



A state-of-the-art review on green synthesis and modifications of ZnO nanoparticles for organic pollutants decomposition and CO₂ conversion

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ABSTRACT

Photocatalysis has emerged as a promising technology to tackle the escalating environmental pollution. Zinc oxide (ZnO), by the virtue of its excellent properties, offers immense potential for simultaneous CO₂ conversion and organic pollutant degradation. The current review comprehensively scrutinizes the green synthesis routes, modifications, and catalytic applications of ZnO nanoparticles for addressing critical environmental challenges. The review explores various green synthesis methods, emphasizing their eco-friendly nature and potential for imparting specific functionalities to the nanoparticles. Subsequently, it explores a wide range of modification strategies, including bimetallic combinations, integration with carbon-based materials, and hybridization with advanced organic polymers, to enhance the catalytic performance of ZnO. The catalytic efficacy of both pristine and modified ZnO nanoparticles in CO₂ conversion is evaluated, along with their in-depth analysis of the underlying mechanisms. Furthermore, the review extensively covers the exploitation of ZnO-based photocatalysts for the decomposition of diverse organic contaminants, like dyes, pharmaceuticals, phenolic compounds, pesticides, herbicides, PAHs, and PFAS. The mechanisms involved in these degradation processes are elucidated, providing insights into the factors influencing photocatalyst efficiency. This review concludes by highlighting the promising prospects of ZnO nanoparticles as sustainable photocatalysts for environmental remediation and the need for further research to optimize their performance and address practical implementation challenges.

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1. Introduction

Water is the most fundamental natural resource for human life. The anthropogenic activities of humans are the leading cause of water contamination and the increasing levels of gaseous CO₂ emissions that pollute the environment (Haruna et al., 2024, Juma et al., 2024). These activities cause various kinds of waterborne diseases, such as cholera, diarrhea, dysentery, and typhoid fever, which deteriorate the quality of life and affect the ecological stability. These serious concerns have resulted in increasing water scarcity and global warming, which, in turn, affects the agricultural farmlands, aquatic lives, and the human health. For example, the textile and tannery industries release toxic effluents that contaminate water bodies (Islam et al., 2023, Khan et al., 2023), farming activities result in the discharge of pesticides (Abuqamar et al., 2024), and military activities and gun firing generates toxic heavy metals (Geřbka et al., 2016, Tauqeer et al., 2020). The various anthropogenic processes also generate greenhouse gases (GHG) (Kamyab et al., 2024). All these factors are responsible for environmental pollution, threatening the human health. Therefore, the presence of gaseous CO₂ and the persistent pollutant within our ecosystem makes them significant points of research study, worthy of deep exploration. For this reason, to mitigate water pollution, significant advancement in advanced wastewater treatment technologies is essential to effectively remove pollutants before discharging treated water into water bodies. Additionally, to combat climate change, developing and deploying carbon capture and utilization technologies to capture and utilize CO₂ emissions from anthropogenic processes and activities is crucial. Furthermore, promoting clean energy efficiency measures in industries, transportation, and buildings can significantly reduce energy consumption and greenhouse gas emissions.

The application of efficient and sustainable technologies to mitigate these pollutants has become increasingly important in the field of environmental sciences (Keshta et al., 2024, Abou-Elyazed et al., 2024). Among the methods, semiconductor-based photocatalytic technology using the solar energy is regarded as a “green chemistry” approach (Wang et al., 2023, Jia et al., 2023). The process involves the generation of electron-hole pairs during light absorption by the photocatalysts (Wang et al., 2023, Jia et al., 2023). The technique has been efficient for the remediation of environmental degradation caused by various pollutants that are highly toxic and deteriorating the environment and human health by extension. It has been particularly useful for the remediation of dyes (Manikanika and Kumar, 2024) (Tran et al., 2024), pharmaceuticals (Manikanika and Kumar, 2024, Tran et al., 2024), phenols (Zheng et al., 2023, Raha and Ahmaruzzaman, 2022), herbicides and pesticides (Shan et al., 2024, Alegría et al., 2024), polycyclic aromatic hydrocarbons (Ramalingam et al., 2022, Yeganeh et al., 2022), heavy metals (Nguyen et al., 2020, Brindhadevi et al., 2024), and other wide spectrum of pollutants of organic and inorganic origins (Brindhadevi et al., 2024, Arslan et al., 2022). The photocatalytic process is also vital for energy crisis mitigation. It has been vital for applications such as photocatalytic hydrogen production (Ma et al., 2022), CO₂ reduction (Jin et al., 2022, Ma et al., 2022) etc. In this review, the relation between organic pollutants decomposition and CO₂ conversion is established. The merging of organic pollutant decomposition and CO₂ conversion in the review is a strategic move that highlights the multifaceted potential of ZnO nanoparticles in addressing environmental challenges. Both these processes are closely related and often involve similar mechanisms, such as photocatalysis and adsorption. Interestingly, both processes involve the generation of electron-hole pairs during light absorption by the ZnO photocatalyst. In the case of photocatalytic degradation, degrading species (hydroxyl radicals and superoxide radical anions) generated on the surface of the ZnO degrade the organic pollutants. For the photocatalytic conversion of CO₂, the accumulated electrons in the C_B of ZnO provides the active sites for CH₄, CO and H₂ production.

Zinc oxide (ZnO), a metal oxide nanoparticles have recently gained

popularity as promising materials due to their fascinating physico-chemical properties, including low cost, non-toxicity, high surface area, thermal stability, strong adsorption capacity, biological activity, and its remarkable photocatalytic activity [(Jiang et al., 2023) - (Majumder et al., 2020)]. Various chemical processes for the preparation of ZnO materials and have been reported elsewhere (Jiang et al., 2023). More recently, the synthesis of ZnO and ZnO-based nanomaterials has increasingly utilized green methods, which employ environmentally benign procedures to reduce the ecological footprint associated with traditional chemical approaches (Ahmed et al., 2017, Dejene and Geletaw, 2023). Green synthesis methods for ZnO nanoparticles benefit from natural resources such as plant extracts, microorganisms, and biodegradable polymers, offering a sustainable alternative to traditional chemical routes (Manikanika and Kumar, 2024, Tran et al., 2024). These methods not only minimize the use of hazardous chemicals but also enhance the biocompatibility and functionality of the produced ZnO-based nanoparticles. Noteworthy, various plant extracts, including those from *Aloe vera* (Jose et al., 2021), *Moringa oleifera* (Matinise et al., 2017), *Calotropis procera* (Gawade et al., 2017), tea leaves (Irshad et al., 2018), neem extract (Sohail et al., 2020) and *Euphorbia hirta* (Ahmad and Kalra, 2020), have been reported to act as reducing and capping agents, facilitating the fabrication of ZnO nanomaterials with controlled size and morphology. The microbial synthesis of ZnO employing bacteria (Barani et al., 2021), fungi (Alavi and Nokhodchi, 2021), and green algae (Hameed et al., 2023), has also demonstrated significant potential, with organisms like *Bacillus subtilis*, *Escherichia coli*, and *Aspergillus niger* producing high-performing materials that have been applied in many technology areas [(Ningthoujam et al., 2022) - (Ma et al., 2022)].

The green synthesis of ZnO nanoparticles aligns with several Sustainable Development Goals (SDGs), particularly those related to clean water and sanitation, environmental remediation, and climate action. By utilizing natural resources and minimizing the use of harmful chemicals, this approach contributes to SDG 12: Responsible Consumption and Production. ZnO nanoparticles synthesized through green methods have potential applications in various fields, including water treatment, where they can be used as effective photocatalysts to degrade organic pollutants, contributing to SDG 6: Clean Water and Sanitation. Additionally, they can be employed for environmental remediation to remove heavy metals and other contaminants from soil and water, further contributing to SDG 6: Clean Water and Sanitation and SDG 15: Life on Land. Furthermore, these nanoparticles can be used as photocatalysts to convert CO₂ into valuable chemicals and fuels, helping to mitigate climate change and contributing to SDG 13: Climate Action. However, while ZnO nanoparticles show promise as photocatalysts, they face several limitations, including rapid charge carrier recombination, limited visible light absorption, photocorrosion, low quantum efficiency, and recovery and reuse, that hinder their widespread application (Lee et al., 2023, Lee et al., 2024, Sun et al., 2023, Zheng et al., 2024).

Recently, the fabrications of ZnO-based materials through doping with metals or non-metals, surface functionalization, and composite formation have been extensively brought under study to augment their photocatalytic efficacy and selectivity for certain applications. Actually, doping ZnO with transition metals, rare earth metals, and non-metals have been reported to alter the electronic structure, leading to augmented visible light absorption and charge separation properties of ZnO nanomaterials [(Jiang et al., 2023) - (Majumder et al., 2020)]. The surface functionalization of ZnO with advanced materials such as metal-organic frameworks (Roy et al., 2023), polyoxometalates (Xing et al., 2023), and organic polymers (Mishra et al., 2023), can increase the removal of targeted pollutants from the environment and also protect the nanoparticles from agglomeration. Furthermore, ZnO composites with other materials, such as graphene (Sudha et al., 2023), TiO₂ (Haruna et al., 2022), and BiFeO₃ (Haruna et al., 2020), can synergistically enhance the photocatalytic performance. Studies have advocated that the practical applications of ZnO-based nanoparticles for environmental degradation of toxic pollutants like dyes, pesticides, and

pharmaceuticals in water and soil have shown promising results (Xu et al., 2021, Jose et al., 2021). Moreover, ZnO-based photocatalysts have been used for conversion of CO₂ into value-added chemicals, including methane, methanol, and formic acid (Matinise et al., 2017, Gawade et al., 2017).

To date, many reviews have provided in-depth analyses on the modification of ZnO nanoparticles. However, most of the reviews have focused on specific applications such as photocatalytic degradation of wastewater (Waghchaure et al., 2022), agricultural uses (Osman et al., 2024), biomedical applications (Singh et al., 2024), building materials (Klienchen de Maria et al., 2024), and other emerging areas (Bhaskar and Bhame, 2024). Therefore, while significant advancements have been made in the field of ZnO nanoparticle research, this article is the first review to focus specifically on the application of modified ZnO nanoparticles for the simultaneous conversion of CO₂ and the photocatalytic degradation of organic pollutants. This work aims emphasizing the various modification technologies for the improvement of the ZnO nanoparticles, making them high-performing materials capable of achieving practical applications of CO₂ conversion and pollutants photocatalytic degradation for the environmental sustainability. Accordingly, the potential research gap lies in the exploration of synergistic effects and optimization techniques for ZnO nanoparticles. This includes investigating the creation of multifunctional ZnO composites by combining it with materials like carbon-based substances or metal oxides to enhance simultaneous organic pollutant degradation and CO₂ conversion. Moreover, tailoring surface properties through surface functionalization with different ligands or polymers can improve adsorption and photocatalytic capabilities for simultaneous conversion of CO₂ and the photocatalytic degradation of organic pollutants, which are underrepresented in the literature. Thus, the novelty of this review lies in its focused approach, which is particularly important in bridging this gap, since no review has ever acknowledged conceptualizing and integrating by interlacing and twisting two strands of problems into one concept, all of which are centered on ensuring environmental sustainability. In a nutshell, while previous reviews have explored various aspects of ZnO nanoparticle research, this review specifically targets the dual functionality of these materials.

Hence, by highlighting the potential of ZnO nanoparticles to address two pressing environmental issues, the review contributes to the advancement of sustainable solutions. This is particularly important since the review discusses strategies for modifying ZnO nanoparticles to optimize their properties for the dual functionality, such as doping, surface functionalization, and composite formation, examining how these modifications can improve the photocatalytic activity, adsorption capacity, and stability of ZnO nanoparticles, aiming to broaden its application spectrum. Furthermore, the review provides a detailed overview of the applications of ZnO nanoparticles in organic pollutant degradation and CO₂ conversion, giving direction involving a deeper understanding of the mechanisms and kinetics underlying photocatalytic reactions involving the ZnO nanoparticles. This aims to provide valuable insights into the mechanisms involved in the processes of photocatalysis and adsorption effects for developing accurate kinetic models that can quantify the rate and efficiency of pollutant degradation and CO₂ conversion, ultimately facilitating process optimization and scale-up. For these reasons, this review focuses mainly on the advances on multifunctional ZnO-based composites. Combining ZnO with other materials, such as carbon-based substances or metal oxides. Synthesis conditions like temperature, pH, and precursor concentration, which significantly impact the properties of ZnO nanoparticles and their performance. Additionally, surface properties through functionalization with ligands or polymers, which also influence adsorption and photocatalytic capabilities. Another crucial area involves the mechanisms and kinetics underlying photocatalytic reactions involving ZnO nanoparticles. However, the review is limited to the theoretical and experimental aspects of ZnO nanoparticles and does not examine the practical implementation of large-scale applications. In addition, though ZnO

nanoparticles, due to their unique properties, find applications beyond photocatalysis in electronics, optoelectronics, sensors, biomedicine, cosmetics, textiles, and energy storage, their application herein is limited to photocatalytic decomposition of organic pollutants and CO₂ conversion.

1.1. Properties of ZnO nanoparticles

ZnO typically exists in three known crystalline phases: hexagonal wurtzite, cubic zinc blende, and rock salt. The zinc blende and rock salt phases are cubic and unstable underneath ambient circumstances, whereas the wurtzite phase is stable (Uikey and Vishwakarma, 2016). ZnO is commonly found in the wurtzite phase (Fig. 1), and has a small nanosized range of about 1 - 99 nm and exhibits novel characteristics which differ from those of bulk materials (Meruvu et al., 2011, Hsueh et al., 2015).

Interestingly, ZnO nanomaterials have received tremendous attention as a widely studied metal oxide material in the realm of catalysis and photocatalysis. ZnO is a highly versatile material that can easily be synthesized in various forms such as nanotubes, nanorods, nanocombs, nanoplates, nanowires, nano pellets, and nanoflowers (Kamal et al., 2023, Lee et al., 2023). It is relatively easy to create defects in the crystal lattice structure of ZnO, resulting in various morphologies depending on the synthesis process (Lim et al., 2016). These defects are introduced in the preparation approach, influenced by the changes in solvent, concentration, temperature, pressure, and synthesis time. These factors can impact the morphology of the ZnO nanostructure, which in turn, alter the material's crystal lattice (Sun et al., 2023, Zheng et al., 2024). In addition, ZnO nanomaterials possess interesting characteristics such as high surface area, optical activity, antimicrobial activity, biological activity, and excellent photocatalytic activity (Joy et al., 2024, Porrawatkul et al., 2023). ZnO and ZnO-based nanoparticles are applicable in a broad range of engineering and scientific fields, including environmental sciences (Sathiyaseelan et al., 2023), medicine (Jha et al., 2023), pharmacy (Omar et al., 2024), agriculture (Nguyen et al., 2024), building (Klienchen de Maria et al., 2024), energy (Saeed et al., 2024), gas sensors (Nunes et al., 2019), and electronics (Vyas, 2020).

1.2. Methods of green synthesis of ZnO nanoparticles

There are many methods developed for synthesizing ZnO nanoparticles, including sol-gel (Thi Bich Hop et al., 2024), co-precipitation (Shreya et al., 2024), hydrothermal (Josun et al., 2024), wet-chemical

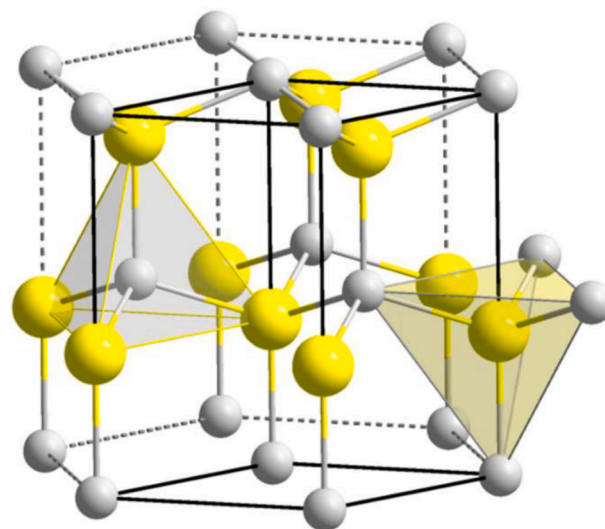


Fig. 1. Structure of the ZnO wurtzite crystalline phase (Zn: yellow, O: white). Reproduced from ref (Borysiewicz, 2019).

(Anandhi et al., 2024), spray pyrolysis (Kumar and Ahmad, 2022), and chemical vapor deposition (Swathi et al., 2021). However, these chemical-based methods are not fully aligned with sustainable development goals, as they often consume significant amounts of energy and rely on toxic and potentially hazardous materials as stabilizing, reducing, and encapsulating agents. In response to the growing concerns associated with chemical techniques, the green synthesis approach, which employs renewable resources such as plant extracts and microorganisms, offers an environmentally benign alternative to the energy-intensive, costly, and potentially toxic methods [(Thi Bich Hop et al., 2024) - (Anandhi et al., 2024)]. This approach is simple and has superior properties aligning with the principles of green chemistry by being safe and minimizes the use of harmful chemicals. Green synthesis of ZnO nanoparticles offers rich advantages including low cost, high yield, and purity (Ahmad et al., 2024). In addition, ZnO prepared through green processes can exhibit enhanced stability in solutions over long periods of time (Thirumavalavan et al., 2024). Ultimately, ZnO nanoparticles produced by the green routes give high-quality particles with controlled shape, morphology, and increased yield (Sedefoglu, 2024). This implies that ZnO nanoparticles, with such unique properties have gained significant attention in diverse applications, ranging from environmental to medicine. Thus, green synthesis methods for ZnO nanoparticles offer a sustainable and environmentally friendly approach, minimizing the use of toxic chemicals and reducing hazardous waste generation. By employing natural resources like plant extracts, microorganisms, or fungi as reducing and capping agents, these methods lower energy consumption through reduced temperature and pressure requirements. The resulting nanoparticles are inherently biocompatible, making them suitable for biomedical applications. Furthermore, green synthesis methods provide precise control over the size, shape, and morphology of ZnO nanoparticles, enabling tailored properties for specific applications. Many of these methods can be scaled up for industrial production, making them economically viable and sustainable (Swathi et al., 2021). While green synthesis methods offer numerous advantages, they also have some limitations. Biological agents can exhibit variability, leading to inconsistencies in the properties of the synthesized nanoparticles from batch to batch. Green synthesis processes often involve slower reaction kinetics compared to traditional methods (Sathiyaseelan et al., 2023, Jha et al., 2023, Omar et al., 2024, Nguyen et al., 2024, Nunes et al., 2019, Vyas, 2020), requiring longer reaction times. The yield of ZnO nanoparticles from green synthesis methods may be lower than that of traditional methods (Swathi et al., 2021). Characterizing the complex interactions between biological agents and metal ions during green synthesis can be challenging and may require advanced techniques (Kumar and Ahmad, 2022, Swathi et al., 2021).

Some considerations are applied in the preparation of ZnO

nanoparticles via the plant-mediated or microbial-mediated routes, depending on the targeted applications. The plant-mediated preparation of ZnO nanomaterials involves using extracts from various plant parts, including bark, leaves, roots, fruits, flowers, and seeds (Al-darwesh et al., 2024). These plant extracts contain several phytochemicals with reducing properties, which are utilized to synthesize ZnO nanoparticles under moderate temperature. The microbial-mediated synthesis involves using bacteria, fungi, virus, algae, and yeast as eco-friendly techniques (Yusof et al., 2019). These microbes produce biologically active molecules, which are used for synthesizing green ZnO NPs. The confirmation of formation of synthesized ZnO and ZnO-based nanoparticles is achieved using several spectroscopic and analytical techniques, such as FTIR (Fourier transform infrared) spectroscopy, TGA (thermogravimetric analysis), UV-Vis (ultraviolet-visible) spectroscopy, XRD (X-ray diffraction), FESEM (field-emission scanning electron microscopy), HRTEM (high-resolution transmission electron microscopy), N₂ adsorption-desorption isotherms, and XPS (X-ray photoelectron spectroscopy). In the present review, we emphasize on these green methods for synthesizing ZnO and ZnO-based nanoparticles and their environmental applications. Table 1 summarizes the two main methods of green synthesis mediated by plants and microorganisms for ZnO nanoparticles and their applications.

2. Modifications of ZnO nanoparticles

The primary drawback of the ZnO photocatalyst is its large band gap of about 3.2 eV, which limits its capability to absorb visible light and renders it only reactive to UV radiation (Das et al., 2021). Moreover, high rate of recombination of photogenerated electrons and holes hinders its photocatalytic activity, leading to energy loss and reduced quantum yield (Li et al., 2014). It is possible to improve absorption in visible light and hence raise the photocatalytic effectiveness by encouraging interfacial charge-transfer processes. Currently, a lot of researchers are attempting to structurally modify ZnO to lower its band gap and make it more active when exposed to visible light. Numerous methods are used to accomplish this objectives include co-doping, metal/non-metal doping, creating composites with different metal oxides, employing carbonaceous materials as adsorbents (Josun et al., 2024, Anandhi et al., 2024).

The efficiency of ZnO nanoparticles in photocatalysis varies significantly depending on the type of doping material used. This variation arises due to the impact of doping on key properties such as the bandgap, charge carrier dynamics, and surface activity (Basavarajappa et al., 2020). Effective doping can reduce the band gap of ZnO, enabling visible light absorption and enhancing photocatalytic performance. For instance, recent reports have shown that metal doping with Al introduce

Table 1

Summary of some plants and microbes used for the green syntheses of ZnO NPs and the applications.

