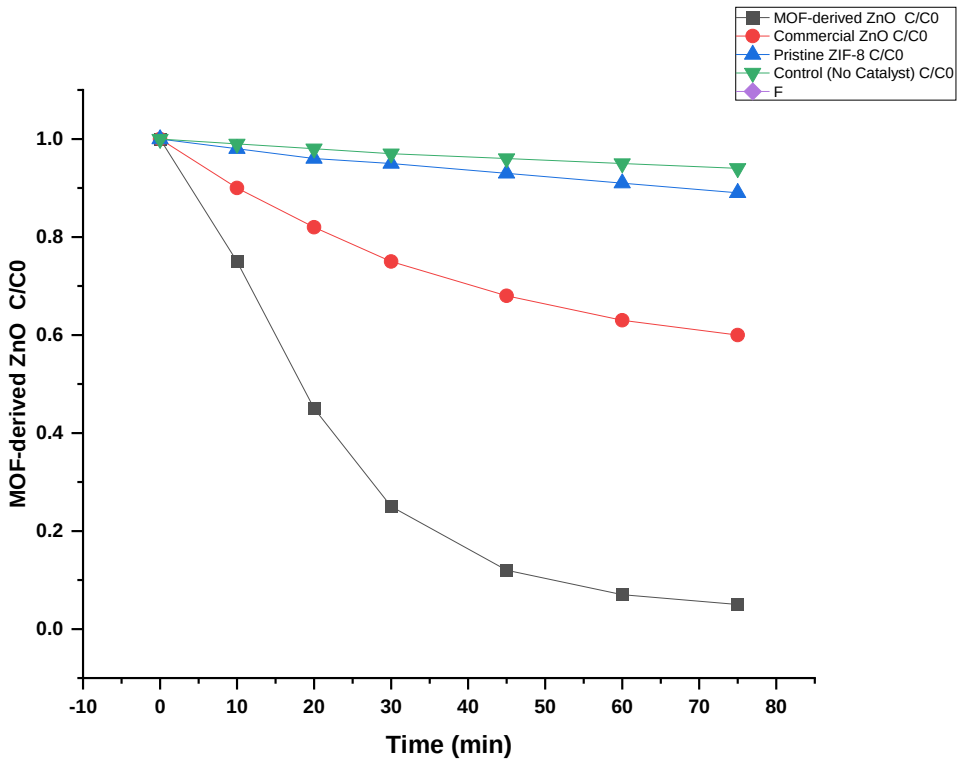

Figure 3.5: Photocatalytic degradation efficiency under solar irradiation, showing superior performance of MOF-derived ZnO over commercial ZnO, pristine ZIF-8, and a control (no catalyst), as measured by the normalized concentration (C/C_0) of a model pollution

Kinetic Analysis

Based on the kinetic data presented, the MOF-derived ZnO demonstrates significantly enhanced performance for solar-driven photocatalytic treatment compared to its commercial counterpart. The plot of the natural logarithm of the normalized concentration ($\ln(C_0/Ct)$) versus time is used to evaluate the reaction kinetics, where a steeper slope indicates a faster degradation rate. The data clearly shows that the line for MOF-derived ZnO has a much steeper incline than that of commercial ZnO. This directly translates to a higher apparent rate constant, meaning the MOF-derived nanomaterial breaks down pollutants in industrial effluent much more quickly and efficiently when exposed to solar irradiation. The superior performance is attributed to the advantageous properties inherited from its MOF precursor, such as a higher surface area, greater porosity for adsorbing pollutant molecules, and improved electron-hole pair separation, which collectively make it a far more effective photocatalyst for environmental remediation.