Entry	Green synthesis source	Particle size (nm)	Applications	Ref
Plant sources				
1.	<i>Sorghum bicolor</i> seed	-	Decolorization of dye pollutants	(Cervantes-Gaxiola et al., 2024)
2.	<i>Neem</i> leaf extract	25.26	Photodegradation of MB	(Yadeta Gemachu and Birhanu, 2024)
3.	<i>Nauclea latifolia</i> fruit	10.05	Removal of Congo red (CR)	(Abegunde et al., 2024)
4.	Wild olive leaves	32.50	Dehydrogenation of formic acid	(Ullah et al., 2024)
5.	<i>Mariposa Christia vespertilionis</i> leaves	38.00–68.00	Sodium-Ion batteries	(Idris et al., 2024)
6.	<i>Azadirachta indica</i> leaves	<10.00	Removal of pharmaceuticals	(Sanjeev and Valsan, 2024)
7.	<i>Epipremnum aureum</i> leaves	29.00	Photodegradation of CR	(Brishti et al., 2024)
8.	<i>Lantana Camara</i> flower extract	25.00	Electrochemical and anti-inflammatory	(Swamy M et al., 2021)
9.	<i>Euphorbia stricta</i>	35.94	Removal of MB pollutant	(Durmaz et al., 2024)
10.	<i>Pyrus communis</i> leaves	79.00–93.00	Anti-diabetic and antimicrobial	(Elankathirselvan et al., 2024)
Microbial sources				
11.	<i>Streptomyces plicatus</i>	41.76	Biomedicals	(Soni et al., 2024)
12.	<i>Lactobacillus</i> spp	32.00	Antimicrobial	(Suba et al., 2021)
13.	Ureolytic bacteria	15.00	Decolorization of dyes	(Dhandapani et al., 2020)
14.	<i>Streptomyces pseudogriseolus</i>	15.00	Wastewater treatment	(Darwesh et al., 2024)
15.	<i>Burkholderia</i> spp	55.08	Antimicrobial	(Roy et al., 2024)

localized energy levels within the band gap (Xie et al., 2024), while non-metal doping with N enable band gap narrowing through hybrid orbital interactions (Sanakousar et al., 2022). In addition, doping improves charge carrier separation and reduces recombination rates, thereby increasing quantum yield. Kumar and Rao (Kumar and Rao, 2017) demonstrated that co-doping of ZnO with metal and non-metal ions synergistically enhances charge separation by creating defect sites that act as electron traps. Furthermore, doping can modify the surface morphology of ZnO nanoparticles, increasing surface area and the availability of active sites, which are crucial for efficient photocatalytic applications (Hasanah et al., 2023).

Unmodified core-shell and surface-modified NPs can elicit different toxicological responses. Improved solubility and easier functionalization with less toxicity. These findings imply that surface changes may be used to mitigate the harmful effects of NPs. Numerous studies have confirmed ZnO NPs' toxicity to many cells and species. To address toxicity, several studies have concentrated on the underlying processes of zinc oxide toxicity by developing innovative methods for creating biocompatible zinc oxide nanoparticles. Since photocatalytic reduction of CO₂ uses abundant and environmentally beneficial solar energy to generate solar fuels from CO₂ and water, such as CH₄ (Mahmodi et al., 2013, Long et al., 2017), CH₃OH (Das et al., 2021, Li et al., 2014), CO, HCHO, and HCOOH, it is often referred to as "artificial photosynthesis" (Sharma et al., 2022). Since they may provide more active sites (low-coordinated sites like edge and corner sites) on a larger surface area than bulk metal catalysts, nanocatalyst are being used for CO₂ conversion at a rate that is steadily growing (Prabhuraj et al., 2021, Basavarajappa et al., 2020). CO₂ requires the right catalyst materials and requires a lot of energy to convert because it is a stable molecule (Habisreutinger et al., 2013). In the industrial setting, condensation of CO₂ with H₂ molecules on Cu/Zn-based catalysts occurs at high pressure and temperature, converting CO₂ to alcohols (Gui et al., 2015).

2.1. Bimetallic ZnO nanoparticles

The versatility of doping ZnO nanoparticles with various metals and metal oxides has shown potential for tailoring bandgap and enhancing optical/magnetic properties. For example, adding 3 wt.% Cu to ZnO thin films reduced the bandgap energy from 3.03 to 2.7 eV and shifted the absorption band edge to 450 nm (Tyona et al., 2017), enhancing visible light absorption. Strong surface plasmonic resonance (SPR) of noble metals like Ag and Au can be manipulated through photo-deposition, improving optical properties (Swathi et al., 2021, Tran et al., 2023). Metal-based nanoparticles, while stable and biocompatible, require further improvement for applications due to toxicity and cellular absorption. Combining two metals to create bimetallic nanoparticles (BNP) reveals enhanced qualities, expanding their functionality and application potential (Ichipi et al., 2022).

Bimetallic nanoparticles have unique physical and chemical properties, making them increasingly intriguing in recent research (Idris and Roy, 2023). Their distinctive characteristics, such as large surface areas, high mobility, and diverse chemical, thermal, catalytic, mechanical, optical, and magnetic properties, set them apart from monometallic counterparts, offering superior performance (Arora et al., 2020). The arrangement of metal atoms determines their potential properties, which can range from core-shell to random alloyed orientations (Keshta et al., 2024, Shanmugam et al., 2022). Bimetallic nanoparticles are created by combining distinct metals in a reaction vessel, resulting in various morphological and structural modifications. These nanoparticles can be produced using diverse combinations of metals and different approaches, including noble and transition metals. The process of creating bimetallic nanoparticles involves either disassembling bulk materials into nanoparticles or synthesizing nanoparticles from their constituent atoms. Two primary methods for bimetallic nanoparticle production are top-down and bottom-up strategies. Bimetallic compounds have gained prominence for their role in producing

heterogeneous catalysts, with significant focus on zinc oxide nanoparticles incorporating various metals. Notably, bimetallic Ag/ZnO nanoparticles, which include silver (Ag) and zinc oxide (ZnO), hold industrial, pharmaceutical, and environmental significance (Ahmad et al., 2024, Thirumavalavan et al., 2024).

The catalytic efficiency of CO₂ hydrogenation to methanol can be enhanced by the strong interactions between the ZnO and other metals. For instance, the ZnO nanoplate conduction band facilitates electron transfer to the Cu Fermi level, increasing oxygen vacancies and strengthening the Cu-plate contacts, thereby improving catalytic properties. A study demonstrated that encapsulated ZnO@FeHCF exhibited superior photocatalytic efficiency in removing endocrine phenols from water contaminated with a smaller band gap, under solar radiation. This resulted in enhanced resistance to charge carrier recombination and amplified OH[•] radical generation (Rachna and Shanker, 2019). In order to simulate wastewater exposed to natural sunshine, the capacity of Zinc oxide coupled copper hexacyanoferrate (ZnO-CuHCF) nanocomposite was synthesized and compared with its parent ZnO and CuHCF nanoparticles, for photocatalysis in the breakdown of those dangerous EBT and RB dyes from spiked (Rachna and Shanker, 2019). The ZnO-CuHCF nanocomposite demonstrated superior dye adsorption and rapid photodegradation of EBT (99%) and RB dyes (97%) when exposed to solar irradiation under ideal conditions. Bimetalization led to improvements in the catalytic properties of the nanoparticles. This approach introduces an additional degree of freedom, enhancing the distinct metallic properties when combined, resulting in differing attributes from those of elemental particles in their pure form (Rachna and Shanker, 2019).

2.2. ZnO nanoparticles modified with carbon-based materials

Carbon-based materials have gradually attracted the interest of researchers owing to their fascinating properties. Ultimately, the favorable photoelectric characteristics of carbon-based materials offer good potential for enhancing the oxidation and breakdown of contaminants. Photoinduced charge separation efficiency is enhanced by these attributes, which include effective electron transit and storage (Hasanzadeh et al., 2023). Due to their capacity to distribute the active locales across the surface of catalyst, researchers are currently looking into the prospect of combining carbon-based materials with ZnO. ZnO interacts with carbonaceous materials with the purpose of slowing down the rate of electron-hole recombination, such as GO (graphene oxide), rGO (reduced graphene oxide), and g-C₃N₄ (graphitic carbon nitride). These substances facilitate the separation of charges and offer a substantial surface area for heterogeneous reactions at the surface, leading to an increase in photocatalytic activity (Zheng et al., 2019).

A range of carbon compounds, including carbon nanotubes, carbon dots, graphene-based materials, and activated carbon, have various surface properties, which affect how the CO₂ molecule interacts with them. The presence of various functional groups in graphene nanostructures, large surface areas, high porosity and thus good adsorption capacities of activated carbons, electron storage capacity of nanotubes, and good electron transfer properties of carbon dots have created favorable conditions for CO₂ adsorption and photoreduction. The efficacy of CO₂ photo reduction is therefore increased when carbon compounds are added to ZnO (Sharma et al., 2022). When ZnO is hybridized with carbon materials, its photostability is enhanced primarily through three mechanisms: In terms of graphite-like carbon, carbon layers create strong barriers that prevent ZnO nanoparticles from aggregating (Zhang et al., 2009), carbon material adheres to the empty ZnO sites and prevents the catalyst oxygen atoms from activating (Fu et al., 2008), and the creation of C-O bonds with decreased graphene oxide composites once more deactivates the oxygen atoms on the ZnO surface, increasing photostability (Zhang et al., 2013).

2.2.1. ZnO modified with CQDs

CQDs show promise as photocatalysts due to their coordinated

fluorescence emission in the visible and near-infrared spectra. Research indicates that semiconductors modified with CQDs exhibit enhanced photocatalytic activity when exposed to visible light. Additionally, CQDs have attracted greater interest than other carbon-based materials due to their superior photo-induced electron transfer and up-conversion capabilities (Gao et al., 2020). Carbon quantum dots (CQDs) have drawn significant attention due to their unique properties, including good water solubility, low cytotoxicity, and up-conversion photoluminescence, influencing ZnO properties (Zirak et al., 2021). They enhance light absorption, improve utilization, and facilitate charge separation when introduced into ZnO (Arora et al., 2020, Keshta et al., 2024). Various studies have demonstrated the enhanced photocatalytic activity of ZnO/CQDs composites, indicating their potential for superior performance under visible light (Qu et al., 2020). For example, Shadowdock peel was used as a carbon source for biomass-derived CQDs synthesized. They created ZnO nanoparticles from ZIF-8, altering CQD contents using a solvothermal technique. The CQD/ZnO nanocomposite structure and modification enhance charge separation efficiency, outperforming ZnO nanoparticles in visible light (Xu et al., 2023).

2.2.2. ZnO modified with biochar

Biochar is cost-effective and has demonstrated the ability to absorb light, and produce charges for degradation of various pollutants (Qin et al., 2020). It has large surface area and oxygen-containing functional moieties which enhances its interactions with contaminants. For example, biochar formed from cassava residue were used to remove Cd (Nugraha and Misran, 2023), methylene blue (Bakhsh et al., 2022), and malachite green (El Hassani et al., 2018) from aqueous solutions. In another development, biochar derived from soybean brane were used to adsorb contaminants from wastewaters, including phosphate, benzidine, o-toluidine, and Congo red. However, derived-pristine biochars have limited adsorption capacity for macromolecules like azo dyes, leading to prolonged adsorption times, making them unsuitable for practical use.

In a recent study, ZnO nanoparticles were used to enhance the adsorption capacity of biochars for the removal of contaminants found in wastewater. Additionally, a TiO₂-ZnO/biochar nanocomposite was found to efficiently degrade furfural, while ZnO NPs immobilized on biochar showed high efficiency in removing Malachite green through photocatalytic degradation. A critical component of increasing photocatalytic activity is thought to be oxygen vacancy, which can generate more reactive species to break down Malachite green through conjugate structure, demethylation, deamination, and benzene ring structure destruction (Jing et al., 2021). The composites created with ZnO nanoparticles and biochar combine their advantages. The large specific surface area of biochar and the dispersion of ZnO nanoparticles create more reactive sites, increasing the photodegradation capacity of the composite catalyst. This synergistic effect enhances pollutant removal through a combination of photocatalysis and adsorption (Mankomal, 2022).

2.2.3. ZnO modified with activated carbon

Recent studies have demonstrated that activated carbon (AC) has a strong ability to adsorb various contaminants, including natural gas, butane, dyes, phenols, and p-chlorophenols (Jahanbakhsh and Ebrahimi, 2016). However, heavy metal adsorption requires specific functional groups on activated carbon. Activated carbon is commonly used in the fabrication of ZnO/activated carbon composites due to its large surface area, good conductivity, and chemical stability. The synthesis of ZnO/activated carbon creates energy sub-levels in the material's bandgap and enhances the duration of photogenerated electron and hole. Supporting ZnO nanoparticles on porous materials like AC increases active adsorption sites and photo reactivity. The combination of zinc oxide's photoactivity and carbon's adsorption ability produces a synergistic effect. The addition of AC increases ZnO specific surface area, pore size, electron transfer, and adsorption capacity for organic

pollutants degradation, resulting in increased catalytic efficiency (Lee et al., 2019). The photodegradation of MB on ZnO/LSAC is 9.79 times larger than that of ZnO, attributed to indirect Methylene blue and AC photosensitization. The indirect Methylene blue and AC photosensitization are attributed to this increased photocatalytic activity (Van Hung et al., 2021). By coupling the large band gap energy ZnO material with activated carbon, the photo response has been successfully extended to the visible area of the spectrum (Vinayagam et al., 2016).

In a published study (Liu, 2016), ZnO nanorod arrays/carbon fiber composites were created using an in-situ controlled method. The composites demonstrated remarkable activity in the photoreduction of CO₂ to CH₃OH, with a maximum yield of 430.2 $\mu\text{mol g}^{-1} \text{ h}^{-1}$ under irradiation with a 7.15-fold increase over that of pure ZnO (60.2 $\mu\text{mol g}^{-1} \text{ h}^{-1}$). We know that sp² hybridization gives carbon atoms on the carbon fiber surface a somewhat negative character, and that Zn²⁺ metal ions tend to adsorb on this surface.

2.2.4. ZnO modified with CNTs

Research indicates that adding organic, inorganic, or biological species to the surface of carbon nanotubes can significantly alter their characteristics. Carbon nanotubes (CNTs) are suitable catalytic supports for metallic particles due to their large surface area and high electron conductivity. Surface modification is the focus of CNT research, with metal oxides and sulphides being used to modify CNTs. Incorporating CNTs into the ZnO layer can improve charge transport and electron lifetime, eliminating the disadvantages of using ZnO alone as a photocatalyst (Das et al., 2021, Li et al., 2014). CNTs also suppress photo-corrosion and increase photocatalytic effectiveness (Mohd Adnan et al., 2019). Research shows that ZnO performs better when CNTs are present, with enhanced mechanical, electrical, and sensing capabilities (Das et al., 2021, Li et al., 2014). ZnO-CNT nanocomposite has been used to create nano resonators, super capacitors, and biosensors with excellent sensitivity and selectivity (Mohd Adnan et al., 2019).

As a result, research shows that ZnO nanocomposites with CNTs perform better than pure ZnO. Zhou et al. created hierarchical ZnO/CNT microsphere composites for photocatalytic abatement of methylene blue, achieving 92.3 and 76% degradation efficiencies (Zhu et al., 2015). Wang and colleagues synthesized CNT-ZnO composites, resulting in enhanced mechanical, electrical, and sensing capabilities. ZnO-CNT nanocomposite has been used to create nano resonators, super capacitors, and biosensors (Zhu et al., 2015). ZnO-CNT nanocomposite has been used to create nano resonators, super capacitors, and biosensors with excellent sensitivity and selectivity. These devices have increased performance and a wide range of uses (Cursaru et al., 2021).

2.2.5. ZnO modified with graphene and graphene oxide

Nanocomposites based on metal nanoparticle-decorated graphene have numerous applications in light energy conversion, sensors, and biosensors due to their stability, broad potential window, and strong electron transport capabilities (Xie et al., 2024, Sanakousar et al., 2022). Planar graphene (GN) and graphene oxide-based nanomaterials have been widely used in sensing due to their exceptional charge transfer properties, large specific surface area, high electrocatalytic activity, and affordability (Dar et al., 2022). Both ZnO and graphene are effective electro-catalysts, and by combining the two with graphene acting as a support, the activity may be further increased. It has been revealed that ZnO NPs directly synthesized on the graphene surface make suitable electrode materials for supercapacitors (Dar et al., 2022). Graphene oxide, a two-dimensional material, has been investigated for applications in biological sensors, photocatalysis, and nanocomposite supports. GO, a more hydrophilic material, is more suitable for incorporation into the ZnO matrix, making the synthesis of ZnO composites simpler (Ara et al., 2022).

Graphene oxide and zinc oxide nanorods have been discovered for multipurpose catalytic uses, with a combination of amino groups and GO carboxyl groups demonstrating great stability and dependability

(Kachere et al., 2022). The suppression of yellow-green emission through luminescence demonstrated the effective transport of electrons from excited ZnO to GO sheets (Jin et al., 2022). ZnO-GO composites with a regulated GO concentration are promising for a range of applications, with the strongest catalytic action during a 360-minute light period compared to pristine ZnO. According to the experimental findings, ZnO-GO exhibited the strongest catalytic action during a 360-minute light period compared to pristine ZnO. Also, study findings indicate that ZnO/GO nanocomposites with a regulated GO concentration are very promising for a range of applications (Kachere et al., 2022), as presented in Fig. 2.

CH_3OH and HCOOH were the primary products of CO_2 photoreduction using a new reduced-GO-ZnO with metal organic framework (UiO-66- NH_2), a three-component system. Since the CB of the included MOF is more negative than the CO_2 reduction potential, it was discovered that the reported system adheres to the Z-scheme mechanism. Therefore, in agreement with the reduction potential values, the accumulated electrons in the CB of UiO-66- NH_2 may easily reduce CO_2 to HCOOH and CH_3OH . Reduced-GO, on the other hand, greatly improved the photocatalytic activity and worked well as an electronic transfer medium (Meng et al., 2019).

Graphene oxide (GO) is gaining significant interest due to its similar qualities to graphene and its unique surface structures created by adding carboxyl and hydroxyl groups for the manufacture of nanocomposites (Li et al., 2012). In particular, the goal to increase photocatalytic efficiency has drawn significant research efforts to the creation of semiconductor/GO composites. The enhanced light absorption range, absorptivity of pollutants, and the effective charge transportation and separation are the three best qualities of a photocatalyst (Zhang et al., 2010). Consequently, it is thought that anchoring orderly ZnO nanostructures on GO sheets can effectively use the complementary advantages of ZnO and GO to produce a photocatalyst with improved performance. Li et al., compared ZnO/GO nanocomposite to GO sheets and flower-shaped ZnO particles, it shows much greater photocatalytic efficacy for the photodegradation of organic dyes from water under visible light (Li et al., 2012). The efficient photosensitized electron injection and repressed electron recombination resulting from the electron-transfer process with GO acting as an electron collector and transporter are responsible for the ZnO/GO nanocomposite's increased photocatalytic activity (Li et al., 2012). The ZnO/GO composite is a

great option for applications pertaining to various environmental challenges because of these characteristics.

Since carboxyl and hydroxyl groups on their surfaces make GO an excellent dispersive material in any solvent, it is a prime candidate among carbon-based materials for integration with ZnO-based photocatalysts. Moreover, when conjugated with ZnO, GO may facilitate charge separation (Mohammed and Shekargoftar, 2021, Mohd Adnan et al., 2019). Due to their superior physicochemical and photo-electrochemical qualities over other nanomaterials, GO-based ZnO nanoparticles have gained popularity recently for photocatalytic applications. Additionally, the formation of effective heterojunctions with intimal contact between ZnO and GO is made possible by their high specific surface, which has many active sites and good support qualities. This accelerates charge transfer and catalyst dispersion, both of which enhance photocatalytic performance (Zhu et al., 2015, Cursaru et al., 2021).

2.2.6. ZnO modified with graphitic carbon nitride

Graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) photocatalysts are popular due to their chemical characteristics and suitable band width for visible light harvesting (Lin et al., 2019). However, their efficiency is limited due to quick recombination of photogenerated carriers and weak oxidation capacity. Hybridizing $\text{g-C}_3\text{N}_4$ with other materials, such as ZnO, can improve photocatalytic activity (Yadav and Sinha, 2017, Sharma et al., 2022). $\text{g-C}_3\text{N}_4/\text{ZnO}$ nanocomposites perform better at degrading dyes (Lu et al., 2015, Rosen et al., 2015) pharmaceuticals (Sun et al., 2022), perfluoroalkyl substances (PFAS) (Navidpour et al., 2024), pesticides and herbicides (Navidpour et al., 2024) as well as wide range of organic and inorganic pollutants. The unique Z-scheme charge transfer channel offers better redox capacity and improved separation of photoexcited electrons and holes (Paul et al., 2020). Zinc oxide-GCN nanocomposites produced from urea and zinc nitrate hexahydrate exhibit enhanced photoactivity under visible light illumination (Paul et al., 2020).

As $\text{g-C}_3\text{N}_4$ has an isoelectric point of 4.6 and ZnO has an isoelectric point of >10 , it is commonly recognized that ZnO and $\text{g-C}_3\text{N}_4$ have +ve and -ve charges, respectively (Zhu et al., 2015). Therefore, electrostatic forces between these two semiconductors are favorable due to which these can be easily combined. In this way the charge separation is stimulated and resulted in an increased stability of the synthesized composite. Using $\text{g-C}_3\text{N}_4$ coated porous ZnO nanosheets, Guo et al. (Guo et al., 2020) investigated CO_2 reduction in the presence of water vapors. Both the chemical adsorption of CO_2 molecules over ZnO nanosheets and light absorption were markedly improved by the loading of $\text{g-C}_3\text{N}_4$. Furthermore, compared to pristine ZnO or $\text{g-C}_3\text{N}_4$, the heterojunctions ($\text{ZnO/g-C}_3\text{N}_4$) that form greatly lower recombination, which increases the CO_2 reduction activity of composites.