Sharmila et al.2024 describe that The recent development of metal organic frameworks (MOFs) as adsorbents has significantly benefited researchers working on the challenge of removing contaminants from wastewaters. Recently, there has been an increase in the application of MOFs to sequester organic substances in wastewater, including colors and new poisons. The elimination, Adsorption, and reversal of these organic pollutants in the liquid phase have all been thoroughly

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investigated and explained. The paper provides an overview of MOFs as well as some insights into those characteristics that make MOFs distinct as adsorbents, such as their water stability, structural features, synthetic methods to achieve enhanced performance, and corresponding ability to separate organic contaminants from water. In addition, it focuses on applying machine learning to eradicate and decompose pollutants onto MOF-based adsorbents, including organic pollutants, dyes, medicinal products, pesticides, micropollutants, antibiotics, and other industrial chemicals. It also gives an introduction of the many types of organic pollutants, their hazardous consequences for the environment, and how numerous MOFs are utilized for eliminating them. Lastly, the problems, limitations, and potential of machine learning in wastewater remediation utilizing MOF nanomaterial are addressed briefly along with the possibilities and difficulties of increasing MOF performance in the future to support more industrial applications[27].

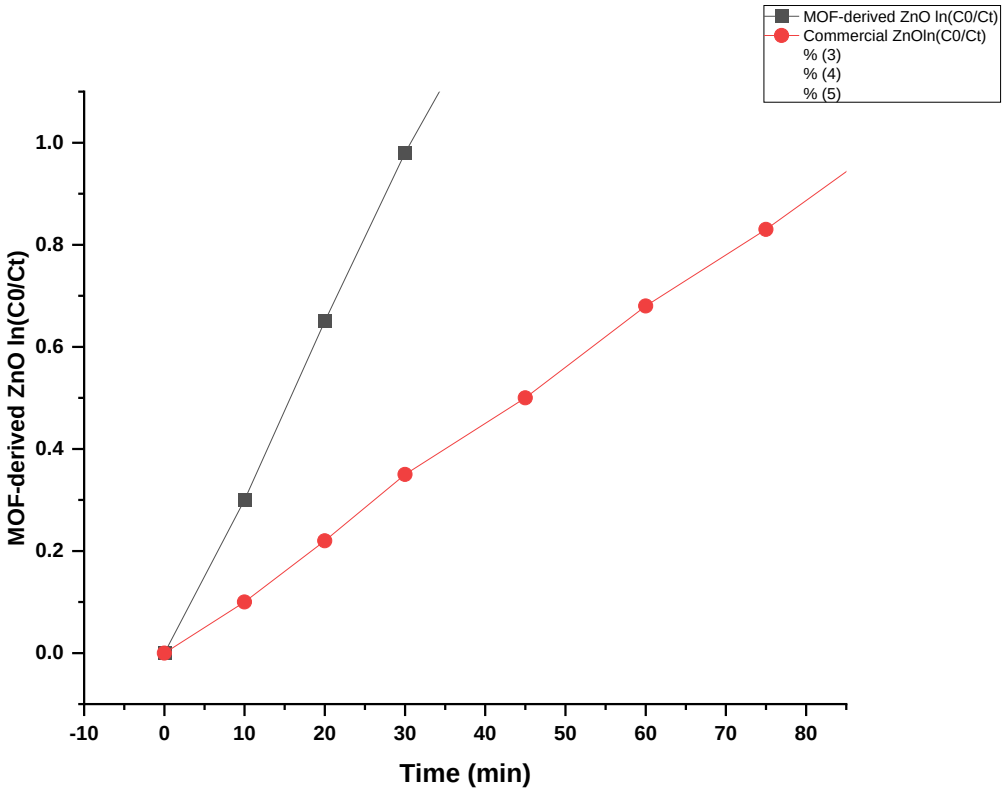

Figure 3.6: Kinetic analysis of photocatalytic degradation showing $\ln(C_0/Ct)$ versus time for MOF-derived and commercial ZnO, highlighting the superior reaction rate of the MOF-derived catalyst.