2.3. ZnO modified with advanced organic polymers

A growing amount of attention has been paid to polymer nanocomposites recently due to the potential uses of nanoparticles scattered throughout a polymer matrix in a variety of scientific and technological domains (Mostafa et al., 2020). The combination of nanomaterials with biopolymers has garnered interest due to its exceptional efficacy and eco-friendliness. Additionally, this link will lessen the possibility of metal concentrations or their oxides seeping into the environment (Rani and Rachna, 2020).

2.3.1. ZnO modified with chitosan

Chitosan, the second most common natural polymer, is effective in removing heavy metals from wastewater, including lead (Pb), mercury (Hg), copper (Cu), chromium (Cr), nickel (Ni), cadmium (Cd), and arsenic (As) (Khalil et al., 2020). Its qualities include biocompatibility, biodegradability, abundant availability, antibacterial action, and non-toxicity (Basit et al., 2024, Hamed et al., 2018, Malerba and Cerana, 2018). However, modified chitosan is more effective than pure

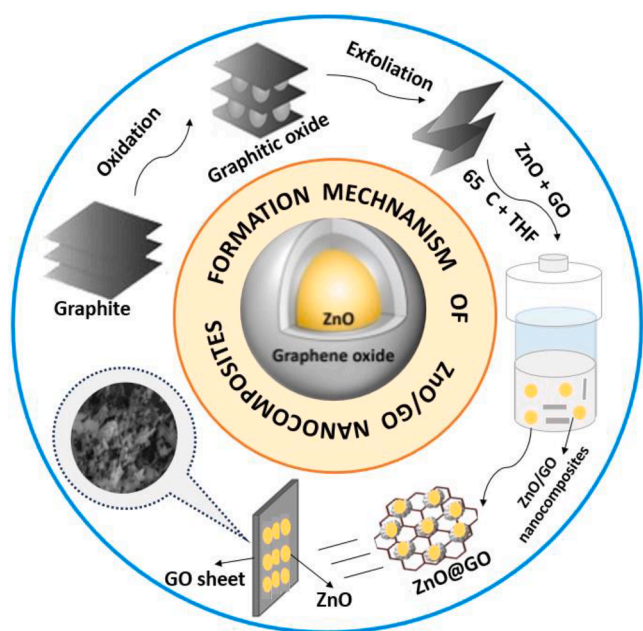


Fig. 2. Formation mechanism of ZnO/GO nanocomposite.

chitosan due to its lack of solubility in acidic settings. Surface modification has been used to enhance structural properties (Shanmugam et al., 2022, Ehsan et al., 2022).

ZnO/chitosan nanoparticles are synthesized using its induced biopolymer, and chitosan functions as a template matrix printer pore on the surface (Rilda et al., 2015). Doping with metal oxide nanoparticles can improve their intrinsic properties, such as surface area and photo-catalytic effectiveness. Chitosan's structure includes amino and hydroxyl functional groups, which are particularly significant for creating composites with metal oxides (Rachna and Shanker, 2019, Hasanzadeh et al., 2023). Chitosan's photocatalytic activity and synergistic impact of sorption processes have led to interest in its modification using nanomaterials, particularly metal oxide nanoparticles like titanium, copper, iron, and zinc (Ma et al., 2016). Transition metal oxide nanocomposites with chitosan have been used in dye abatement (Zango et al., 2022), with successful results in removing carcinogenic PAHs and adsorbing dyes from an aqueous medium (Rani and Rachna, 2020).

2.3.2. ZnO modified with MOFs

Due to their ample surface area and adjustable structure (Zarekarizi et al., 2018), metal organic frameworks (MOFs), are hybrid organic-inorganic molecules that have attracted a lot of interest in a variety of exploitations, including catalysis (Haruna et al., 2023a, Haruna et al., 2023b), gas sorption and separation (Zirak et al., 2021, Gu et al., 2019), sensing (Dong et al., 2019) and pollutants remediation (Adamu et al., 2023). MOF-5 has recently been employed as a sacrificial precursor in the pyrolysis or thermolysis process to create ZnO/C composites with a wide specific surface area and various porous nano/micro shapes (Qu et al., 2020, Xu et al., 2023). According to reports, the ZnO nanoparticle in ZnO/C composites made from MOFs distributed uniformly within a very porous carbon matrix (Hussain et al., 2019). According to Hu et al., MOF-5 that had been partially hydrolyzed was annealed to create the ZnO/C nanocomposite. With aggregation of ZnO nanoparticles and a porous structure, the resulting ZnO/C maintained the petaloid morphology. According to the findings, ZnO/C shown exceptional adsorption and photocatalytic activity on MB breakdown when exposed to sunshine (Hu et al., 2020).

According to the report by Buasakun et al (Buasakun et al., 2021), due to the exceptional qualities of both ZnO and MOF, their coexistence can improve photocatalytic efficiency by reducing the energy band gap, preventing the recombination of electrons and holes, enhancing the capacity to absorb light from the UV to visible regions, and increasing the adherence of dye. According to our findings, ZnO@MOF-46(Zn)-DW functions as an effective photocatalyst in MB degradation due to the synergistic effect of ZnO and MOF-46(Zn). Adamu et al., employed the modification of MIL-101(Cr) with bio synthesized ZnO nanoparticles for the photocatalytic degradation of phenanthrene (Adamu et al., 2024). Accordingly, almost complete degradation of the pollutant (98%) was achieved within shortest irradiation time of 150 minutes which has been attributed to the lower bandgap of the MIL-101(Cr)@ZnO composite (Adamu et al., 2024).

Based on report by Da Trindade et al (Ramasubbu et al., 2019), when compared to the value obtained for the pure ZnO, the band gap value of the composites reduced due to the addition of Zr-MOF. The band gap decrease is contingent upon various parameters such as surface morphology, optical characteristics, and particle size. Zr-MOF was integrated with ZnO particles to form a hierarchical porous structure. This porous structure and the smaller particles give the ZnO/MOF material with rough surface. Because they enable light photons to enter the pores more deeply and reflect severally before easily exiting, these rough surfaces are advantageous. As a result, photons linger in these porous surfaces for comparatively long time. Because there is less incident photon scattering loss on the rough surface, there is more light absorption, which lowers the band gap (da Trindade et al., 2021). In comparison to pure Zr-MOF, the composite that was produced when ZnO was added to the Zr-MOF (substrate) has greater surface area and

significantly better hierarchical pore structure. Thus, it displays typical type IV isotherm with type H3 hysteresis loop. The increased pore capacity and surface area are advantageous for raising performance. Better photocatalytic performance is demonstrated by the ZnO/ZrMOF generated in the report (Cui et al., 2019).

2.3.3. ZnO modified with COFs

A class of crystalline porous organic polymers with highly organized structures and persistent porosity are called covalent organic frameworks (COFs). With their distinct morphologies and conformations, COFs can interact with photons, electrons, holes, spins, ions, and molecules to create limited molecular spaces and interfaces that can be used for molecular design and functional development (Geng et al., 2020). By combining COFs with other functional substances including metal oxides, perovskites, and metal particles, composites are created that blend unique physical and chemical features of the functional materials with COFs' high porosity and large surface areas (El Hassani et al., 2018, Jing et al., 2021). Additionally, by bandgap engineering the composites, metal oxide/COF heterojunctions with superior activity in photovoltaic units and as photocatalysts may be developed (Zhang et al., 2020).

2.3.4. ZnO modified with MIPs

Molecularly imprinted polymers (MIPs) have been employed as an effective sorbent in solid-phase extraction (SPE) recently. MIPs are highly selective materials possessing unique molecular recognition capabilities for target molecules (Mankomal, 2022, Jahanbakhsh and Ebrahimi, 2016). Since MIPs are resistant to high temperatures and pressures, easy to prepare, have good selectivity, chemical stability, physical toughness, and are inexpensive, they have been used widely as sorbents in the extraction of analytes (Didaskalou et al., 2017). The high exterior surface area to volume ratio of nanoparticles (NPs) leads to increased chemical reactivity and capacity as well as quick binding kinetics, making them attractive substrates for surface imprinting. The chemical and physical characteristics of sorbents, such as their uniform spherical geometry and easy, steady dispersion, are enhanced by NPs. ZnO-NPs are one kind of NP that is readily available (Siddiqi et al., 2018). Due to ZnO NP's unique compatibility with both organic and aqueous solvents, it can be incorporated into the majority of material processing operations (Vinayagam et al., 2016, Liu, 2016).

Using a surface imprinting polymerization approach, MIP on ZnO-NPs was easily prepared for the purpose of determining meloxicam in real samples under ultrasonic radiation (Rahmati and Rafiee, 2019). The use of high surface area ZnO-NPs as a suitable support for surface imprinting in this investigation was innovative. ZnO-NPs serve as nanoscale support for specific recognition, and the resulting MIPs have high adsorption and particular recognition properties in addition to being biocompatible and biosafe. ZnO-NPs have therefore been developed to work in conjunction with the surface imprinting polymerization method.

Ultimately, research involving the modifications of ZnO has been done so much and it continues to advance with great potential for commercialization. The type of photocatalyst material, pollutant and its concentration, light source, and energy band gap significantly influence the photocatalytic degradation. A comparison of the factors affecting photocatalysis using ZnO and ZnO-based nanoparticles is presented in Table 2.

2.4. Role of ZnO morphology and surface properties for catalytic application

The ZnO nanoparticles surface properties and morphology have been key factors for the catalytic activities of the material. It exhibited various surface morphologies with different nanostructures. Some common ZnO nanoparticles surface morphologies include structures such as nanospheres (Rani and Rachna, 2019), nanotubes (Vijayakumar et al., 2020), nanowires and nanorods (Luo et al., 2020), nanostars (Veerakumar

Table 2

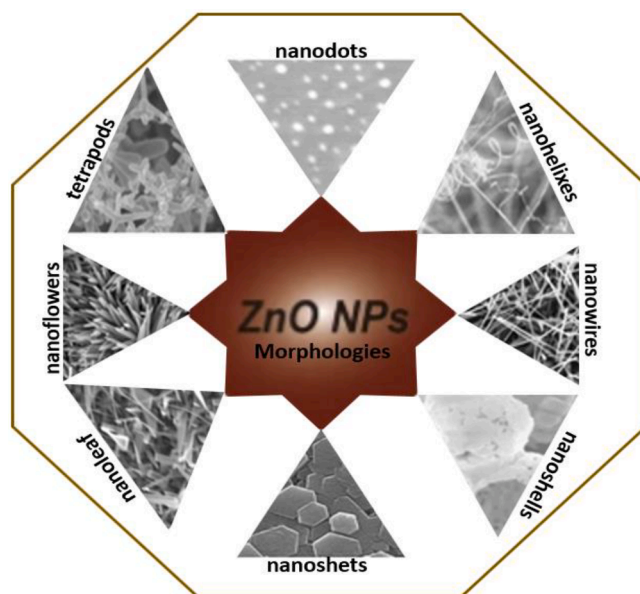
A thorough comparison of factors affecting photodegradation of pollutants using ZnO and ZnO-based photocatalysts.

Entry	Photocatalyst	Pollutants	Experimental conditions	Band gap (eV)	Degradation (%)	Ref.
1.	ZnO	MB	UV light/15.00 mg/L/1–3 h	2.93	100.00	(Luque-Morales et al., 2021)
		MO			85.00	
		Rh B			92.00	
2.	ZnO	Rh B	Solar light/50.00 mg/L/3 h	2.94	93.00	(Luque et al., 2022)
3.	ZnO	MB/Mathanil yellow	UV light/20.00 mg/L/100 min	2.93	99.00	(Priyadharshini et al., 2022)
4.	ZnO	CR	6 W UV light/120.00 mg/L/3 h	2.88	99.00	(Gaur et al., 2023)
5.	Co-ZnO	CR	8 W UV light/35.00 mg/L/75 min	2.74	91.00	(Kumar et al., 2022)
6.	Cu-ZnO	Indigo Carmine	30 W UV light/15.00 mg/L/80 min	3.23	92.20	(Karthik et al., 2022)
7.	Eu/ZnO	MB	15 W UV light/40.00 mg/L/30 min	3.04	99.00	(Haladu et al., 2025)
8.	ZnFe ₂ O ₄ /ZnO	Rh B	30 W visible light/10.00 mg/L/4 h	1.89	91.87	(Nguyen et al., 2022)
9.	ZnO-SnO ₂	MB	300 W visible light/10.00 mg/L/2 h	2.84	82.45	(Dharmana et al., 2024)
10.	CoCr ₂ O ₄ /ZnO	Malachite green (MG)	50 W visible light/10.00 mg/L/2 h	2.80	90.91	(Fadhila et al., 2024)
11.	Fe-ZnO/TiO ₂	MO	14–23 W visible light/10.00 mg/L/2 h	-	78.99	(Davoodi and Shafeeyan, 2024)
12.	GO/ g-C ₃ N ₄ /ZnO	MB	100 W visible light/15.00 mg/L/1 h	-	90.00	(Shakoor et al., 2024)
13.	GO ₅ @Ag ₂ -ZnO	Crystal violet	50 W visible light/5.00 mg/L/150 min	-	97.00	(Kaur et al., 2024)
14.	Ni-ZnO/TiO ₂	Chlorpyrifos	UV light/50.00 mg/L/200 min	-	92.30	(Esfandian et al., 2024)
15.	ZnO@MWCNTs	CR	UV light/2.00 mg/L/90 min	3.17	92.00	(Abisha et al., 2024)
16.	ZnFe ₂ O ₄ /Er-ZnO	Tetracycline	300 W visible light/10.00 mg/L/1 h	1.94	97.00	(Yu et al., 2025)
17.	ZnO/TiO ₂ /CdO/g-C ₃ N ₄	MB	200 W visible light/10.00 mg/L/30 min	2.12–2.85	99.70	(Upadhyay et al., 2025)
		MG			99.80	
		MO			99.90	

et al., 2021), nanosheets (Rani and Shanker, 2019), nanoflowers (Katiyar et al., 2020) etc. Each possessed unique structural features which has influence on their surface properties and catalytic applications. The nanospheres comprised of particles with spherical morphology, while the nanotubes have tubular structures with the nanorods having rod-like morphologies. Similarly, the nanowires are made up of elongated wire-like shapes and the having the flower-like or hierarchical structures. The nanostructure ZnO exposed to crystal facets {001} has higher catalytic activity, while the one having higher percentage of the {100} crystal facets have may exhibit unique surface properties and catalytic behavior. Similarly, the ZnO having combination of the crystal facets possessed higher adsorption and catalytic efficiency. The mesoporous ZnO possessed porous and nanostructures that allow for rapid mass transfer and adsorption of pollutant molecules for photocatalytic applications (Singh et al., 2013), whereas, the hierarchical nanostructures ZnO has multiple branches of interconnected networks, that facilitates the light harvesting efficiency (Wang et al., 2017). On the other hand, the hollow structure ZnO possessed porous shell structure and offer high surface area and catalytic activities (Kovács et al., 2022). For the ZnO with synergistic effects, the core-shell structure nanoparticles consisting of a material (e.g., metal, semiconductor) encapsulated within ZnO shell has been the best option (Matei et al., 2023). Thus, understanding the relationship between ZnO surface morphology has been vital for the optimization of the performance of the material. Fig. 3 has depicted some ZnO nanostructure morphologies for the catalytic applications.

Thus, the ZnO nanostructures with distinct morphologies possessed different surface characteristics, in terms of surface area, crystal facets, surface defects, and electron transport properties which affect the catalytic efficiency of the materials. Some key aspects of how ZnO morphology influences its catalytic performance are:

- Surface Area:** For ZnO nanostructures with high porosity provide avenue for guest molecules adsorption. For examples nanosheets, nanotubes, and nanorods, the materials offer available number of adsorption sites for uptake of molecules and generate sufficient reactive oxygen species for the catalytic applications.
- Crystal Facets:** The ZnO nanoparticles crystal facets such as {001}, {100}, or {110}, has higher photocatalytic applications. The catalytic efficiency of the materials is influenced by their affinity of adsorption towards the target molecules and their efficiency for the generation of reactive oxygen species (ROS).

**Fig. 3.** Different morphologies of ZnO nanostructures.

- Surface Defects:** The occurrence of defects on the ZnO surface e. g., oxygen vacancies, can generate active sites for the guest molecules adsorption. The defects also facilitate the electron-hole pairs and ROS generation which contributed to ZnO materials higher catalytic activities (Manna and Sen, 2023).
- Charge Carrier Dynamics:** The ZnO morphology has influence on the electrons and holes migrations and effective separations. For instance, hierarchical and mesoporous structures prevent frequent recombination of photogenerated species and promote their separation which enhance the lifetime of the generated ROS.
- Light Harvesting Efficiency:** The morphological features of hierarchical structures influence the ZnO light harvesting efficiency and improve the materials performance for the solar light absorption and scattering effect for the catalytic applications.
- Synergistic Effects:** The coupling of two or more ZnO to form hybrid materials or incorporation of other material into ZnO to form composites generate distinct morphologies with synergistic

effects for photocatalytic applications. For instance, hybrid material of ZnO/ZnO (Matysiak and Zaborowska, 2019) and ZnO with g-C₃N₄ (Wang et al., 2023), improved the adsorption performance as well as light absorption efficiency and charge separation efficiency of the materials for catalytic applications.

Overall, the ZnO nanostructures morphology and surface properties play significant role in their adsorption and photocatalytic activities particularly their affinity to the target molecules, light harnessing efficiency, and synergistic interactions with other functionalized materials. Thus, tailoring the ZnO materials morphology by controlling the synthesis condition provide avenue optimizing their performance for catalytic and versatile applications including environmental remediation, wastewater treatment, and energy conversion.

2.5. Benchmarking the efficiency of ZnO over other latest materials towards CO₂ reduction

Recently, ZnO and their NPs' derivatives have been increasingly drawing attention, notably over the past decade due to their distinct physical and chemical properties, making them ideal for use in multitudinous applications across various fields including CO₂ reduction. ZnO possesses high surface area, efficient charge separation, and tunable electronic properties, which enhance CO₂ adsorption and catalytic conversion (Raha and Ahmaruzzaman, 2022). Typically, ZnO plays a crucial role in enhancing CO₂ adsorption across various applications through several key mechanisms. First, they enable chemisorption due to their strong affinity for CO₂ via Lewis acid-base interactions, creating additional binding sites that increase adsorption capacity and efficiency. Second, typically, they featured a larger surface area by their modified adsorbents, allowing more CO₂ molecules to be captured, which boosts performance (Lee et al., 2016). Additionally, ZnO improves the stability of adsorbents, reducing material degradation and extending their lifespan, thus supporting more sustainable CO₂ capture systems. Besides its prominence in CO₂ reduction, ZnO is applicable in areas like photocatalysis, biomedical, sensors, and energy storage. Strategies such as doping, nano-structuring, and surface modifications are used to adjust ZnO's physical and chemical properties to enhance CO₂ reduction, however, with favourable band gap of ZnO is considered a key remarkable feature that supports efficient photocatalytic activity (Sun et al., 2023). For instance, a direct band gap of approximately 3.2 eV for ZnO, is ideal for photocatalytic applications. This energy level allows ZnO to absorb UV light, making it effective in harnessing solar energy for the photocatalytic reduction of CO₂ (Mubeen et al., 2023).

Though only the UV portion of sunlight is absorbed which is limited, the band gap can be tuned by doping with various elements to shift light absorption into the visible spectrum. Lee et al., (Schott et al., 2017) reported that ZnO's efficient charge separation characteristics help minimize electron-hole recombination. Such that this allows more electrons to be available for the reduction of CO₂ into useful products, such as methanol or carbon monoxide. In related work, Ibrahim et al. (Khan et al., 2019) reported that a broad range of nanostructures, such as nanorods, nanowires, nanosheets, and nanoparticles synthesized from ZnO, possess high versatility with a wide range of nanoscale morphologies and tunable growth which often increases the number of active sites available for CO₂ reduction. Moreover, the incorporation of the nanostructures as supporting precursors, often upscale the CO₂ reduction capability of the ZnO due to the expansion of high surface area and mesoporosity. Further established is that ZnO nanomaterials contained oxygen vacancies, which act as active sites for CO₂ adsorption and conversion. These defects help activate the CO₂ molecules, lowering the energy barriers required for the reduction reaction (Le Pivert et al., 2019).

Abir and Somnath (Chakravorty and Roy, 2024) highlighted ZnO as a non-toxic and environmentally friendly compound, in contrast to heavy metals like Cd and Pb, which pose environmental risks. They

emphasized ZnO's superior chemical and thermal stability, making it less prone to photo-corrosion than photocatalysts like TiO₂. Additionally, ZnO serves as both a photocatalyst and electrocatalyst, offering multifunctional capabilities for CO₂ reduction, requiring lower overpotentials and thus less energy than other oxides such as TiO₂ and Fe₂O₃. In yet another work by Ewelina et al., photocatalytic reduction of CO₂ to CO, CH₄, and H₂ using Zn-based photocatalysts in alkaline and aqueous environments was investigated (Kusiak-Nejman et al., 2024). The ZnO photocatalysts showed high solubility in water, forming a homogeneous solution with slightly lower photoactivity than the heterogeneous suspension due to a reduced concentration of bicarbonate ions. The selectivity order was H₂ > CO > CH₄, with -Zn-O-Zn- hydrous bridges playing a key role in CO₂ transport. Zhang et al reported superior photocatalytic activity for CO₂ reduction to fuels compared to CdS alone under visible light. In a gas mixture of 15% CO₂ and 85% Ar, with 10 mL of water, the catalyst produced 35.2 μmol/g/h of CO and 5.9 μmol/g/h of CH₄ over 4 hours at 0.4 MPa pressure. Guo et al. developed a ZnO₂-promoted ZnO photocatalyst through H₂O₂ treatment, which increased surface area and oxygen vacancies. As a result of the enhancement, the catalyst demonstrated 21 times higher CO₂ reduction efficiency to methane and methanol compared to pristine ZnO (Gao et al., 2017). However, while ZnO possesses impressive attributes for efficient CO₂ reduction as highlighted in Fig. 4, an improvement in the performance ability can be enhanced through the creation of heterojunctions with other semiconductors (such as g-C₃N₄, CuO, or TiO₂) that can optimize light absorption and charge separation of ZnO, utilizing ZnO quantum dots or further engineering its nanoscale morphology can enhance light absorption and electron mobility (Kaur et al., 2024, Esfandian et al., 2024).

3. CO₂ conversion with ZnO-based materials

The pollution due to CO₂ resulting natural and anthropogenic processes is inducing serious environmental issues. The CO₂ has been a greenhouse gas that is majorly released into the atmosphere through burning fossil fuels, like crude oil, natural gas, coal, due to energy demand and transportation that resulted in release of the CO₂ into atmosphere in large quantity (Photo-oxidation et al., 2020, Kumar et al., 2018). Deforestation and excessive land-use also largely contribute to the release of CO₂ into the atmosphere but to a lesser degree than the fossils burning. Additionally, the CO₂ is released due to various industrial practices such as steel manufacturing, cement production chemical production, and other heavy industrial practices that emit CO₂ as a byproduct (Chauhan et al., 2019, Lin et al., 2019). When accumulated in the atmosphere, the CO₂ and other greenhouse exert blanketing effect by trapping the solar heat which otherwise will escape into the space. The trapping effect of the CO₂ causes Earth's surface and atmospheric warming (Zhou et al., 2017, Ding et al., 2017). Thus, it served as major contributor to the global warming that causes climate change that disrupt ecosystem because of increasing global temperature, ocean acidification and extreme weather condition (Zango et al., 2024). There is excess of CO₂ which accounted up to the 3.9% with respect to the natural carbon cycle (Tseng et al., 2002). Still, to keep up with the economic growth, consumptions of fossil fuels is expected to keep on rising which directly translates into more CO₂ emission to the atmosphere (Sun et al., 2022).

Thus, CO₂ mitigation is an urgently needed to address the recurring atmospheric phenomenon that is destructive to the ecosystem. Over the years, researchers have made efforts to achieve a carbon neutral environment (Ren et al., 2021). Such efforts include capturing and recycling CO₂ to produce energy-rich products. Due to the chemical stability of the CO₂ its conversion to useful products requires high temperature and pressure and often catalysts are needed to achieve faster and higher yield of conversion (Sun et al., 2022). Currently, the valorization approaches for CO₂ includes CO₂ decomposition, CO₂ hydrogenation, RWGS (reverse water gas shift) and DRM (dry reforming of methane)

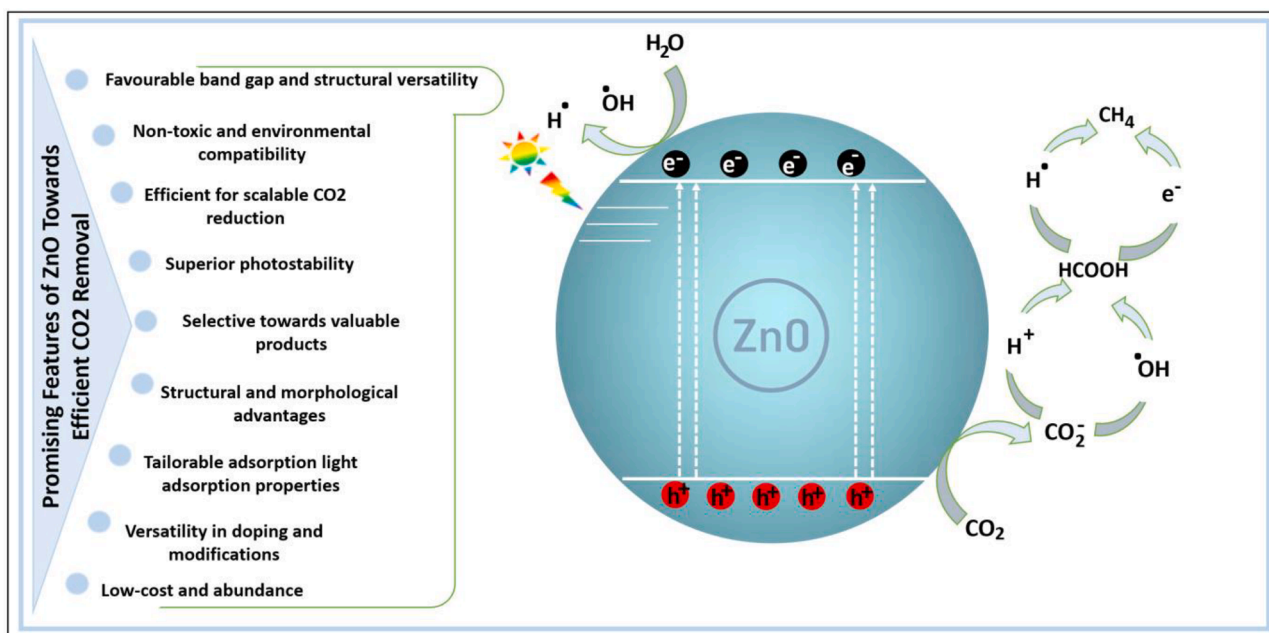


Fig. 4. Impressive attributes of ZnO for efficient photocatalytic CO₂ reduction to other valuable products.

with CO₂ (Sun et al., 2022). However, due to the stability of CO₂, its conversion to chemical building blocks and synthetic fuels is often a tedious process (Sun et al., 2022). Currently, the use of artificial photosynthesis is an ideal method for CO₂ conversion into liquid hydrocarbons (Sayed et al., 2021). The process is facile, green and does not require high reaction temperature or pressure to be maintained. In early 1979, semiconductors like TiO₂, ZnO, CdS, SiC and GaP were reported to show photocatalytic performance towards CO₂ conversion into methanol and ethanoic acid. Other approaches for CO₂ conversion include electrocatalysis and chemocatalysis (Guzmán et al., 2022).

Recently, methods for CO₂ conversion technologies present significant environmental implications that must be carefully considered. While these technologies, such as carbon capture and utilization (CCU), electrochemical conversion, and biological conversion, offer potential solutions for reducing greenhouse gas emissions, they often require substantial energy inputs that can diminish their carbon reduction benefits if the energy is derived from fossil fuels (Turakulov et al., 2024). Additionally, the water footprint associated with these processes can be considerable, particularly in water-scarce regions (Kula et al., 2024). To enhance sustainability, researchers are investigating the integration of renewable energy sources and reclaimed water into CO₂ conversion processes. Ultimately, the effectiveness of these technologies in mitigating climate change is closely linked to the sources of energy used and their compatibility with ecological systems, highlighting the need for a balanced approach in their development and implementation.

3.1. Pristine and modified ZnO nanoparticles for CO₂ conversion

ZnO is an n-type semiconductor that has earned significant attention owing to its low cost, physical and chemical stability and low toxicity with a band gap of ~ 3.37 eV (Darwesh et al., 2024; Singh et al., 2013; Wang et al., 2017). It has a high electron mobility ($115\text{--}205\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$) and large excitonic binding energy (60 meV) (Zanardo et al., 2023). ZnO has a conduction band with a negative potential ($E_{\text{CB}} = -0.44$ eV) and is able to photocatalytically reduce CO₂ to CO or CH₄ (He et al., 2015). However, in view of the unsatisfactory performance of activating thermodynamically stable CO₂ by pristine photocatalysts, various forms of modified photocatalysts/cocatalyst have been synthesized for effective separation of charge carriers so as to have better CO₂ reduction ability (Sayed et al., 2021). Among the photocatalysts, ZnO has been

frequently used for catalysis due to its efficiency to harness light from solar and other artificial sources to generate photoexcited species that reacts with water and oxygen to generate free radicals species that causes the photoinduced the CO₂ conversion (Geioushy et al., 2022).

For instance, synthesis of ZnO using thermal decomposition at 300, 350, and 400 °C for CO₂ photoreduction was conducted for the CO₂ conversion to CH₃OH and CH₃CHO (Hegazy et al., 2020). Highest performance was recorded using ZnO synthesized at 350 °C. The low performance in the case of ZnO synthesized at 400 °C was attributed to oxygen vacancies which served as either recombination centers or electrons trap sites. Similarly, the methanol generation increased in the order $\text{NaHCO}_3 > \text{NaOH} > \text{NaCl}$ when added to the solvent. The effect of crystal facet ($\{110\}$ and $\{001\}$) in porous ZnO nanocatalyst towards photoreduction of CO₂ was also studied (Li et al., 2020). The photocatalytic performance of the porous ZnO with the exposed $\{110\}$ facet was found to be higher than the one with exposed $\{001\}$ facet. The enhanced performance was assigned to good charge-separation efficacy, high CO₂ sorption capability, and efficient activation of CO₂. Although, the sacrificial reagent Na₂SO₃ almost had no impact on the CH₄ yield, it could improve the production yield of CO. Besides facets, the effect of defects in porous zinc oxide nanoplates upon CO₂ photoreduction has been studied (Li et al., 2019). Initially, the porous zinc oxide nanoplates with V_O defects were prepared by ZnS(en)_{0.5} annealing for 2h in air, and amount of vacancy defects could be tailored by ameliorating heating temperature (600, 650 and 700 °C). The number of defects was found to decline with augmentation in annealing temperature. Highest separation of charge carriers, CO₂ sorption capacity and CO₂ activation were achieved using ZnO annealed at 600 °C. This was followed by ZnO annealed at 650 °C and the least performance recorded using ZnO annealed at 700 °C. The sequence of the activity has been confirmed by the transient photocurrent response. Unfortunately, Zn₅(OH)₆(CO₃)₂ was detected during CO₂ reduction, vouchsafing that the ZnO did not have a high stability as a photocatalyst.

The effect of light source on CO₂ conversion using pristine ZnO and ZnS/ZnO nanocomposite has been studied (Akbari and Sharifnia, 2017). The CO₂ conversion percentage in case of ZnO was 14% underneath UV light and 3% underneath visible light. The CO₂ conversion percentage in the case of ZnS/ZnO nanocomposite was enhanced to 45% underneath UV light and 13% underneath visible light. The better visible light performance by the ZnS/ZnO nanocomposite as compared to pristine

ZnO is assigned to the augmented visible light absorption capability and effective separation of charge carriers. There was a study by Lei et al. (Lei et al., 2015) involving hydrogenation of CO₂ to CH₃OH over Cu/ZnO photocatalysts with ZnO having filament-like and rod-like morphology. The Cu/ZnO catalysts with ZnO having filament-like morphology (CZ-filament) exhibited 16.5% conversion of CO₂ and 78.2% selectivity of methanol. The enhanced performance was attributed to more oxygen vacancies and stronger interaction between ZnO and Cu in CZ-filament. The role of copper structure (Cu(100) or Cu(111)) in ZnO/Cu catalyst on the hydrogenation of CO₂ in methanol synthesis was examined (Palomino et al., 2018). The copper substrate structure was found to have impact on the performance of the catalysts. The activity of the catalysts was found to increase in the order Cu (111) < Cu (100) < ZnO/Cu (111) < ZnO/Cu (100).

The impact of morphology on the performances of Pd/ZnO photocatalysts for CO₂ hydrogenation into formic acid was studied (Zhang et al., 2020). During the formation of the catalysts, Pd was loaded upon zinc oxide nanosized crystals with different morphologies, viz. ZnO nanoplates (p-ZnO), ZnO nanorods (r-ZnO), and commercial ZnO (c-ZnO) (Zhang et al., 2020). A morphology-dependence of ZnO in the Pd/ZnO photocatalysts was identified. The performance of different Pd/ZnO nanocatalyst towards CO₂ hydrogenation into formic acid obeyed the sequence of Pd/r-ZnO > Pd/p-ZnO > Pd/c-ZnO. There was greater selectivity to CH₃OH, reaching over 70% with lesser degree of CO production, when Cu is in contact with ZnO plate. However, when zinc oxide rods were exploited, there was a small positive change in CO₂ conversion, whilst significantly low CH₃OH selectivity was obtained. It displayed the role of morphology-controlled strong metal-support interaction, which had large impact on selectivity for the hydrogenation of CO₂ to CH₃OH (Zhang et al., 2020). However, Liu et al. employed the use of zinc oxide micro/nanomaterials with various morphologies and ratios of {0001} facets for the photoreduction of CO₂ (Liu et al., 2016). The ZnO microspheres, ZnO micro flowers and ZnO nanorods were found to have different formation rates. Due to its largest surface area and high ratio of {0001} facets, ZnO nanorods displayed greater CO formation speed (3.814 μmol/g/h), compared to zinc oxide microspheres and zinc oxide micro flowers (3.357 and 1.627 μmol/g/h) (Liu et al., 2016). Due to the drawbacks possessed by ZnO such as rapid electron-hole recombination and narrow light absorption range that diminishes its photocatalytic efficiency. These issues could be resolved by doping with metals through formation of Schottky junction which slows down electron-hole recombination, improves crystalline transformation, enhances absorption of visible light, and surface area to volume ratio of the material. Thus, doping enhances optical, electrical, and magnetic properties of the material (Abebe and Murthy, 2022, Keshta and Gemeay, 2022). Also, research findings have confirmed doping ZnO with heteroatoms such as nitrogen, bismuth, sulfur, and phosphorus enhances its photocatalytic activities (Swathi et al., 2021, Matei et al., 2023). The incorporation of such dopants not only stimulates a great change in the materials' conductivity and structure but also decreases the reaction activation energy barrier (Le Pivert et al., 2019, Chakravorty and Roy, 2024).

Au_xCu/ZnO bimetallic catalysts displayed wider S_{BET}, lower sizes of metal particles, higher oxygen vacancies, more strenuous metal-support interactions, and more copious medium basic locales than the Cu/ZnO monometallic catalyst (Xie et al., 2023). Moreover, in comparison to Cu/ZnO monometallic catalyst, the Au_xCu/ZnO bimetallic catalysts demonstrated comparable CO₂ conversion but augmented CH₃OH selectivity and STY_{MeOH}. They reported that addition of Au enriched active sites modulated the sorption configuration of methoxy species and promoted CO₂ activation (Xie et al., 2023). In a different study, the effect of Au loading in Au/ZnO catalyst towards reduction of CO₂ to methanol was examined (Xie et al., 2023). Increase in Au loading resulted in an increase in Au particles' size in the Au/ZnO catalyst and enhanced selectivity. CO₂ conversion using pristine ZnO and Ag/ZnO through photocatalysis and sonophotocatalysis was also reported. The

performance of the catalysts was higher through sonophotocatalysis as compared to photocatalysis; an effect attributed to the impact of ultrasonic waves in the case of pristine ZnO. The general enhanced performance by the Ag/ZnO catalysts was due to rapid charge carriers' separation and raised O₂ activation by Ag. The main product of the CO₂ conversion is CO and CH₄ (Khan et al., 2022). A study on the surface plasmon resonance mediated CO₂ photoreduction was conducted using (Ag, Au and Pd)/3D porous ZnO nanosheets. Over bare metal oxides, CO₂ is photocatalytically converted to CO with minor amounts of CH₄. Au or Pd loading was found to change product selectivity and augment the hydrocarbon formation, whilst Ag enhanced the CO production more. The selectivity of the principal product, C₂H₆, is parallel to the Au loading. However, the CH₄ selectivity is declined reversely. This mentions that CH₄ is further converted into C₂H₆. Ag loading prompts the CO selectivity and decreases CH₄ selectivity. Pd loading escalates CH₄ evolution rate and decreases CO (Khan et al., 2022). Table 3 is a compilation of various ZnO-based photocatalysts for CO₂ conversion. Table one summarized findings reported on the applications of pristine and modified ZnO for the CO₂ conversion.

The simultaneous conversion of CO₂ can play a dual role in to address environmental challenges not only mitigates the impact of CO₂ on climate change but also is useful in simultaneously converting CO₂ into useful chemicals products or fuels. He et al., developed and evaluated a ZnO/g-C₃N₄ photocatalyst for the efficient conversion of CO₂ into valuable products under visible light irradiation (He et al., 2015). The research focuses on enhancing photocatalytic activity through the formation of a hetero-junction structure that improves charge separation and reduces electron-hole recombination. Ultimately, the study seeks to contribute to sustainable energy solutions by addressing CO₂ utilization. The ZnO/g-C₃N₄ photocatalyst facilitates simultaneous CO₂ conversion by forming a hetero-junction structure that inhibits the recombination of electron-hole pairs, enhancing photocatalytic performance. The loading of ZnO on g-C₃N₄ increases its activity for CO₂ reduction, achieving a CO₂ conversion rate of 45.6 μmol h⁻¹ g_{cat}⁻¹, significantly higher than that of g-C₃N₄ or P25 alone. This efficient charge separation and transfer between the two components under visible light irradiation contribute to the catalyst's effectiveness in CO₂ conversion. The TEM analysis results indicate that ZnO nanoparticles are closely coupled with g-C₃N₄ in the composite. This close coupling suggests effective interaction between the two materials, which is beneficial for charge transfer and enhances photocatalytic performance. Additionally, the analysis confirms the successful formation of the ZnO/g-C₃N₄ hetero-junction structure. The photocatalytic CO₂ reduction using the ZnO/g-C₃N₄ catalyst primarily produces CO, methanol, methane, and ethanol, with CO being the dominant product (He et al., 2015). The study demonstrates that the catalyst effectively converts CO₂ into useful fuels, contributing to sustainable energy solutions. The production of these fuels indicates the potential for utilizing CO₂ as a resource rather than a waste product.

3.2. Adsorption kinetics of CO₂ on ZnO nanoparticles

Adsorption kinetics is a crucial process in various applications, including carbon capture and conversion, as well as catalysis. Understanding the kinetics of CO₂ adsorption on ZnO is essential for optimizing these technologies and designing more efficient materials (Gordijo et al., 2023). ZnO, a versatile semiconductor material with a surface characterized by a number of key features that significantly influence their properties and applications and thus, makes it an attractive adsorbent for CO₂ (Raha and Ahmaruzzaman, 2022). Surface area and morphology significantly influence the CO₂ adsorption kinetics of ZnO nanoparticles. Due to their small size, ZnO nanoparticles exhibit a significantly larger surface area compared to bulk ZnO (Raha and Ahmaruzzaman, 2022). This high surface area provides numerous potential adsorption sites for CO₂ molecules, increasing the overall adsorption capacity. Furthermore, the shape and texture of the ZnO

Table 3
Summary of applications of ZnO-based materials for CO₂ conversion.