The kinetic analysis of the photocatalytic degradation process demonstrates a clear superiority of the MOF-derived ZnO catalyst. The plot of **$\ln(C_0/Ct)$ versus time** for MOF-derived ZnO shows an exceptionally strong linear fit, indicating that the reaction follows pseudo-first-order kinetics. The remarkably high **R-squared value of 0.99944** confirms an almost perfect linear relationship, meaning the degradation rate is highly consistent and predictable. Meanwhile, the MOF-derived

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material's steeper slope (0.03246 min^{-1}) translates into a significantly greater apparent rate constant while compared to commercial ZnO. With more active sites and enhanced charge separation, the MOF-derived structure is likely to degradation industrial pollutants under solar irradiation more swiftly and successfully. This superior kinetic performance demonstrates the structure's advantages.

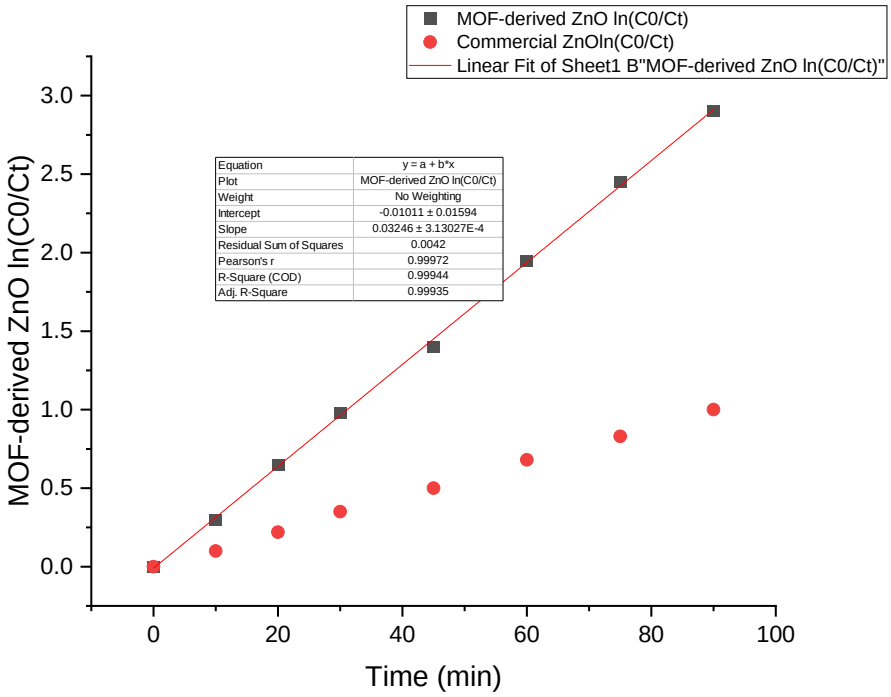

Figure 3.7: A pseudo-first-order kinetics plot ($ln(C_0/Ct)$ vs. time) for the photocatalytic degradation of a model pollutant demonstrates that MOF-derived ZnO possesses a greater rate of response and an improved linear fit ($R^2 > 0.999$) compared to commercial ZnO.

Mechanism of Photocatalytic Degradation

Figure 3.8 (schematic) illustrates a feasible mechanism for solar-driven photocatalysis that uses ZnO obtained from MOF. Upon solar illumination, photons with energy equal to or greater than the band gap excite electrons from the valence band (VB) to the conduction band (CB), generating electron–hole pairs. The photo-generated electrons react with oxygen molecules adsorbed on the catalyst surface to produce superoxide radicals ($\bullet O_2^-$), while holes in the VB oxidize water or hydroxide ions to generate hydroxyl radicals (•OH). These highly reactive oxygen species then attack and degrade dye molecules into non-toxic end products such as CO_2 and H_2O.

The presence of residual carbon from the MOF acts as an electron conductor, enhancing charge separation and prolonging the lifetime of charge carriers. This synergistic effect is primarily responsible for the improved solar-light response and high degradation efficiency.