Catalyst	Experimental condition	Product(s)	Yield (μmol/g)	Reusability	Remarks	Ref
ZnO NPs	125 mg/L of Na ₂ CO ₃ ; 30 mg/L catalyst;	CH ₃ OH	18	5	The Pt NPs incorporation onto the ZnS–ZnO formed heterojunction with extended lifetime and improve the catalytic efficiency.	(Mohamed et al., 2021)
ZnS–ZnO	300 W Xe lamp and 9 hours of irradiation		36			
Pt/ZnO			667.5			
Pt/ ZnS–ZnO			700			
C–ZnO CTSHS	80 kPa of CO ₂ ; 50 mg/L of photocatalyst; 300 W Xe lamp; and 4 hours of irradiation	CO	0.83	4	The stability and efficiency of the ZnO was improved by the presence of C and Mn co-dopants.	(Sayed et al., 2021)
Cu/ZnO	25 bars; 270 °C; H ₂ /CO ₂ /N ₂ molar ration commensurate to 3/1/ 1	CH ₃ OH	5.27	-	The photocatalytic efficacy was improved by the Cu incorporation.	(Guzmán et al., 2022)
Ag/ZnO	CO ₂ /H ₂ O; dose = 0.1 g/L, 250 W Xe lamp; time = 4 hours	CO	1.75	5	The ZnO combination with Ag improved the material stability and catalytic efficiency.	(Khan et al., 2022)
Cu/ZnO rod	3 CO ₂ /H ₂ ; 0.3 g/L of catalyst; 3.0Mpa pressure; 300 W Xe lamp; and 4 hours of irradiation.	CH ₃ OH	23.0	-	The Cu/ZnO filament has exhibited higher efficiency due to better interaction betwixt the ZnO and Cu.	(Lei et al., 2015)
Cu/ZnO filament			0.21			
Cu/ZnO catalyst			0.55			
ZnO/g-C ₃ N ₄	0.4 MPa; 10 mg/L of catalyst; 500 W Hg Xe lamp and 4 hours of irradiation	CO	0.24	6	The ZnO/g-C ₃ N ₄ exhibited synergistic effects for the photoreduction of the CO ₂ to fuels.	(He et al., 2015)
ZnO/MoS ₂ in NaHCO ₃	0.5 M of NaHCO ₃ ; 0.5 g/L of catalyst; 150 W Hg Xe lamp and 4 hours of irradiation	CH ₃ OH	45.6	-	The NaHCO ₃ has the highest yield of methanol production upon irradiation for 4 hours.	(Geioushy et al., 2022)
ZnO/MoS ₂ in NaOH	0.5 M of NaOH; 0.5 g/L of catalyst; 150 W Hg Xe lamp and 4 hours of irradiation	CH ₃ CHO	170.5	-	The greater photocatalytic activity in the NaOH was attributed to the OH ⁻ formation by the photocatalyst.	(Geioushy et al., 2022)
ZnO/MoS ₂ in NaCl	0.5 M of NaCl; 0.5 g/L of catalyst; 150 W Hg Xe lamp and 4 hours of irradiation	CH ₃ OH	30.97	-	The Cl ⁻ from the NaCl promotes charge separation for the photoreduction process.	(Geioushy et al., 2022)
ZnO-300 in NaHCO ₃	0.5 M NaHCO ₃ ; 0.1 g/L of catalyst; 150 W Hg lamp; 1 hour of irradiation.	CH ₃ CHO	2.26	-	The ZnO-300 has the highest conversion efficiency because it has the highest excessive oxygen vacancies which prevent the charge recombination.	(I.M. Hegazy et al., 2020)
ZnO-350 in NaHCO ₃		CH ₃ OH	6.79			
ZnO-300 in NaOH	0.5 M NaOH; 0.1 g/L of catalyst; 150 W Hg lamp; 1 hour of irradiation	CH ₃ CHO	17.79	-	Similarly, the ZnO-300 has the highest conversion efficiency because of its excessive oxygen vacancies.	(I.M. Hegazy et al., 2020)
ZnO-350 in NaOH		CH ₃ OH	5.07			
ZnO-400 in NaOH		CH ₃ CHO	52.0			
ZnO-600	0.25 M N ₂ SO ₃ ; 30 mg/L ZnO; 300 W Xe lamp; time and 4 hours of irradiation.	CH ₃ OH	12.2	-		
ZnO-650		CH ₃ CHO	11.0			
ZnO-700		CH ₃ OH	11.6			
Au/ZnO	3 MPa CO ₂ ; WHSV of 24,000 mL/h/g; 0.1 g/L of catalyst; temperature of 200 - 275 °C for 1 hour.	CH ₃ OH	11.6	2	The ZnO possessed the lowest activity for the CO ₂ conversion.	(I.M. Hegazy et al., 2020)
Cu/ZnO		CH ₃ CHO	94.5			
Au ₀₋₀₀₅ Cu/ZnO		CH ₃ OH	19.5			
Au/m-ZnO	0.1 bar of CO ₂ ; 0.1 g/L of catalyst; 300 W Xe lamp; 6 hours of irradiation.	CH ₃ CHO	10.9	-	The ZnO-600 has the greatest photoreduction Efficiency for the CO ₂ conversion.	(C. Li et al., 2019)
Ag/m-ZnO		CO	3.8			
Pd/m-ZnO		CH ₃ OH	3.1			
Pd/r-ZnO	1 MPa CO ₂ and 1 MPa H ₂ ; 10 mg/L of Pd-ZnO; temperature of 100 °C, 1 hour and stirring rate of under 800 r/min	CH ₃ CHO	2.5	4	The Au ₀₋₀₀₅ Cu/ZnO has exhibited higher stability and excellent photoreduction efficiency for the CO ₂ conversion to methanol.	(Xie et al., 2023)
Pd/p-ZnO		CH ₃ OH	32.8			
Pd/c-ZnO		CH ₃ CHO	179.7			
Cu–ZnO _{Cel-T}	0.1 bar of CO ₂ ; 50 mg/L of catalyst; 300 W Xe lamp; irradiation for 6 hours.	CH ₃ CHO	314.4	2		
CuO–ZnO _{Cel-T}	0.1 bar of CO ₂ ; 50 mg/L of catalyst; 300 W Xe lamp; and 6 hours of irradiation.	CH ₃ OH	21.0	4	The metal nanoparticles particularly the Au have significantly improved the light absorption efficiency of the ZnO for the CO ₂ photoreduction.	(J. Zhao et al., 2019)
CuO–ZnO _{C-T}		C ₂ H ₆	27.0			
CuO–ZnO powder		CO	25.0			
ZnO	0.05 g/L of catalyst; solar light; and 6 hours of irradiation.	CH ₄	18.0	4	The Pd incorporation improved the photoreduction efficiency of the ZnO for the CO ₂ conversion.	(J. Zhang et al., 2020)
Ag/ZnO		HCOOH	10.1	4		
ZnO	0.1 M NaOH; 60 mL of CO ₂ ; 100 mg/L of catalyst; 300 W Xe lamp; and 180 min of irradiation.	CH ₃ OH	8.8	6	The CuO–ZnO _{Cel-T} demonstrated enhanced UV–visible light absorption the CO ₂ reduction.	(Shi et al., 2022)
ZnO-rGO		CH ₄	5.2	6	The CuO–ZnO _{Cel-T} has also demonstrated good stability for effective photoreduction of the CO ₂	(Shi et al., 2022)
		CO	184.56			
		CH ₃ OH	0.52			
		CO	51.63			
		CH ₄	24.60			
		CH ₃ OH	5.08			
		CO	3.2	10	The presence of Ag in the composite has improved the light absorption and stability of the ZnO for effective photoreduction of the CO ₂	(Hoai et al., 2022)
		CH ₄	0.56			
		CO	9.8			
		CH ₄	2.4			
		CH ₃ OH	263.17	3	The incorporation of rGO improved the light harnessing efficiency of ZnO for the adsorption and photoreduction of the CO ₂ .	(Zhang et al., 2015)
		CH ₃ OH	52.36			

nanoparticles, such as porous structures with high surface roughness, can also influence CO₂ adsorption (Petrovic et al., 2021). These structures can provide additional adsorption sites within the pores, further enhancing CO₂ uptake. Due to their small size, ZnO nanoparticles exhibit a very high surface area-to-volume ratio (S. Raha and Ahmar-uzzaman, 2022). This large surface area provides numerous active sites

for chemical reactions, making them highly effective catalysts and adsorbents (Nalwa et al., 2017). The surface chemistry of ZnO nanoparticles significantly influences their CO₂ adsorption kinetics. Surface charge plays a crucial role in their interactions with other molecules and materials. Electrostatic interactions between the charged surface and CO₂ molecules can significantly impact the adsorption process (Petrovic

et al., 2021).

Furthermore, the presence of surface functional groups, such as hydroxyl groups (-OH), can also influence CO₂ adsorption. These groups can interact with CO₂ molecules through hydrogen bonding or other weak interactions, enhancing the adsorption process (Petrovic et al., 2022). The surface of ZnO nanoparticles often contains various defects, such as oxygen vacancies, zinc interstitials, and surface hydroxyl groups (Nagpal et al., 2022). These defects can act as active sites for chemical reactions (Wawrzyńczyk et al., 2018) and can significantly influence the adsorption of CO₂ over the nanoparticles. In fact, surface defects, such as oxygen vacancies and zinc interstitials, significantly influence CO₂ adsorption kinetics on ZnO nanoparticles (Mahmud et al., 2023). Oxygen vacancies on the ZnO surface act as active sites for CO₂ adsorption, significantly enhancing the adsorption capacity and kinetics. In this study, among the synthesized ZnO materials, the 1:4 ZnO formulation demonstrated superior photocatalytic CH₄ production, yielding 1.3×10^{-1} μmol, a remarkable three-fold enhancement compared to commercial ZnO (4.8×10^{-2} μmol). The robustness of this 1:4 ZnO photocatalyst was further validated through a four-cycle stability test, exhibiting a modest 7.7% performance reduction after the fourth cycle (Keshta et al., 2024). This study presents a novel mechanistic framework for CO₂ photoreduction to valuable fuels utilizing defective ZnO nanoparticles. These findings are expected to contribute significantly to advancing sustainable industrial practices. In a different study, the engineered oxygen vacancies within the ZnO structure exhibited a pivotal role in facilitating efficient charge transfer, minimizing recombination, and consequently enhancing catalytic activity. The ZnO sample synthesized at 350 °C utilizing HCO₃⁻ anions in an aqueous solution demonstrated the highest catalytic efficiency, achieving a maximum methanol yield of approximately 113 μmol/g (Hegazy et al., 2020). Accordingly, the study explored various scenarios, highlighting the synergistic interplay between anion type and the presence of oxygen vacancies. Furthermore, the investigation encompassed a proposed hypothesis for the reaction mechanism governing CO₂ photoreduction over the ZnO catalyst. Similarly, Zn interstitials can also act as adsorption sites for CO₂, further influencing the adsorption process (Huang and Huang, 2023).

The surface of ZnO nanoparticles can be modified through various techniques, such as coating with polymers or inorganic materials, or functionalization with organic molecules. This surface modification can alter the properties of the nanoparticles and expand their range of applications. Doping ZnO with other elements can alter its electronic properties and create additional adsorption sites for CO₂. In this context, density functional theory calculations revealed that doping ZnO (0001) monolayers with transition metals significantly enhances CO₂ reduction reaction (CRR) activity by lowering the overpotential compared to pristine ZnO. The oxidation state of the transition metals, determined by their d-orbital occupancy, governs the catalytic behavior. Early transition metals (Sc-Cr) with +3 oxidation states favored CH₄ production, while late transition metals (Mn-Cu) with +2 oxidation states preferentially produce HCOOH. Notably, Co-ZnO demonstrated exceptional performance, producing HCOOH at an ultra-low overpotential of 0.02 V and exhibiting promising potential for CH₃OH production with an overpotential of only 0.45 V (Sikam et al., 2021). Coating ZnO nanoparticles with other materials, such as polymers or metal oxides, can further enhance their CO₂ adsorption properties. Certain metal oxides or polymers function as co-catalysts, accelerating the kinetics of CO₂ adsorption. This catalytic activity is achieved through the facilitation of chemical reactions between the CO₂ molecules and the coated ZnO nanoparticles material, consequently enhancing the overall efficiency of CO₂ capture and conversion processes. Furthermore, the incorporation of metal oxides or polymer contributes significantly to the stability and durability of the ZnO nanoparticles material. By mitigating the risk of the material degradation, metal oxides or polymers effectively prolong the lifespan of the ZnO nanoparticles material, thus ensuring the long-term sustainability and operational efficiency of CO₂ capture

systems (Khdayr et al., 2022, Fathalian et al., 2024).

The adsorption process, involving the interaction between CO₂ molecules and the ZnO surface, leads to the formation of a physical or chemical bond. The rate of this adsorption is influenced by various factors, including temperature, where higher temperatures generally accelerate the process due to increased molecular kinetic energy. Thermal desorption spectroscopy (TDS) experiments revealed a strong correlation between the presence of surface defects and CO₂ adsorption behaviour (Wang et al., 2005, Wang and Burghaus, 2005). Two distinct TDS peaks were observed. Hydrogen pre-exposure eliminated the high-temperature peak, while sputtering enhances its intensity. These findings suggested that the high-temperature peak originates from CO₂ adsorption on specific defect sites, such as oxygen vacancies, while the low-temperature peak corresponds to CO₂ adsorption on pristine ZnO(0 0 1) surface sites. The observation of two distinct TDS peaks in the study strongly suggests the presence of at least two different adsorption mechanisms. The low-temperature peak likely corresponds to weaker, physisorption-like interactions of CO₂ with pristine ZnO surface sites. These interactions are generally characterized by weaker and less specific forces. In contrast, the high-temperature peak, associated with defect sites, suggests stronger chemisorption interactions. These interactions are likely stronger due to the localized electronic perturbations and charge imbalances introduced by the defects (Tang and Luo, 2013).

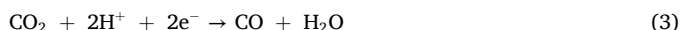
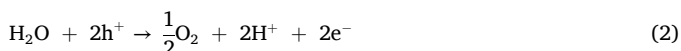
Regarding kinetics implications, defect sites, due to their stronger interactions with CO₂ molecules, are likely to exhibit faster adsorption rates compared to pristine sites. This implies that the presence of defects can significantly enhance the overall rate of CO₂ adsorption on ZnO. Furthermore, the stronger binding of CO₂ molecules to these defect sites may also influence the desorption kinetics, potentially leading to slower desorption rates and consequently higher CO₂ retention capacities. Pressure also plays a role, with increased pressure enhancing the adsorption rate by increasing the concentration of CO₂ molecules available for adsorption (Soo et al., 2024). As pressure increases, so does the van der Waals energy, which can make adsorption rate faster (Hong et al., 2024). This implies that as the pressure of the CO₂ gas increases, the concentration of CO₂ molecules in the vicinity of the ZnO surface also increases. This increased molecular density leads to stronger van der Waals forces between the CO₂ molecules and the ZnO surface. Stronger van der Waals forces, in turn, translate to a stronger attractive force between the CO₂ molecules and the ZnO surface (Gordijo et al., 2023). This increased attractive force facilitates faster adsorption, as the CO₂ molecules are more readily drawn towards and captured by the available adsorption sites on the ZnO surface (Gordijo et al., 2023).

By studying the adsorption kinetics of CO₂ on ZnO, researchers can gain valuable insights into the mechanisms of this process and develop strategies to improve the performance of ZnO-based materials in various applications. This implies that with methodical studies of the kinetics of CO₂ adsorption on ZnO, researchers can gain invaluable insights into the intricate mechanisms governing this process. This includes identifying the rate-limiting steps, such as determining which step in the adsorption process (e.g., diffusion of CO₂ to the surface, adsorption onto specific sites, surface diffusion), which is the slowest and thus controls the overall adsorption rate. Furthermore, characterizing the adsorption isotherms, which involves understanding how the amount of CO₂ adsorbed varies with pressure and temperature, provides crucial information about the strength and nature of the adsorbent-adsorbate interactions. Additionally, investigating the influence of surface properties, such as surface area, morphology, and the presence of defects, on the adsorption kinetics is crucial for a comprehensive understanding of the adsorption process.

3.3. Mechanisms for CO₂ conversion

The mechanism for conversion of CO₂ using ZnO nanomaterials varies depending on the nature of the ZnO material in the study. The

usual mechanism could be explained using the study involving the ZnO photocatalyst use for reduction of CO₂ to CO (Fig. 5) (Liu et al., 2016). As shown in eqns. (1–3), upon visible light illumination, electrons from the valence band (VB) are excited to conduction band (CB), holes at the VB then oxidize H₂O to O₂, while the photogenerated electrons reduces CO₂ to CO. However, in the study by Hegazy et al. (Hegazy et al., 2020) involving the use of ZnO with optimized (Zn300 and Zn350) and excess (Zn400) oxygen vacancies, the performance of the ZnO was oxygen vacancy dependent. Although both catalysts resulted in the conversion of CO₂ to CH₃OH via reduction at the CB, however, the excess vacancies in Zn400 resulted in the formation of recombination centers, which resulted in a decrease of photocatalytic activity.



Doping is another enhancement approach which has resulted in promising results. The modification not only impact on the photocatalytic performance but sometimes on the product selectivity. Usually, CO₂ is converted to CO with minor amount of CH₄ on bare metal oxide photocatalysts (Woolerton et al., 2010). However, in the study by Zhao et al., the loading of Au NPs on m-ZnO NSs array resulted in the formation of C₂H₆ besides CH₄. Notwithstanding, Au/ZnO-NRs and Au/ZnO-NPs did not produced C₂H₆, but only CO and CH₄ (Zhao et al., 2019). The main point was the product selectivity during the applications of the NPs for CO₂ conversion. Usually, CO₂ is converted to CO on bare metal oxides, together with some amounts of CH₄ (Tseng et al., 2002, Sun et al., 2022). Interestingly, loading of plasmonic metals such as Au, Ag or Pd changed the product selectivity as well as increased the CH₄ and C₂H₆ production. Loading Au promoted C₂H₆ yield, Ag yielded mainly CO with small amounts of CH₄, while Pd mainly promoted CH₄ conversion. Similarly, they also found that Ag/m-ZnO-x predominantly generates CO, while Pd/m-ZnO-x predominantly generates CH₄. Thus, Ag is more positive for production of CO, while Au or Pd loading alters the product selectivity and remarkably raise the production of hydrocarbon. The study suggested that, the change in the product selectivity

could be attributed to a strong metal-semiconductor interaction that alters CO₂ conversion pathways. In a different study, Sayed et al., introduced Mn ions having switchable valence states to form Mn, C-co-doped ZnO. The presence of Mn ions in C-doped ZnO could form impurity levels/defect states, reduce the band gap, improve light harvesting, act as distinctive active sites/enrich existing active sites, CO₂ adsorption, and enhance overall catalytic conversion due to its ability to share electrons with reactants/intermediates. As shown in Fig. 6, the process commenced via the activation CO₂ to highly active radical anion at confined Mn active centers. The intermediate anion undergoes an electron-coupled proton transfer process resulting in the formation of CO (Sayed et al., 2021).

Besides photocatalytic applications, there was a study on electrocatalytic reduction of carbon dioxide to carbon monoxide (Geng et al., 2018). The electrochemical reduction of CO₂ to CO usually involves

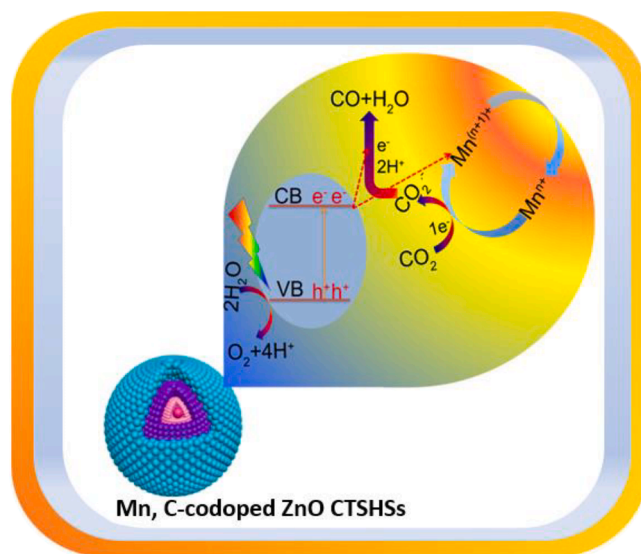


Fig. 6. Schematic illustration of CO₂ activation and reduction over Mn, and C-co-doped ZnO. Adapted from ref. (Sayed et al., 2021).

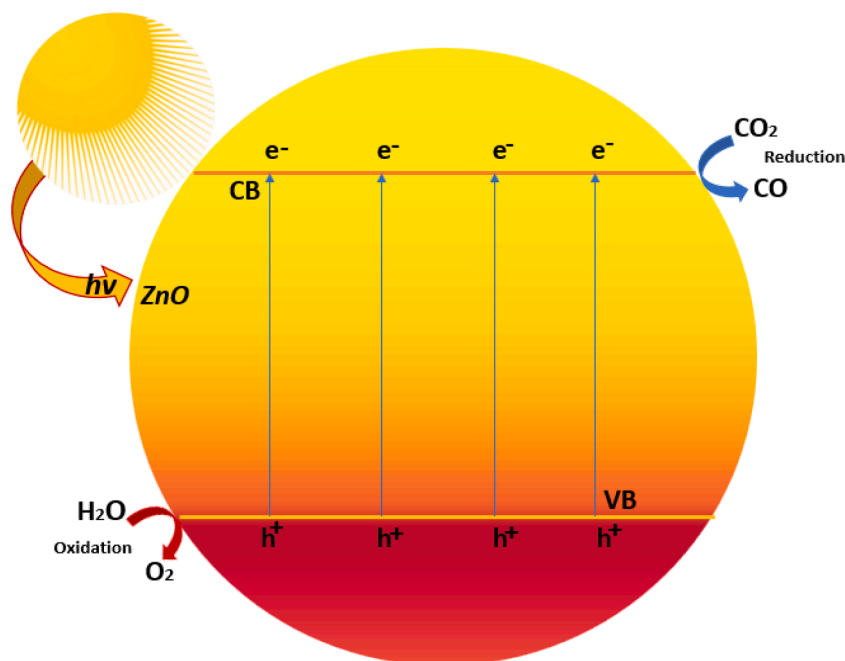
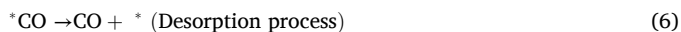
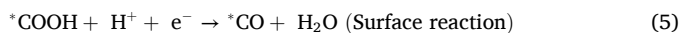
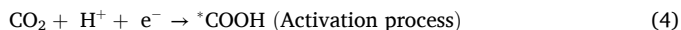


Fig. 5. Schematic diagram of CO₂ photoreduction mechanism involving ZnO.

three processes of activation, surface reaction and desorption as shown in eqns. (4 – 6). Also, there was another study on the effect of oxygen vacancy in ZnO (101) during the electroreduction of CO₂ to CO (Zong et al., 2022). The *COOH formation on ZnO (101) without oxygen vacancies had the largest energy barrier, while there was a low ΔG value of 3.53 eV for *COOH in the case of ZnO (101) with oxygen vacancy. Such evidence reveals that oxygen vacancy enhanced the performance of ZnO (101) towards CO₂ reduction (Zong et al., 2022).



However, Xue et al also appraised the mechanism of CO₂ hydrogenation to CH₃OH by catalytic conversion using Cu/ZnO and Au_xCu/ZnO (Xie et al., 2023). The process follows formate pathway, as previously reported (jun Wang et al., 2019). The formation of metal oxide interfaces with abundance of oxygen vacancies have been recognized as active locales for the process. Au incorporation into the Cu/ZnO catalysts formed homogeneous bimetallic alloy of Au-Cu composition which generates more metal interfaces by declining the size of the metal particles. Also, incorporation of Au increased the number of oxygen vacancies in the composite, which enhanced the number of active sites for CO₂ adsorption. Additionally, presence of Au enriched the basic medium sites of the catalyst which promotes the CO₂ activation. Thus, the Au-Cu alloy cause the configuration of methoxy intermediate products to be adsorbed, resulting in more effective catalytic conversion route. As such, the bimetallic Au_xCu/ZnO catalysts work synergistically in boosting the methanol synthesis. Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) has also suggested the formate pathway. Upon addition of the Au, the sorption configuration of methoxy species was changed. Notably, Only *bOCH₃- species was the species detected when Au_{0.005}Cu/ZnO catalyst was used. However, in the presence of Cu/ZnO catalyst, two species (*bOCH₃- and *tOCH₃-) were identified. An intermediate of *HCOO was formed when the *CO₂ with the dissociated *H atoms is attacked by the catalysts (Liu et al., 2022). The hydrogenation of the *HCOO intermediate was formed *H₂COO, *H₂COOH, *H₂CO and *CH₃O as the successive intermediates before the final formation of the CH₃OH (Fig. 7) (Xie et al., 2023).