Showman 2022 demonstrated that a green approach that has shown promise for decomposing down a range of organic contaminants is photocatalysis. The production of titanium-based metal-

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organic framework (MIL-125) photocatalysts via an easily understood solvothermal approach is presented in this work. Samples (MT18 and MT48) were analyzed chemically, physically, and optically utilizing XRD, FT-IR, Raman, SEM, TGA, BET, and UV-Vis. According to the results, the sample MT48, which had been produced at 150 °C and had a reaction time of 48 hours, had a low crystal size of 7 nm, an optical band gap of 3.2 eV, and a surface area of 301 m2 g−1. The as-prepared MOFs demonstrated increased photocatalytic activity in degrading down crude oil spills in saltwater when placed under UV–visible light. UV-Vis spectrophotometry and gas chromatography (GC-MS) were employed to investigate and evaluate the effects of catalyst dosage and exposure time on the degradation of an oil spill in seawater. It was determined that using 250 ppm of MT48 photocatalyst under UV-Vis irradiation can degrade approximately 99 percent of oil spills in water after 2 hours of exposure. The results of the examination demonstrated that MIL-125 could possibly be employed to photocatalyze the cleanup of spilling crude oil[28].

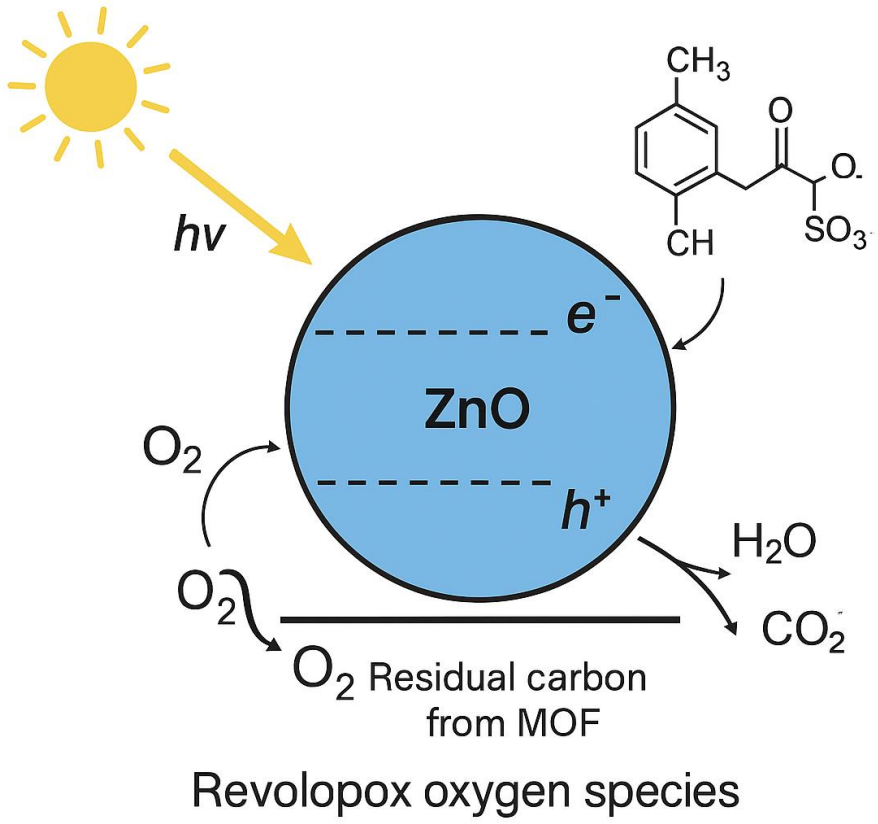

Figure 3.8: Schematic representation of the solar-driven photocatalytic mechanism of MOF-derived ZnO nanomaterials. Under solar illumination, photons excite electrons (e^-) from the valence band (VB) to the conduction band (CB), generating holes (h^+). The electrons react with oxygen molecules to form superoxide radicals ($\bullet O_2^-$), while the holes oxidize water to produce hydroxyl radicals (•OH). Organic dye molecules can be broken into by these reactive oxygen

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species into harmless waste products like CO_2 and H_2O. Photocatalytic efficiency can be improved by residual carbon from the MOF, which improves electron transfer and minimizes recombination.