The mechanisms for CO₂ conversion over ZnO materials involve

photocatalytic activation, where visible light excites electrons from the valence band to the conduction band, generating electron-hole pairs. The photogenerated electrons reduce CO₂ to products like carbon monoxide and methanol, with efficiency enhanced by oxygen vacancies that serve as active sites. ZnO's high surface area and effective charge separation minimize electron-hole recombination, increasing available electrons for reduction. Additionally, defects such as oxygen vacancies facilitate CO₂ adsorption and conversion. Overall, these characteristics position ZnO as a promising material for efficient CO₂ conversion.

The scalability of CO₂ conversion processes using ZnO materials is supported by several studies, indicating that these processes can be effectively scaled up for practical applications. Further research and development would be necessary to evaluate the practical scalability of these methods in real-world applications. ZnO-based catalysts can be synthesized using scalable methods. For instance, the AuAg/ZnO catalyst for electrocatalytic CO₂ reduction was prepared using an easily scalable method, demonstrating high Faradic efficiency and controllable composition and morphology (Sarno et al., 2020). Similarly, ZnO/h-BNC hybrids were prepared using a scalable one-step thermal treatment (Yamuna et al., 2015). A low-carbon, scalable mechanochemical strategy has been developed to convert spent ZnO from alkaline batteries into Zn-MOF-74, which is effective for CO₂ capture (Ma et al., 2024). This method reduces energy consumption by around 50% compared to traditional methods, highlighting its scalability and efficiency. The aerosol-assisted method for synthesizing mesoporous Cu/ZnO-ZrO₂ catalysts is another scalable process (Wang et al., 2023). This method produces catalysts with high thermal and photothermal performance for CO₂ reduction to methanol, demonstrating the potential for large-scale production. ZnO-based materials have been shown to be effective in both electrocatalytic and photocatalytic CO₂ reduction processes. For example, ZnO nanosheets prepared by a solvothermal method exhibited high CO faradic efficiency and stability, making them suitable for scalable applications (Wang et al., 2023). Additionally, ZnO's properties make it an ideal candidate for photocatalytic CO₂ reduction, with various modification techniques enhancing its performance (Kshirsagar et al., 2024). The Zn/ZnO thermochemical cycle for CO₂ splitting is another scalable approach. This method promises rapid hydrogen and carbon monoxide production rates with complete conversion of zinc-to-zinc oxide, significantly improving cycle efficiency (Abanades, 2022).

The conversion of CO₂ into valuable products is a critical area of

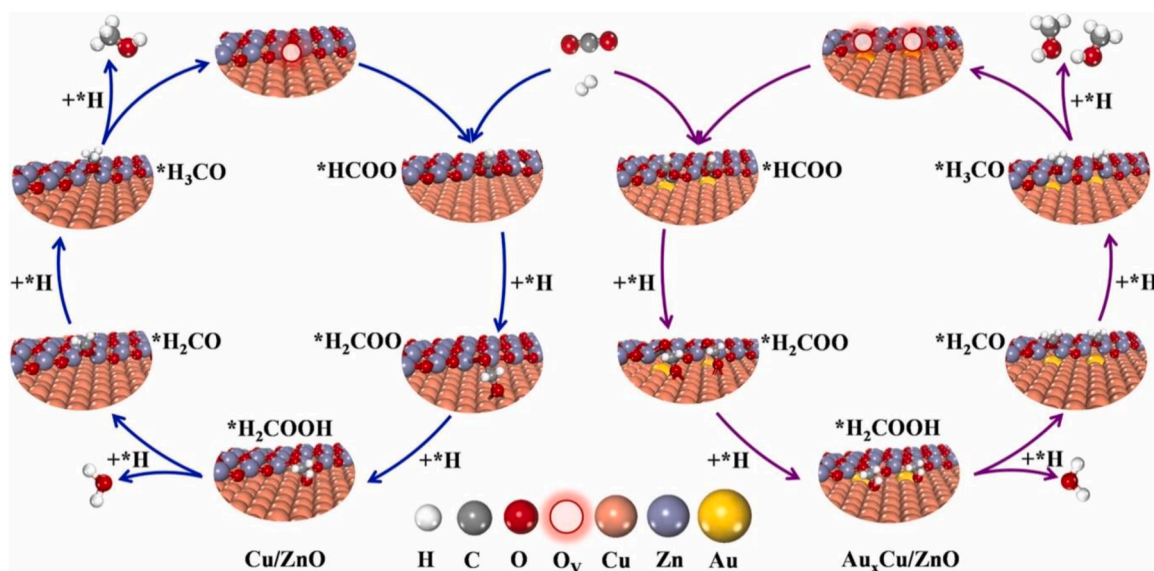


Fig. 7. Proposed mechanism for the application of Cu/ZnO (left) and Au_xCu/ZnO (right) catalysts for CO₂ hydrogenation to methanol. Reproduced from ref (Xie et al., 2023).

research aimed at reducing atmospheric CO₂ levels and mitigating climate change. Various methods have been developed for CO₂ conversion, each with its own advantages and challenges. Below is a comparison of different CO₂ conversion methods and their effectiveness compared to other compounds (Table 4).

In summary, while both photocatalysis and electrocatalysis using ZnO materials aim to convert CO₂ into valuable chemicals, they operate under different mechanisms and conditions. Photocatalysis relies on light to generate reactive species, whereas electrocatalysis uses an external voltage to drive the reaction. Each method has its own set of challenges and requires specific modifications to optimize performance. Table 5, highlighted the main comparison between them. Both photocatalysis and electrocatalysis using ZnO materials have their unique advantages and challenges in CO₂ conversion. However, combining these processes into a photoelectrocatalytic system can leverage the strengths of both methods, leading to enhanced efficiency and selectivity for CO₂ reduction. This combined approach holds promise for developing more effective and sustainable catalytic systems for CO₂ conversion.

4. Photocatalytic degradation of organic pollutants

Water pollution due to organic contaminants such as personal care products, drugs, pesticides, industrial chemicals, heavy metals, and their metabolites has caused serious environmental issues. The organic pollutants are synthetically produced for domestic and industrial use. These pollutants can contaminate the environment as they are found in soils, and water bodies which disturb the environment and the ecosystem (Adamu et al., 2024). Primarily, the pollutants are discharged as effluents from petroleum exploration, chemical processing industries, and mining activities. The major concern with these pollutants is their long range of transportation, persistency, and bioaccumulation (Hamidon et al., 2024). Hence, public concern has been raised about their effects and toxicities to both human and the ecosystem. They are highly toxic to human, plants, and the aquatic organisms. The existence of teratogenic, carcinogenic, and mutagenic properties in these compounds might pose significant dangers for both aquatic animals and human health (Liu et al., 2023). They have been reportedly detected in different water bodies including fresh waters, sea, and ocean. Many hazardous

Table 5
A brief comparison between photocatalysis and electrocatalysis using ZnO materials aim to convert CO₂.

Aspect	Photocatalysis	Electrocatalysis
Mechanism	Light-induced electron-hole pair generation and redox reactions (Cappelletti et al., 2015, Chopra, 2022, Bae et al., 2017).	Electron transfer from electrode to CO ₂ under applied voltage (Wang et al., 2023, Yadav and Purkait, 2016).
Catalyst Structure	ZnO with modifications like doping or hybrid structures to enhance performance (Bae et al., 2017).	ZnO nanosheets with rough surfaces and mesoporous structures for more active sites (Wang et al., 2023).
Reaction Conditions	Ambient pressure and temperature, UV or visible light (Cappelletti et al., 2015, Chopra, 2022, Bae et al., 2017).	Specific electrolytes and applied potentials
Challenges	Limited to UV light, prone to photocorrosion, requires modifications (Cappelletti et al., 2015, Qi and Yu, 2020).	Dependent on electrolyte and potential, maintaining selectivity and stability (Yadav and Purkait, 2016).

chemicals and their products have been found in domestic and industrial effluent samples, surface, and marine waters. These harmful chemicals are only partially removed and even in some instances not entirely treated before discharge into the water bodies by the industries (Ramasubbu et al., 2019, da Trindade et al., 2021).

Due to the rising concern about the consequences of hazardous organic compound pollution of water bodies, environmental agencies recommended rules to prevent the indiscriminate discharge of organic pollutants into freshwater sources. Environmental scientists and regulatory bodies are fascinated by the search for effective and novel techniques to cleaning up contaminated water bodies (Bhatt et al., 2023). For instance, the Stockholm Convention was aimed to investigate ways to perhaps eradicate the pollutants in the environment. Their main focus has been on implementing low-cost approaches for pollutant detection, control, and treatment (Sousa et al., 2018).

Various wastewater treatment methods such as coagulation (Jabbar et al., 2022), Fenton degradation (Ahmad et al., 2023), chemical precipitation (Minas et al., 2017), photocatalytic degradation (Haruna et al., 2022, Haruna et al., 2020) etc. have been developed for wastewater remediation. Among the treatment methods, photocatalytic

Table 4
A comparison of different CO₂ conversion methods.

Method	Description	Products	Advantages	Challenges	Ref
Thermal Catalysis	High-temperature conversion	Methanol, methane, hydrocarbons	High conversion rates	High energy input	(Sabri et al., 2021)
Photocatalysis	Light-driven conversion	Formic acid, formaldehyde, methanol	Utilizes solar energy	Limited by light availability	(Sabri et al., 2021)
Electrocatalysis	Electrical energy-driven conversion	CO, formic acid, ethylene	High reaction rates	Limited to C1 and C2 products	(Okonkwo and Biswas, 2021)
Photothermal Catalysis	Combines light and heat for enhanced efficiency	Various hydrocarbons	Efficient energy utilization	Complex setup	(Shah et al., 2023)
Microbial Fixation	Microorganisms convert CO ₂ into organic compounds	Organic acids, hydrocarbons, bioplastics	High selectivity and variety of products	Slow reaction rates	(Shah et al., 2023)
Enzymatic Conversion	Enzymes convert CO ₂ under mild conditions	Fuels, chemicals	High selectivity and yields	Scalability issues	(N.V.D. Long et al., 2017)
Non-Thermal Plasma	Room temperature dissociation of CO ₂	Methanol, syngas	High energy efficiency, near-zero emissions	Technology still in development	(Ashford and Tu, 2017)
Chemical Absorption	Amino-containing absorbents capture and convert CO ₂	Oxazolidinones, carbamates	Effective at low pressures	High energy input for desorption	(Ashford and Tu, 2017)
MgO and TiO ₂ Surfaces	Adsorption and thermal reduction of CO ₂ on metal oxide surfaces	Various hydrocarbons	Insights into surface reaction mechanisms	Limited scalability	(Ashford and Tu, 2017)
Ionic Liquids	Molecularly tailored for CO ₂ separation	Purer gases, higher combustion efficiencies	High efficiency	High cost of ionic liquids	(Zhang et al., 2011)
ICCC Integrated Carbon Capture and Conversion	Integrated capture and conversion in a single unit	Various chemicals and fuels	Cost-effective, efficient	Technology still in development	(Sabri et al., 2021)
ZnO based method	Including photocatalysis, electrocatalysis, and thermocatalysis	Various chemicals and fuels	Cost-effective, non-toxicity, high surface area, and strong photocatalytic activity efficient	limited reusability and stability	This review

degradation stands out due to its simplicity, efficiency, environmentally friendly, and contemporary approach (Haruna et al., 2018). The method is effective in converting pollutants into less harmful material like carbon dioxide and water, at the same time maintaining low operational cost (Nyamutswa et al., 2018). In photocatalysis, excitation of band gap photons, generates electron-hole pairs which in-turn causes transferring of electrons from VB to CB. The electronic excitation as well as the holes generation in photocatalytic degradation process depends of incident photons energy that should have energy that is equal or greater than that of semiconductor's band gap (Zango et al., 2023). Thus, the energy band gap corresponds to the distance between VB and CB. Hence, the band gap should be of appropriate size so as to minimize the energy necessary for transferring electrons from VB to CB (Abdulhusain et al., 2021). The photogenerated electrons and holes have a lifetime of few nanoseconds which is enough to initiate chain reaction on the photocatalyst surface that react with the pollutant molecules, thereby converting them to harmless substances (Fauzi et al., 2022). Among the most used metal oxides for photocatalytic degradation of pollutants include MoS₂, WO₃, CdS, TiO₂, SnO₂, and ZnO. Their usage in this area is attributed to their suitable band gaps, high stability, and high photocatalytic activity that effective for pollutants degradation. Additionally, carbon-based substances such as graphitic carbon nitrides, graphene, and its oxide have appeared to be a promising photocatalyst. These materials absorb visible light, have large surface areas, and may be incorporated into the other semiconductors (to form composites) to improve charge separation and visible light absorption. Interestingly, TiO₂ and ZnO are the most popular photocatalysts because to their high efficiency, low cost, and environmental friendliness. Despite the photocatalysts desirable advantages, they have certain defects such as large energy bandgap, optical corrosion, and electron-hole recombination.

4.1. Pristine and modified ZnO nanoparticles for organic pollutants degradation

Recently, ZnO as a semiconducting photocatalyst is gaining more attention from researchers which could be because of its excellent properties and wide applications in many fields. The nanoparticle is outstanding in its optical and electrical properties as well as superior chemical and heat stability (Ong et al., 2018). It is widely applied in photodetectors (Huynh et al., 2024), gas sensors (Gui et al., 2024), solar cells (Sekar et al., 2024), and also in photocatalysis (Ranjbari et al., 2024). The pristine ZnO exhibits splendid photocatalytic activities for degradation of organic dyes (Kumar et al., 2024), pharmaceuticals (Omar et al., 2024), phenols (Hanafi and Sapawe, 2024), bacterial inactivation (Kumar et al., 2024), and many more due to its good redox capability. Despite such advantages, zinc oxide intrinsically suffers from disadvantages such as large band gap that made it to have low efficiency for sunlight absorption, and easy recombination of photogenerated charges that hinders its photocatalytic abilities. The disadvantages encountered in pristine ZnO could be solve through certain ways that will enhance the catalytic abilities of the nanoparticles such as facet engineering, addition of oxidants, doping, morphology control, and surface modification (Porcu et al., 2022). Of all the strategies employed to improve photocatalytic activity of ZnO, incorporation of different types of dopants using different metals, formation of heterostructures with other materials, and employment of support materials as adsorbents enjoyed popularity among researchers. Thus, such modifications help in obtaining a ZnO nanocomposites with smaller band gap, high charge carriers' separation, and more surface-active sites. These attributes help in obtaining a nanocomposite with enhanced photocatalytic abilities when compared with the pristine ZnO.

4.2. Dyes photocatalytic degradation

Dyes of the most widely utilized organic compounds that contaminates water. They are widely used in textile industries to impart colour

to fabrics and many other materials. Their release into the environment without proper treatment, contributes to aquatic ecosystem degradation that cause harm to the organisms as well as leads to water bodies eutrophication when accumulated (Nagpal et al., 2022, Wawrzyńczyk et al., 2018). However, dyes are used widely for various industrial applications in textile, pharmaceutical, cosmetic, food, paint, plastic, ink, paper, and photographic industries (Mahmud et al., 2023, Hegazy et al., 2020). When dumped in lakes, rivers, streams, and other water bodies, the dyes mix with waters and contaminate them, causing them to get harmful for humans as well as for every sort of aquatic lives (Huang and Huang, 2023, Sikam et al., 2021). Therefore, their utilization requires attentive handling and suitable disposal in order to abate health problems and environmental hazards (Karthik et al., 2022, Haladu et al., 2025). These dyes when released into the environment without proper treatment, are carcinogenic and toxic to both aquatic life and humans. The colours imparted by these dyes into the water bodies, restricts its fundamental usage including reduction in photosynthesis that caused reduction in growth of important plants and algae that plays an essential part of the food chain. Hence, their treatment before disposal into the environment is very vital (Eleryan et al., 2024). Also, many effects caused by these pollutants to humans include eye irritation, skin diseases, respiratory tract infections and gastrointestinal issues (Bhaphkar and Bhamre, 2024). As a result, laws governing the handling of hazardous chemicals and investigative techniques are devised to determine the chemicals' existence in environmental waterways. Consequently, initiatives are being made to improve the quality of the water by reducing, managing, and addressing the effects of harmful chemicals using wastewater remediation techniques.

The impact of advanced oxidation processes (AOP) for dyes degradation has been well documented (Dharmana et al., 2024, Fadhila et al., 2024). Currently, getting rid of dyes from polluted water is a challenging but important undertaking. Even if their treatment difficult, dye contaminations need to be well-pre-treated before release into the environment (Yuan et al., 2023). Because of its ease of use, cheap cost, and high effectiveness, photocatalytic dye degradation is the most promising and effective way to address the issue of contaminated water. In contrast to conventional methods, photocatalytic technology may effectively break down pollutants without creating new ones (Shakoor et al., 2024, Kaur et al., 2024). Photocatalytic technique is a popular method applied for dyes degradation in the aqueous medium. ZnO has attracted a lot of interest as a prospective material for photocatalysis due to a number its important characteristics. Some of the characteristics that made ZnO an effective photocatalyst is, its broad band structure, spectral overlap with solar emission, good photocatalytic performance, biological and chemical stability, low toxicity, and ease of use in both harsh and ambient environmental conditions (Mirzaeifard et al., 2020). Like TiO₂, ZnO photocatalysts are extensively researched for degradation of different organic recalcitrant contaminants in wastewaters' remediating applications. Like TiO₂, it has several drawbacks that are amendable by doping with metals, non-metals, and transition metal oxides to improve the photocatalytic efficiency. For example, ZnO has a large bandgap that needs high energy to excite electrons and can be hindered by photo corrosion.

Thus, using doped zinc oxide is the simplest method for reducing the bandgap and increasing its absorption of visible light (Zheng et al., 2023). For example, a green technique for creating a ZnO-ZrO₂ nanostructured catalyst for Rhodamine 6G dye degradation underneath a solar light simulator is presented by Haq et al (Haq et al., 2021). They demonstrate how the ZnO-ZrO₂ structure's heterojunctions improve this material's properties by reducing electron/hole pair recombination (Haq et al., 2021). There have been various reports of using ZnO nanoparticles as effective photocatalysts to mineralize contaminants. For instance, Lee et al. synthesized a plasmonic nanocomposite ZnO/Au/Pd via eco-friendly and facile three-step pulsed laser ablation and photo deposition method in liquid for improved photocatalytic efficiency underneath visible light. The Au NPs plasmonic properties

combined with the outstanding trapping of photoexcited electrons on the Pd resulted its meliorated photocatalytic performance. From Fig. S1 (a), they present degradation of MB underneath visible light irradiation, the photocatalytic performance of intact zinc oxide, ZnO/Au5/Pd5, ZnO/Au10/Pd5, and ZnO/Au15/Pd5 composites (Jung et al., 2018). The MB decomposition kinetics for each catalyst developed in this investigation are shown in Fig. S1(b). The ZnO/Au5/Pd5, ZnO/Au10/Pd5, and ZnO/Au15/Pd5 composites, as well as pristine

ZnO, have k values of 0.0027, 0.0042, 0.0145, and 0.0048/min, respectively. Among the synthesized photocatalysts, ZnO/Au10/Pd5 nanocomposites exhibit the highest decomposition rate constant of MB, approximately 5.4 folds larger than that of pristine. Table 6 presents the compilation of the applications of ZnO and its composites for dyes photocatalytic degradation.

Table 6

Summary of the applications of ZnO-based materials for photodegradation of dyes.