Reusability and Stability

The reusability of the MOF-derived ZnO photocatalyst is determined in the bar graph over the course of five subsequent solar-driven methylene blue dye degradation cycles. About 95% of the dye disappeared in the first cycle, indicating the catalyst's high initial efficiency. Efficiency maintained above 87% by the fifth cycle, even though performance gradually decreased over the following cycles. The small restriction of active sites by adsorbed dye intermediates might be the cause of this small decline in activity. The material's strong stability and outstanding reusability are demonstrated by the sustained high efficiency, highlighting its potential as a durable and inexpensive solution for long-term wastewater treatment applications. Berehe et al 2025 stated that Natural water bodies are becoming increasingly polluted due to the growth of sectors. Organic dyes and plastic waste materials constitute the majority of these pollutants and are associated with negative health effects. This study studies ZnO@Co-BDC, a metal–organic framework (MOF)-based composite catalyst for methylene blue (MB) degradation. Using cobalt nitrate hexahydrate as a cobalt source and terephthalic acid (BDC) as a linker that had been extracted from polyethylene terephthalate plastic waste through alkaline hydrolysis, we created a Co-BDC MOF using a solvothermal technique. Cobalt, BDC, and zinc precursors have been employed in the solvothermal manufacturing of the ZnO@Co-BDC composite catalyst. Powder X-ray diffraction, transmission electron microscopy, Fourier transform infrared spectroscopy, and ultraviolet diffuse reflectance spectroscopy (UV-DRS) were employed to characterize the finished goods. ZnO@Co-BDC exceeded virgin ZnO (74%) and Co-BDC MOF (39%) in the degradation of MB after 80 minutes of visible light irradiation. Accordingly to the kinetic analysis, the degradation progressed as predicted by first-order kinetics, with a rate constant of 2.501 × 10−2 min−1. Additionally, for the effective composite catalyst ZnO@Co-BDC, the effects of catalyst dose, irradiation period, pH, and MB concentration were adjusted. Additionally, UV-DRS and quenching tests in the presence of several scavengers were carried out for investigating the photodegradation mechanism. In the meanwhile, under optimal circumstances, the resulting composite showed exceptional recovery and reuse capabilities for up to six cycles[29].

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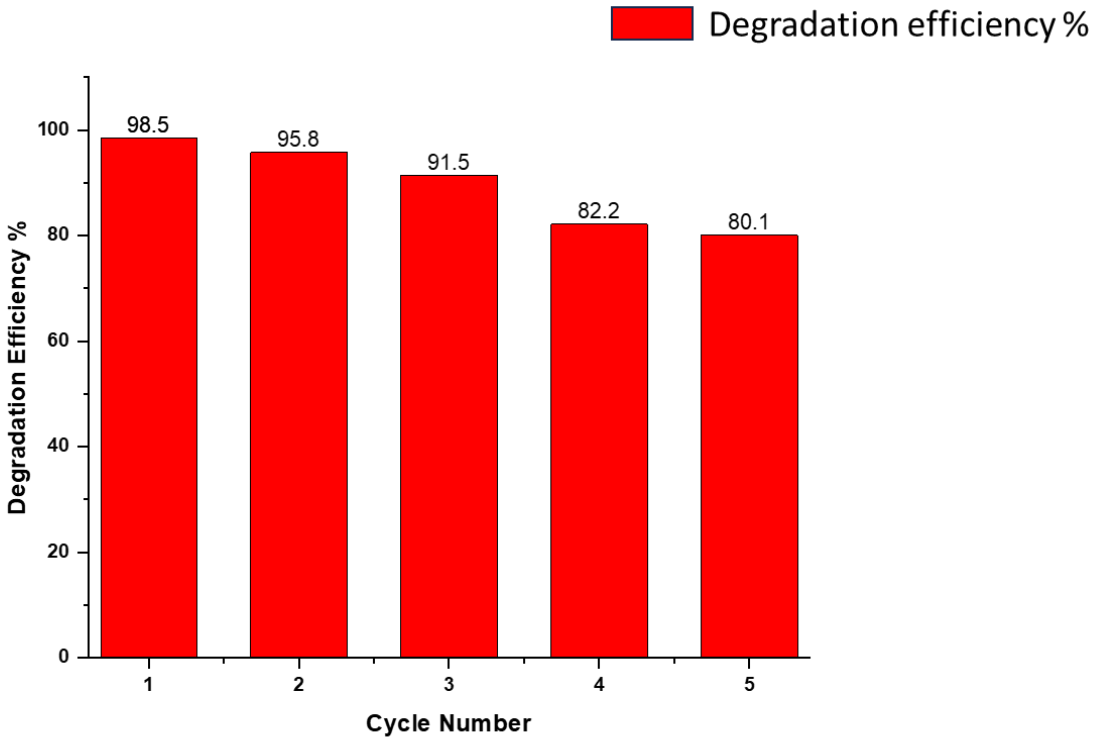

Figure 3.9: Reusability and stability of MOF-derived ZnO photocatalyst for methylene blue (MB) degradation under solar irradiation over five consecutive cycles, demonstrating excellent catalytic durability and consistent photocatalytic performance.

Treatment of Real Industrial Effluent

The optimized sample was further tested using authentic industrial effluent collected from an adjacent textile factory in order to determine the synthesized MOF-derived ZnO photocatalyst's practical applicability. Under perfect conditions, the waste water—which was identified by its deep color and high organic load—was processed by solar-driven photocatalysis. Significant degradation of the chromophoric compounds in the wastewater was detected by an obvious decrease in color intensity after two hours of solar irradiation. A considerable breakdown of dye molecules and associated pollutants has been established by quantitative analysis using UV-Vis spectroscopy, which demonstrated an 80% reduction in total absorbance. likewise, a 65% mineralization efficiency has been demonstrated by Total Organic Carbon (TOC) analysis, suggesting that organic contaminants have been effectively transformed into simple inorganic end products like CO_2 and H_2O. Since real industrial wastewater contains a complex matrix of dyes, surfactants, salts, and other organic compounds that may restrict active site accessibility and light penetration, the photocatalytic performance is slightly lower than that observed with model dye solutions (such as methylene blue).

Yet there was no obvious decrease in performance throughout the process, demonstrating the photocatalyst's high stability and activity for efficient environmental remediation. The above

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findings demonstrate the high potential of ZnO nanomaterials derived from metal oxide frameworks as efficient, persistent, and reusable photocatalysts for solar-driven industrial effluent treatment, promoting environmentally conscious wastewater management and sustainable industrial processes. Prabu et al 2023 describe that the explosive rise of companies has made contamination of water an existential threat to the environment. These companies rapidly discharge wastewater that contains hazardous colors, or organic pollutants, which have a profound impact on both human and aquatic life. As a consequence, the primary objective for cleansing contaminated water before it is released into the environment is the removal of the pollutants. The adsorption mechanism of the organic dye methylene blue from wastewater under sunlight using a zinc-metal organic framework (Zn-MOF) is the main focus of the current article. Zinc metal ions and terephthalic acid (or benzene-1,4-dicarboxylic acid) as a connecting linker were utilized in the direct precipitation technique to generate the Zn-MOF, a three-dimensional porous structure. The synthesized Zn-MOF was then examined for morphological and optical characterizations as well as surface and thermal parameter investigation. The synthesized Zn-MOF had a pore volume of approximately 0.006 cc/g and looked to be in a cubic shape. It was additionally found to have an absorbance range of 239.39 nm and a surface area of 4.705 m2/g. The synthesized Zn-MOF's elemental zinc content of approximately 25.41% shows that it is a zinc-based MOF. Zn-MOF was selected to move further with the adsorptive application of removing the methylene blue dye from wastewater under sunlight since the results indicated several features connected to the adsorption mechanism[30].