Photocatalyst	Pollutant	Experimental condition	Degradation efficiency (%)	Reusability	Remark	Ref
PPy/CZ	Methylene blue	Concentration = 60 mg/L, dose = 1 g/L, pH = 7, temperature = 28–44.5 °C, Sunlight, and time = 210 min.	92	3	Integration of CZ into PPy reduces the band gap and recombination of electron-hole pairs, that leads to enhanced photocatalytic activity in the presence of sunlight	(Patil et al., 2023)
RGO/ γ -Fe ₂ O ₃ / ZnO	Malachite green Methyl orange Rhodamine B	Concentration = 20 mg/L, dose = 1 g/L, pH = 9, temperature = 25 °C, UV lamp 125W, and time = 40 min.	100 100 100	3	The improved RGO/ γ -Fe ₂ O ₃ /ZnO efficiency was because of suppressed carrier recombination rate.	(Yadav et al., 2024)
Cu-ZnO/CdS/ rGO	Direct Blue	Concentration = 50 mg/L, dose = 0.5 g/L, pH = 6.5, temperature = 25 °C, UV light, and time = 100 min.	93	5	The synergy within Cu-ZnO/CdS/rGO photocatalyst that allows exceptional photocatalytic efficiency, durability, and ease of recycling	(Tran et al., 2024)
Ag-Ce/ZnO	Rhodamine B	Concentration = 30 mg/L, dose = 1 g/L, pH = 7, temperature = 25 °C, Xenon lamp 300W, and time = 30 min.	97	6	The high efficiency was due to ample surface area, available active sites, and high photocatalytic attributes.	(Liu et al., 2023)
ZnO/TiO ₂	Ciprofloxacin	Concentration = 5 mg/L, dose = 1 g/L, pH = 7, temperature = 20–25 °C, Hg arc lamp 300W, and time = 120 min.	97	8	The optimized annealing technology leads to a great augmentation in photocatalytic performance of material.	(Li et al., 2024)
ZnO/BT	Crystal Violet Congo Red Methylene blue	Concentration = 160 mg/L, dose = 0.3 g/L, pH = 7, temperature = 25 °C, Hg arc lamp 300W, and time = 150 min.	99 99 100	5	The synergy between the nanoparticles is due to immobilization of bentonite on ZnO which increases its photocatalytic activity.	(Aaga et al., 2023)
Co-ZnO-g- C ₃ N ₄	Eosin yellow	Concentration = 1 mg/L, dose = 1 g/L, pH = 7, temperature = 25 °C, Xenon lamp 150W, and time = 180 min.	96	-	The synergy between Co and ZnO-g-C ₃ N ₄ helps in suppressing charge carrier recombination that improved the photocatalytic activity of the material	(Bandoh et al., 2024)
ZnO-NPs	Methylene blue Malachite green Congo red Methyl orange	Concentration = 15 mg/L, dose = 0.5 g/L, pH = 7, temperature = 25 °C, Xenon lamp 150W, and time = 60 min.	98.5 95 95 96.7	5	The catalyst almost neutral surface and interaction between K and Na within the composite enhanced the photocatalytic activity of the ZnO nanoparticles.	(Sreelakshmi et al., 2024)
ZnO@ZrO ₂	Methylene blue	Concentration = 10 mg/L, dose = 0.2 g/L, pH = 7, temperature = 25 °C, Sun light, and time = 240 min.	84.52	-	The synergy between ZnO and ZrO ₂ is significant in enhanced photoactivity.	(Landge et al., 2024)
ZnFe ₂ O ₄ /ZnO	Methylene blue Rhodamine blue	Concentration = 20 mg/L, dose = 1 g/L, pH = 11, temperature = 25 °C, Sun light, and time = 120 min.	80	-	The ZnFe ₂ O ₄ narrow band gap coupled with the ZnO improved the photocatalysis procedure under visible light.	(Zoubier et al., 2020)
ZrO ₂ /ZnO	Acid orange 8 dye	Concentration = 20 mg/L, dose = 0.2 g/L, pH = 7, temperature = 25 °C, UV light 30W, and time = 120 min.	93	5	The synergy between ZrO ₂ and ZnO gives a photocatalyst with reduced band gap which enhanced the photoactivity.	(Gurushantha et al., 2017)
ZnO	Methylene blue	Concentration = 10 mg/L, dose = 0.6 g/L, pH = 7, temperature = 25 °C, Sun light, and time = 150 min.	69 – 73	-	The as-synthesized nanoparticles have small band gap and reduced recombination rate which translates to formation of high photoactive material	(El Golli et al., 2021)
NiO/ZnO	Methylene blue	Concentration = 20 mg/L, dose = 0.8 g/L, pH = 9, temperature = 25 °C, Sun light and Hg vapor lamp 250W, and time = 90 min.	97.6	3	The synergistic influence as well source of light used enhanced the photocatalytic activity of the nanoparticles.	(Singh et al., 2024)
ZnO@PANI/C	Congo red	Concentration = 5 mg/L, dose = 0.5 g/L, pH = 6, temperature = 25 °C, Metal halide lamp, and time = 100 min.	100	5	The catalytic activity of ZnO was enhanced after blending with PANI which was supported on the coal substrate.	(Sayed et al., 2024)
ZnO/Ag ₂ O/g- C ₃ N ₄	Methylene blue	Concentration = 10 mg/L, dose = 0.5 g/L, temperature = 10 °C, Metal halide lamp 400 W, and time = 60 min.	94.5	5	The band gap of ZnO nanorods narrows down after Ag ₂ O and g-C ₃ N ₄ inclusion which improved visible light absorption, supports photogeneration of excitons that facilitates photocatalytic activities.	(Das and Sahu, 2024)
ZnFe ₂ O ₄	Methylene blue	Concentration = 10 mg/L, dose = 0.5 g/L, pH = 9, temperature = 25 °C, Hg lamp 250 W, and time = 60 min.	80	5	The synergy within the nanoparticles made it to have an average size, high surface charge, and magnetic properties that enhanced its photocatalytic activity.	(Azizi and Kazemi, 2024)

4.2.1. Mechanism for dyes degradation

The mechanism of dyes degradation by ZnO and ZnO-based materials have been studied by many researchers. Light from the sun or other artificial source strikes ZnO, producing h^+ in the VB and e^- in the CB. On the surface of semiconductor photocatalysts, oxidation and reduction reactions are made possible by creation of e^- and h^+ . Thus, mechanism for eosin yellow dye by cobalt-doped ZnO-g-C₃N₄ heterostructures was studied (Bandoh et al., 2024). The energy level positions of a photocatalyst's VB and CB have a significant impact on its photocatalytic activity. Therefore, the easiest way to understand the eosin yellow dye degradation mechanism is to estimate the CB and VB energies of ZnO and g-C₃N₄ (Mubeen et al., 2023, Schott et al., 2017). In general, the photogenerated charge carriers exhibits affinity for low oxidation and reduction potentials. When simulated solar light is irradiated on Co-ZnO-g-C₃N₄ nanocomposite, charge separation of electron-hole pair occurs at g-C₃N₄ solely because of its lower band gap of 2.72 eV against 3.10 eV for ZnO. The photogenerated e^- transferred to the CB of zinc oxide, given that CB of g-C₃N₄ is more negative (-1.14 eV) than that of ZnO (-0.26 eV). Also, the VB for ZnO (+0.84 eV) was more positive than VB of g-C₃N₄ with value of +1.58 eV, and this allow the photogenerated holes to migrate into the VB of g-C₃N₄. These electrons and holes can then react with O₂ and H₂O to yield the radical O₂ and OH which can react with dyes molecules in order to degrade and subsequently convert the molecules into non-toxic substances such as H₂O and CO₂ (Khan et al., 2019, Le Pivert et al., 2019). The effect of Co, ZnO, and g-C₃N₄ are presented for eosin yellow degradation as described in Eq. 7–13.



Similarly, the mechanisms of cationic dyes including congo red, methylene blue and rhodamine B, have been studied using ZnO-CeO₂

(Manikanika and Kumar, 2024). The mechanism involves several reaction processes. Initially, the dye molecules are adsorbed onto the surface of molecules and the photoexcited charge carriers, allowing for the efficient electron transfer. In the presence of light from UV source, the photocatalyst becomes excited, thus, electrons are transferred to its conduction band, resulting in the electron-hole pairs (e^-/h^+) generation. The electrons from the surface of the CeO₂ migrated to the ZnO conduction following the difference in the energy level difference and the ZnO-CeO₂ interface band alignment. Oxygen vacancies are formed on the catalyst surface when the Ce⁴⁺ is reduced to Ce³⁺ which formed trap centers for the electron that prevents the charge carrier's recombination. Moreover, the oxygen vacancies provide active sites for the redox reactions. Alternatively, the electron migration to the surface of the ZnO promotes surface-bound oxygen molecules reduction and formed superoxide radicals (O_2^-). The holes formed on the ZnO and CeO₂ valence band combined with the surface absorbed water molecules and formed the powerful $\cdot\text{OH}$. Being stronger oxidizing agents, the O_2^- and OH ROS attack the dye molecules and consequently break them, resulting into formation of less harmful intermediate products and their complete mineralization to CO₂ and water as depicted in the Fig. 8. Overall, the z-scheme heterojunction formation facilitates the ROS generation and prevents the charge carrier's recombination, resulting into faster and complete degradation of pollutants.

4.3. Photocatalytic degradation of pharmaceuticals

Pharmaceuticals are chemicals and substances, like drugs or medications that are employed for diagnosis, cure, and prevention of diseases to modify or restore organs' functions. The industrial pharmaceutical sectors play a vital role in our society by providing several developmental opportunities. Through inventive medication and their manufacture, they can secure the population's well-being and have an impact on economic and financial gains. Examples of such pharmaceuticals include antibiotics, antilutetics, antidepressants, antipyretics, analgesics, and many other categories (Upadhyay et al., 2025, Yadav and Purkait, 2016). Nevertheless, such industries contribute to a wide range of environmental contaminants identified as pharmaceutical waste that are synthesized through various processes. Pharmaceutical wastes are residues or effluents obtained from production processes which contains organics or active ingredients that presents tremendous threats to human health and the environment (Qi and Yu, 2020, Adamu et al., 2024). Pharmaceuticals are frequently found in industrial and municipal

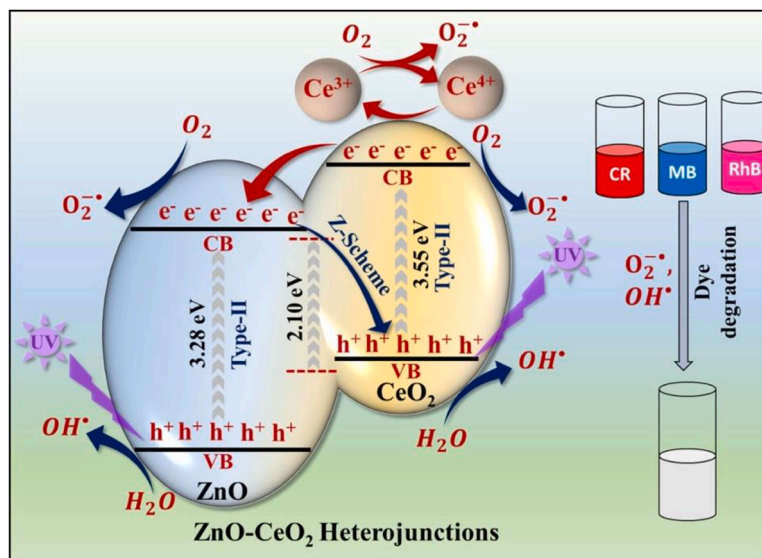


Fig. 8. Proposed mechanism of congo red, methylene blue, and rhodamine blue degradation by ZnO-CeO₂ Z-scheme photocatalyst. Reproduced from ref. (Manikanika and Kumar, 2024).

wastewater discharges because of overuse of the compounds. The existence of such pollutants in environmental wastewaters is a well-known and a serious issue. Their presence in the environment poses health challenges to the public in several pathways including the risk of contracting pulmonary and respiratory illnesses, cancer, disease outbreaks, infertility, birth defects, hormonal disruption, and many more (Zango et al., 2023, Hamidon et al., 2024). Additionally, due to their persistent nature and potential toxicity, pharmaceutical waste poses a risk to the quality of the air and waters, the food chains, agricultural products, animals, ecosystems, augmentation in greenhouse gas emission, wild lives, and even higher animal mortalities (Molla-Mahmoudi et al., 2018).

Recently, Amir et al. claimed the synthesis of a biochar-ZnO (BC-ZnO) composite for improved degradation of ciprofloxacin. They reported the adsorption-desorption experiments of a prepared samples in the dark and then in visible light before the actual photocatalytic decomposition (Amir et al., 2022). After 60 minutes in the dark, the photocatalyst materials BC, ZnO, BCZ-1, BCZ-2, and BCZ-3 showed 42, 12, 44, 49, and 53% ciprofloxacin adsorption respectively. Upon illumination with light, the biochar photocatalyst displayed only a little change in its ciprofloxacin degradation and the curve becomes almost linear from 60 to 240 minutes indicating that it is only good adsorbent, but a poor photocatalyst. The augmentation in the decomposition rate could be attributed to creation of more superoxide (O_2^-) and hydroxyl ($OH^\bullet$) radicals in the composites which interact with the ciprofloxacin molecules on BCZ surface that leads to higher ciprofloxacin degradation. Amongst all the synthesized photocatalysts, the degradation efficiency followed the pattern BCZ-3 > BCZ-2 > BCZ-1 > ZnO > BC, showing BCZ-3 having the highest photocatalytic degradation of 98.55% due to synergy between the pure BC and ZnO. Hence, it can be inferred that the ciprofloxacin photocatalytic degradation increases with an increase in ZnO loading amount on BC surface.

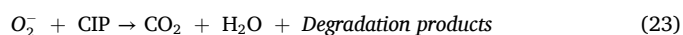
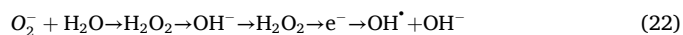
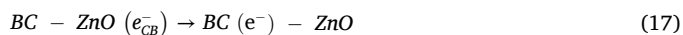
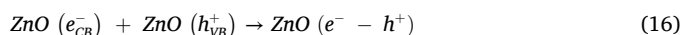
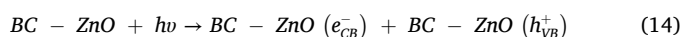
When studying the practical applications of a photocatalysts, two important aspects to consider are their stability and reusability. The regeneration results indicated that recycling of the photocatalysts somewhat reduced the photocatalytic degradation of the adsorbate, as illustrated in Fig. S2(c). Following its fourth cycle of regeneration, BCZ-3 has attained the highest rate of photocatalytic degradation (80.3%), compared to other photocatalysts. this suggests that BCZ-3 has strong photocatalyst stability and recyclability to break down ciprofloxacin molecules into small substances on exposure to visible light, which increases the process's economic viability for commercial use. The ability of the antibiotic for photocatalytic decomposition to harmless substances was further scrutinized by COD (chemical oxygen demand) experiments, as demonstrated in Fig. S2(d). For every sample, the COD removal (%) was found to be between 45.7 and 98.1%. Utilizing biochar and zinc oxide samples, the COD elimination (%) was calculated up to 45.7% and 57.8%, respectively. In BC, the COD removal was as a result of adsorption of ciprofloxacin molecules on the BC surface, while the removal by ZnO was because of its photocatalytic activity after light illumination. The highest COD removal of 98.1% was obtained using BCZ-3 composite which confirmed its superiority due to being the one with the highest ZnO loading.

Huang et al. investigated the synthesis and photocatalytic performance of a CeO_2/ZnO heterojunction composite, fabricated through hydrothermal and wet chemistry methods. Characterization techniques, including SEM and UV-vis spectroscopy (Fig. S3 a-b)). Their findings revealed that the composite exhibits a 3D nanoflower-like structure, enhancing its surface area and photocatalytic activity, achieving a 95.9% degradation of tetracycline (TC) within 75 minutes (Fig. S3 d). The analysis of active species and stability through cyclic testing indicates that while the catalyst maintains its structure, its efficiency decreases after multiple uses due to residual TC on its surface (Fig. S3c). The photodegradation mechanism involves the generation of charge carriers (electrons and holes) under visible light irradiation, primarily facilitated by the CeO_2/ZnO heterojunction. The holes (h^+) play a

crucial role in the degradation of TC, while reactive species such as superoxide radicals (O_2^-) and hydroxyl radicals ($OH^\bullet$) contribute to the process, with the order of importance being $h^+ > O_2^- > OH^\bullet > e^-$. This mechanism enhances the separation of charge carriers, leading to improved photocatalytic efficiency in degrading organic pollutants. Table 7 presents various research results on applications of ZnO and its composites for pharmaceuticals photocatalytic decomposition. A summary of the composite's optimal parameters, percentage degradation performance, reusability, and remarks on the process has been provided.

4.3.1. Mechanism for pharmaceuticals degradation

Researchers have widely reported the mechanism of pharmaceuticals degradation by the ZnO nanoparticles. In the degradation of pharmaceuticals, the photogenerated e^- and h^+ charged particles and $OH^\bullet$ and O_2^- radicals were responsible for the degradation process. Thus, a study reported proposed mechanism for ciprofloxacin photocatalytic degradation using optimized BCZ-X nanomaterial. The mechanism for ciprofloxacin degradation has been widely reported that, when light is irradiated on ZnO photocatalyst, the VB electrons of the ZnO are excited to CB which subsequently leaves holes in VB of the ZnO. The photo-created electrons are then transported to photocatalyst surface where they combine with oxygen molecules to create O_2^- radicals. In this research, as shown in Fig. 9, the BCZ-X used for the pollutant degradation as a biochar-based ZnO composite combine adsorption and photocatalytic decomposition processes (Ribao et al., 2019). The photocatalytic degradation take place in stages as follows; irradiation of light which generates electron-holes in ZnO; photo-created electrons then react with the oxygen for superoxide radicals (O_2^-) generation; the photo-generated e^- of CB and h^+ of VB of ZnO rapidly recombine; when BC-based ZnO composites were synthesized, the photo-excited e^- of CB in ZnO transfers to surface of biochar and this grant a new conductive path for e^- and oxygen molecules are then converting to superoxide radicals. On the other hand, the holes within ZnO VB reacts with hydroxyl ions/water molecules to be converted to $OH^\bullet$ radical, the released electron from the redox process dissociates water to form H^+ and OH^- . Additionally, oxidation of OH^- to $OH^\bullet$ happens through filling up holes existing in the VB of zinc oxide NP. In the final stage, O_2^- and $OH^\bullet$ react with the pollutant to form CO_2 and H_2O along with other less harmful intermediates, as generally shown in (eqn. 14 & 24) (Ani et al., 2018).



4.4. Phenols photocatalytic degradation

Phenols are a diverse class of chemical compounds with an aromatic ring connected to a hydroxyl group functional group (-OH). They are

Table 7

Summary of the application of ZnO and ZnO-based nanoparticles for photodegradation of pharmaceuticals.

Photocatalyst	Pollutant	Experimental condition	Degradation efficiency (%)	Reusability	Remark	Ref
ZnO/Fe ₃ O ₄ -Sep	Ibuprofen, Acetaminophen, Antipyrine	Concentration= 250 mg/L, dose = 10 g/L, pH = 7, Xe lamp 450W, and time = 600 min.	100 85 70	3	The photocatalyst exhibits superparamagnetic that offers easy recovery and reusability after several cycles of operation.	(Akkari et al., 2018)
Ag/g-C ₃ N ₄ /ZnO	Paracetamol, Cefalexin, Amoxicillin	Concentration= 40 mg/L, dose = 0.08 g/L, pH = 7, Visible light 300W, and time = 180 min.	85.3 71.74 41.36	5	The high photocatalytic ability of the nanorods was due to synergy between the constituent particles.	(Thang et al., 2021)
ZnO: Au	Ciprofloxacin	Concentration= 5 mg/L, dose = 1 g/L, pH = 8, UV light 8 W, and time = 60 min.	93	4	The photocatalyst exhibits high degradation potential due to incorporation with Au.	(Zheng et al., 2023)
ZnO-NiCoMn	Ampicillin, Ciprofloxacin	Concentration= 20 mg/L, dose = 0.3 g/L, pH = 6.5, Halogen lamp 250 W, and time = 100 min.	96 94	5	The nanostructures have superior photocatalytic activity due to high interfacial contact which made effective charge separation.	(Murugan et al., 2024)
Ag-ZnO-La ₂ O ₃ CO ₃	Caffeine	Concentration= 20 mg/L, dose = 0.3 g/L, pH = 7.5, UV mercury lamp 400 W, and time = 210 min.	99.4	3	The improved photocatalytic activity was due to interfacial heterostructure in the 5% Ag-ZnO-Al ₂ O ₃ catalyst.	(Elhalil et al., 2019)
WO ₃ -ZnO/RUAC	Tetracycline	Concentration= 33 mg/L, dose = 0.85 g/L, pH = 4.57, Xe lamp 300W, and time = 108 min.	96.5	5	Enhanced photocatalytic activity was due to AC incorporation that reduce photocarrier recombination and charge transfer resistance	(Mohtaram et al., 2024)
P25-TiO ₂ /Fe ⁰ /ZnO	Oxytetracycline	Concentration= 30 mg/L, dose = 0.28 g/L, pH = 7.5, Visible LED 10 W, and time = 120 min.	89.3	4	The synergism between the ZnO and TiO ₂ improved the pollutant degradation	(Azadi et al., 2024)
ZnO	Paracetamol	Concentration= 20 mg/L, dose = 0.4 g/L, pH = 6, temp = 25 °C, UV light, and time = 180 min.	95	6	The nano size, small bandgap of the ZnO enhanced its photoactivity.	(Lakshmi et al., 2024)
Sb-ZnO/MoS ₂	Ciprofloxacin	Concentration= 5 mg/L, dose = 0.5 g/L, pH = 7, Visible light 30 W, and time = 180 min.	72	5	The synergistic effect of ZnO incorporation into MoS ₂ showed photocatalysis coupled with piezo-photocatalysis that generated piezoelectric field which greatly suppressed holes recombination, as well as lead to high photoactivity of the nanoparticles.	(Masekela et al., 2024)
ZnO	Tetracycline, Sulfamethoxazole, Chloroquine, Diclofenac	Concentration= 10 mg/L, dose = 0.1 g/L, pH = 9–11, Sun light, and time = 60 min.	51 65 61 55	5	The synthesized ZnO-mediated solar photocatalyst in combination with natural solar energy enhanced photocatalytic activity of the nanoparticles.	(Gayathri et al., 2023)
Ce-ZnO	Nizatidine, Levofloxacin, Acetaminophen	Concentration= 5 mg/L, dose = 1 g/L, temp. = 25 °C, UV-B Hg lamp 8 W, and time = 270 min.	96 96 65	-	The Ce-doped ZnO exhibited enhanced photocatalytic activity due to Ce showcasing finer grain size, smaller cluster size, and ability to act as trap for the inhibition of photogenerated electron-hole recombination.	(Al Abri et al., 2019)
MgO-ZnO/Graphene	Sulfamethoxazole	Concentration= 55 mg/L, dose = 0.8 g/L, pH = 9, temp. = 25 °C, UV-A lamp 90 W, and time = 120 min.	100	6	The remarkable synergy between US, MZG, and LED irradiations lead to enhanced photodegradation of the pollutant.	(Moradi et al., 2020)
g-C ₃ N ₄ /Ce-ZnO/Ti	Cefixime	Concentration= 10 mg/L, dose = 0.8 g/L, temp. = 25 °C, Visible light 72 W, and time = 330 min.	80	5	The immobilization of g-C ₃ N ₄ and Ce-ZnO on Ti grid sheets provided synergy for the degradation of the pollutant.	(Sheydaei et al., 2021)
ZnO-SrO-CdS	Tetracycline	Concentration= 20 mg/L, dose = 0.1 g/L, pH = 7, temp. = 25 °C, Sun light, and time = 120 min.	98.8	5	The ZnO-SrO-CdS formed Z-scheme heterojunction for the pollutant degradation	(Omar et al., 2024)
Ag/g-C ₃ N ₄ /ZnO/Fe ₃ O ₄	Pantoprazole	Concentration= 30 mg/L, dose = 0.6 g/L, pH = 6, temp. = 25 °C, Sun light, and time = 40 min.	98.24	7	The degradation of pantoprazole was due to the synergistic effects, and high plasmon resonance that results to enhanced photoactivity.	(Raha and Ahmaruzzaman, 2022)
BCZ-3	Ciprofloxacin	Concentration= 100 mg/L, dose = 10 g/L, pH = 7, LED light 3 W, and time = 240 min.	98.6	4	The synergy between BC and ZnO made the material to combine high adsorption and photocatalytic activity.	(Amir et al., 2022)

extensively used in many industrial processes, including synthesis of petrochemicals, dyes, insecticides, herbicides, medicines, and cosmetics (Garba et al., 2016). In addition, they are frequently utilised in household items including mouthwash, cleansers, and flavourings. Therefore, human activity has a major role in the environmental presence of

phenols, which frequently results in high quantities of these chemicals in wastewater. Phenols are widely used in both domestic and industrial settings, and as a result, they are frequently found in municipal wastewater and the effluents that these companies discharge (Isiyaka et al., 2023). If phenols are not adequately removed and controlled from

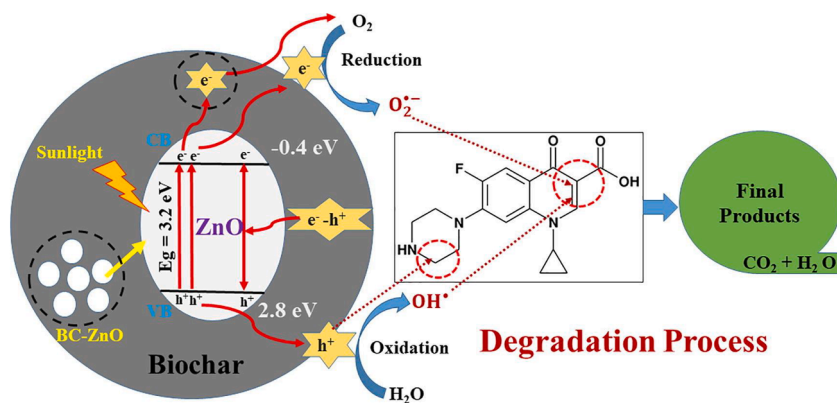


Fig. 9. Proposed mechanism for the photocatalytic degradation of ciprofloxacin using BCZ-X composite. Reproduced from ref (Amir et al., 2022).