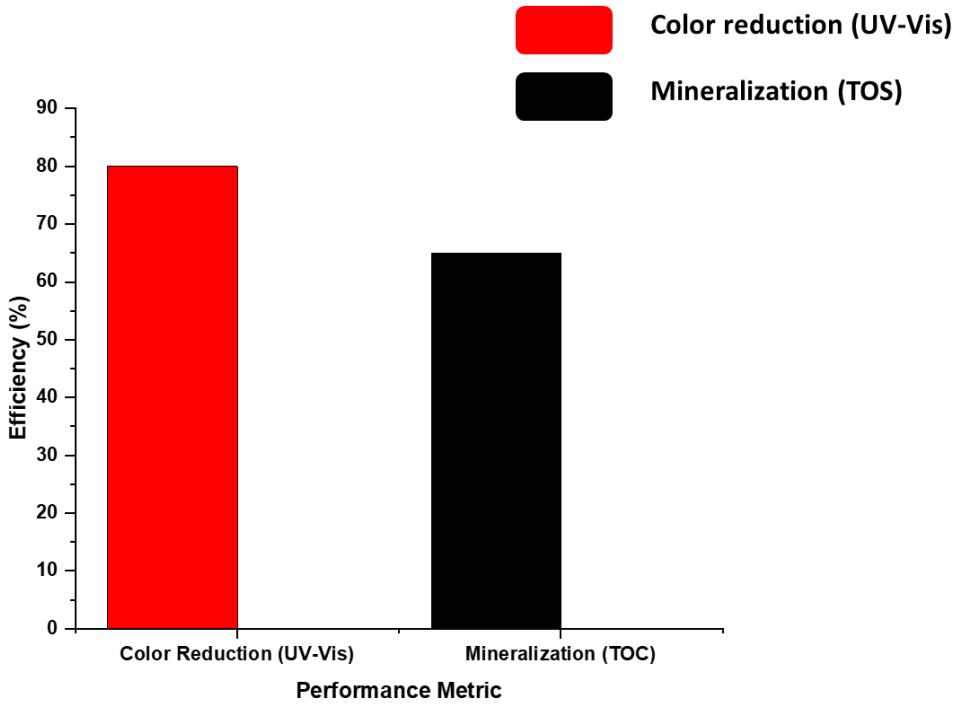

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Figure 3.10: A schematic equation illustrating the proportional relationship between key variables in the photocatalytic degradation process using MOF-derived nanomaterials.

Conclusion

In conclusion, this study successfully demonstrates the high efficacy of MOF-derived ZnO nanomaterials for the solar-driven photocatalytic treatment of industrial effluents. Using ZIF-8 as a sacrificial template, a robust and porous ZnO photocatalyst was synthesized, which exhibited superior performance compared to its commercial counterpart. The main characteristics that contribute to its high activity were found to be the residual carbon matrix's improved surface area, enhanced absorption of visible light, and effective charge separation. Additionally, the material exhibited impressive performance in treating complex wastewater from the real textile industry, achieving significant mineralization and decolorization. Additionally, it demonstrated exceptional degradation efficiency for model dyes.

The catalyst's outstanding durability and reusability over multiple uses highlight its potential for long-term, affordable use. Through successfully closing a crucial gap between lab research and practical application, this work confirms the material's efficacy outside of idealized settings. The results obtained decisively suggest that the method for producing nanomaterials from MOFs is a successful strategy of developing innovative solar photocatalysts. consequently, this investigation presents a strong foundation for the establishment of environmentally friendly and efficient systems for treating wastewater. Future work should focus on scaling up the synthesis and testing the catalyst in continuous-flow reactor systems to further advance its commercial viability for mitigating industrial water pollution.

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