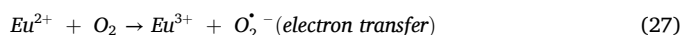
environmental waterways, pollution may occur, which could have a negative impact on the health of living things. The toxic phenols effects in human include respiratory and track complication, skin and eye irritations, gastrointestinal issues, and many others. Additionally, impact of phenols in the environment can disrupt ecosystems as well as pose a threat to aquatic organisms (Zango et al., 2022). As a consequence, it is important to address the chemicals' discharge through appropriate wastewater treatment and the application of legislation to reduce their negative effects on the environment and public health (Garba et al., 2023).

Numerous photocatalysts have been employed to study the degradation of phenols, viz. metal oxide nanoparticles like ZnO nanoparticles and their composites. Thus, Jiang *et al.*, reported the synthesis and applications of a BiOI-loaded ZnO composites via a facile two-step method (Jiang et al., 2017). The report showed that, after two hours of exposure to simulated solar light, the phenol decomposition efficacy of pristine ZnO was only 40%, while that of BiOI/ZnO composites display higher phenol decomposition activity. The degradation efficiencies of phenol for 5, 10, and 15% BiOI/ZnO composites were 66.8, 99.9, and 78.6% after two hours of simulated sun-light irradiation, respectively. The experiments data in Fig. S4(a) may be fitted to the Langmuir-Hinshelwood model and the linear fitting curve against the irradiation time get plotted to obtain the rate constant k (Fig. S4(b)). The rate constant was found to be 0.0042, 0.00915, 0.031030, and 0.0288 min^{-1} for pristine ZnO, 5% BiOI/ZnO, 10% BiOI/ZnO, and 15% BiOI/ZnO, respectively. The time-dependent UV-vis absorption spectra for the phenol catalysed by 10% BiOI/ZnO underneath simulated solar light illumination, are displayed in Fig. S4(c). Upon a 2-hour irradiation, the 10% BiOI/ZnO powders are capable of up to 99.9% phenol degradation underneath simulated solar light. The results of photocatalytic studies show that 10% of BiOI is enough to load onto the surface of ZnO to facilitate the breakdown of phenol. Based on the UV-Vis DRS results, the BiOI/ZnO was shown to exhibit a notable absorption in spectra range between 300 and 550 nm. To investigate the source of the increased photocatalytic activity, phenol was degraded by ZnO, 10% BiOI/ZnO, and BiOI catalysts under various light irradiation wavelengths. As can be seen in Fig. S4(d), BiOI/ZnO catalyst showed the highest decomposition rate when exposed to UV light of $\lambda > 510$ nm wavelength. Summary of pristine and modified ZnO for phenol degradation was highlighted in Table S1.

4.4.1. Mechanism for phenols degradation

Several studies have reported the mechanism of photocatalytic degradation of phenols. As a result, different photocatalytic degradation mechanisms have been suggested, based on active species involved during the degradation process. It was proposed that, the most potent regenerating species that attack and degrade phenol molecules are O_2^- , $\text{OH}^\cdot$, and (h^+) radicals. Thus, application of europium doped ZnO

hierarchical micro/nanospheres was employed to degrade phenols (Sin et al., 2014). When exposed to radiation, ZnO's valence band electrons (e_{CB}^-) are energised to move into the conduction band, leaving h_{VB}^+ behind. The standard redox potentials for $E^0(\text{Eu}^{3+}/\text{Eu}^{2+}) = -0.35$ V, $E^0(\text{O}_2/\text{O}_2^-) = -0.33$ V, and $E_{VB}(\text{ZnO}) = -0.50$ V against normal hydrogen electrode. The Eu^{3+} that has partly filled f orbitals within the ZnO is a strenuous Lewis acid that can easily trap e_{CB}^- and as well hinder the recombination with h_{VB}^+ . Hence, the Eu^{2+} being in reduced form is unstable so that the e_{CB}^- can become de-trapped and be transferred to O_2 molecules that promotes fabrication of O_2^- that can be converted to $\text{OH}^\cdot$. Thus, the results indicate that the dopant (Eu) serves as an efficient charge carrier trap as well as a facilitator for transfer of the excited e_{CB}^- under sunlight irradiation. Consequently, the Eu dopant in ZnO was thought to have caused this entrapment, which caused separation of the charge carriers, increased amount of $\text{OH}^\cdot$ produced during the breakdown of phenol that greatly enhanced Eu/ZnO photocatalytic activity. Table S3 summarizes the application of ZnO and composites in the photocatalytic degradation of phenol. The detailed decomposition mechanism for the Eu/ZnO hierarchical nanospheres can be presented as follows.



Recently, Alegria et al and coworkers investigated the effect of copper doping on the photocatalytic performance of 2D ZnO-stearic acid (SA) composites for the degradation of indigo carmine (IC) and 4-chlorophenol (4-CP) under simulated sunlight (Alegria et al., 2024). Fig S5 shows that the copper-doped samples, especially the $\text{Zn}_{0.95}\text{Cu}_{0.05}\text{O-SA}$ composite, exhibited significantly enhanced photocatalytic activity compared to the pristine ZnO-SA sample. The $\text{Zn}_{0.95}\text{Cu}_{0.05}\text{O-SA}$ composite achieved complete degradation of IC (Fig S5a) and approximately 65% degradation of 4-CP (Fig S5b), outperforming the undoped ZnO-SA and the commercial TiO_2 (P25) photocatalyst. The kinetic analysis in Fig S5c reveals that the $\text{Zn}_{0.95}\text{Cu}_{0.05}\text{O-SA}$ composite had a degradation rate constant for IC that was four times higher than that of the ZnO-SA sample, indicating the beneficial effect of copper doping. Fig. 10a

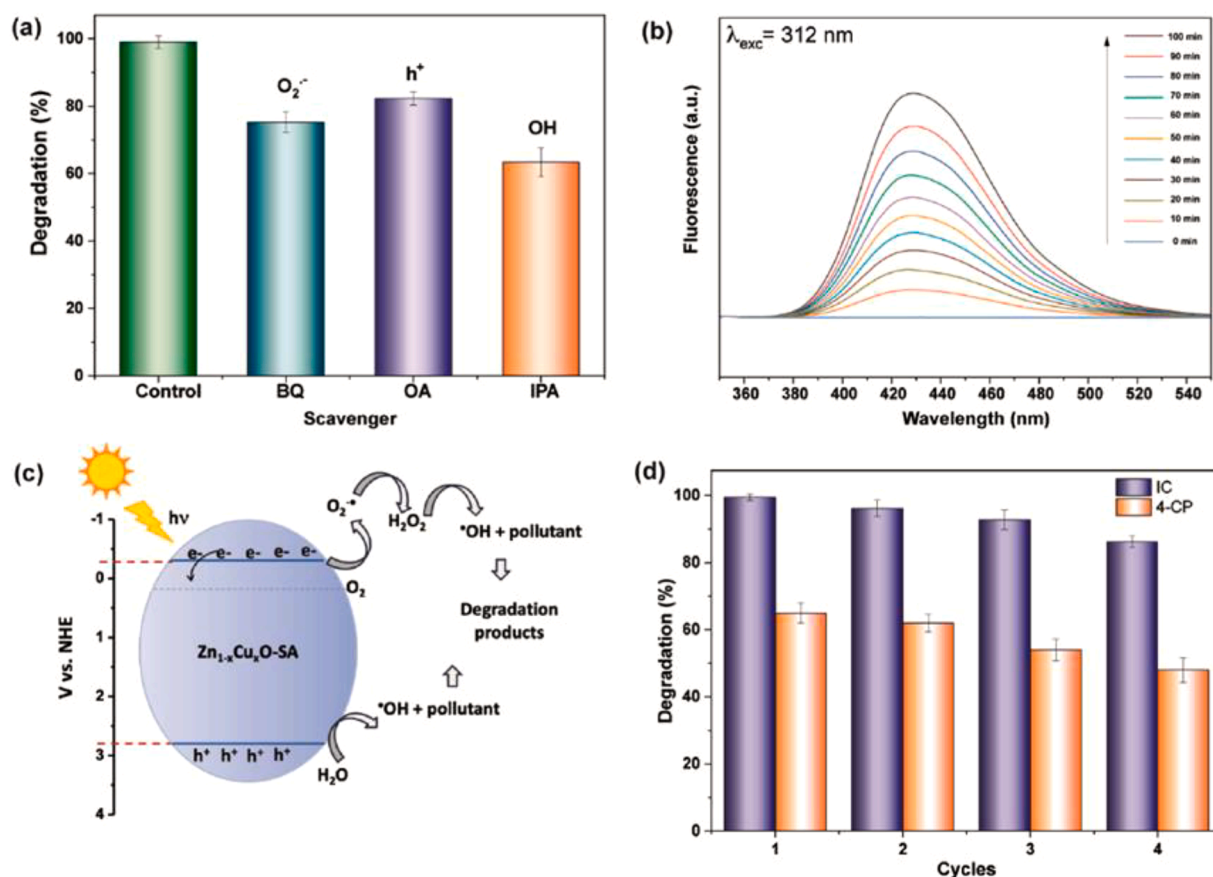


Fig. 10. Degradation rate of IC after adding different scavengers assisted by Zn_{0.95}Cu_{0.05}O(SA) (a), PL of 2-hydroxyterephthalic acid (b), Mechanism for the photodegradation of contaminants (c) Reusability of Zn_{0.95}Cu_{0.05}O(SA)_{0.13} (d). Reprinted from (Alegria et al., 2024).

demonstrates that the presence of radical scavengers, such as isopropanol, benzoquinone, and ammonium oxalate, reduced the photocatalytic activity of the Zn_{0.95}Cu_{0.05}O-SA composite, suggesting the importance of hydroxyl radicals, superoxide radicals, and photo-generated holes in the degradation process. Fig. 10b shows the increase in hydroxyl radical generation over time, as measured by the photoluminescence of 2-hydroxyterephthalic acid, further supporting the role of hydroxyl radicals in the enhanced photocatalytic performance of the copper-doped composite. The proposed mechanism in Fig. 10c suggests that the decreased bandgap of the copper-doped sample, compared to the undoped ZnO-SA, facilitates the generation of electron-hole pairs and the formation of reactive oxygen species, leading to the improved photocatalytic degradation of the organic contaminant. Fig. 10d illustrates the reusability and chemical stability of the Zn_{0.95}Cu_{0.05}O(SA)_{0.13} photocatalyst over four consecutive degradation cycles of the contaminants. The photocatalytic efficiency of the Zn_{0.95}Cu_{0.05}O-SA_{0.13} sample remains relatively stable after four reaction cycles, with only a minor performance loss of 7–12% observed. The slight decrease in performance over multiple cycles is attributed to the potential reduction of Cu (II) to Cu(I), which is not typically observed in sensitized ZnO-stearic acid systems.

4.5. Herbicides and pesticides degradation

Pesticides and herbicides are one of the most frequent water contaminating organic compounds. They are widely employed in agriculture for control of weeds and pests. However, upon application to the crops, they are often washed off by rainfall or water from irrigation source, thus, they get transported to water bodies such as lakes, rivers, and streams (Isiyaka et al., 2021). Usually, they become accumulated in

the surface waters through the runoff and could result in the contamination of the aquatic ecosystems, causing harmful effects on living organisms (Isiyaka et al., 2021). In human body, they increased the toxicological effects as they are associated with adverse health risks such as developmental effects, acute and chronic toxicities. Recent studies have shown that long-term exposure to these chemicals may cause skin rashes, respiratory ailments, reproductive complications, neurological disorder, cancer, and endocrine disruption (Isiyaka et al., 2021). Due to the toxic effects of the herbicides and pesticides, they are classified as possible human carcinogens (Veerakumar et al., 2021). Thus, regulations on the use of the toxic chemicals and detective measures are developed to identify the presence of the chemicals in the environmental waters. Additionally, efforts are being put forward using wastewater remediation processes to reduce, manage, and address their impacts of toxic chemicals by improving the water quality.

The use of ZnO nanoparticles as efficient photocatalysts is reported for the mineralization of the herbicides. For example, the application of 3D ZnO nano stars (ZnONSt) for the degradation of methyl parathion (MP) herbicide as well as that of pendimethalin (PDM) and trifluralin (TFL) pesticides has been investigated (Veerakumar et al., 2021). The ZnONSt has possessed star-like morphology and hexagonal wurtzite phase with specific BET surface area and bandgap of 48.81 m²/g and 3.31 eV, respectively. Thus, it has demonstrated MP degradation of 92% under visible light illumination of 200 min at $\lambda_{max} = 400$ nm (Fig. 19a). Similarly, 180 minutes was sufficient for the degradation of PDM (Fig. 11a), which was observed by the total disappearance of the yellow color of the pollutant. For the TFL degradation, 160 min. The efficacy of the material has been attributed to its ability to harness the visible light efficiently which produced the ROS that attack the pollutant molecules (Veerakumar et al., 2021). Surprisingly, inefficiency for the ZnO was

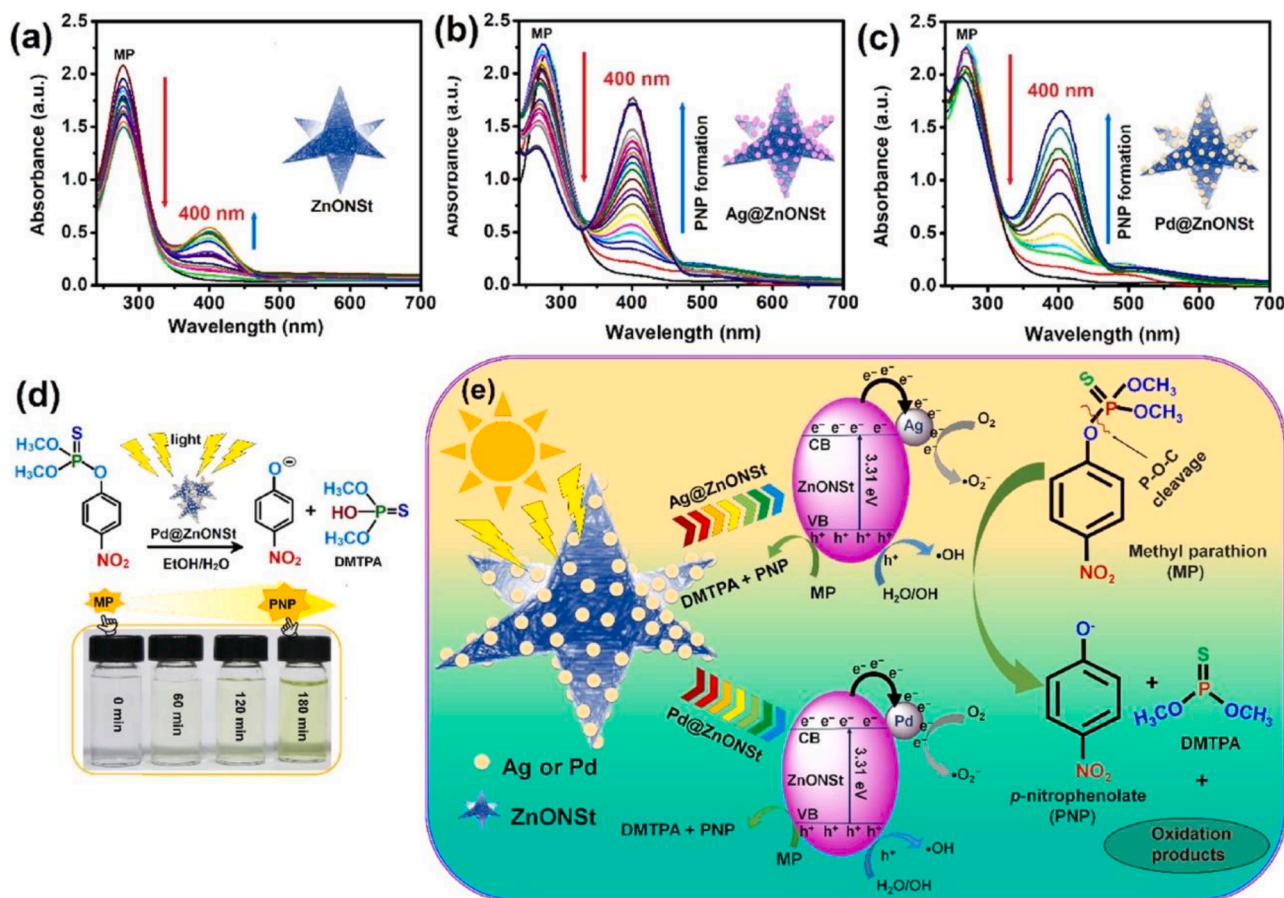


Fig. 11. A spectra of methyl parathion degradation by (a) ZnONSt, (b) Ag@ZnONSt (c) Pd@ZnONSt photocatalysts (d) change in color during the pollutant degradation (e) proposed mechanism for the pollutant degradation by the photocatalysts, Reproduced from ref (Veerakumar et al., 2021).

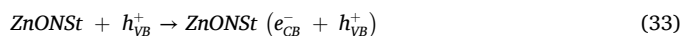
reported for the diazinon pesticide degradation (Sakineh et al., 2019). Using the pristine material (ZnO/UV) only 3.3% of the pollutant was degraded. However, the degradation efficiency was improved to when the UV/PMS was employed, achieving degradation efficiency of 55% (Sakineh et al., 2019). The lower performance of the ZnO necessitates its modification for the pollutant degradation.

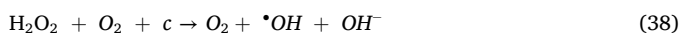
Similarly, decoration of the ZnONSt with Pd and Ag nanoparticles has been illustrated to improve the surface properties and light absorption efficiency of the material (Veerakumar et al., 2021). The BET surface area was 32.34 and 39.72 m²/g, whereas the bandgap was 3.11 and 3.14 eV for the Pd@ZnONSt and Ag@ZnONSt, respectively. The degradation of MP has been shown to improve to over 99% when Pd@ZnONSt and Ag@ZnONSt photocatalysts were employed which prolonged its stability and reusability up to 6 degradation cycles. Both Pd@ZnONSt and Ag@ZnONSt have revealed the formation of *p*-nitrophenolate (PNP) and dimethyl-triphosphoric acid (DMTPA) as by-products with gradual decrease in the absorbance and formation of new peak at λ_{max} 278 and 400 nm, respectively. Additionally, the UV light illumination time has been shown to reduce from 180–90 min for the PDM degradation using the Pd@ZnONSt and Ag@ZnONSt photocatalysts, respectively (Fig. 11(b and c)). Their kinetics have compared and was found higher than that of TiO₂, ZnO nanoparticles and ZnONSt (Fig. 11(d) (Veerakumar et al., 2021). Table S2 summarized the finding reported on the application of ZnO and their composites for the degradation of the pollutant.

4.5.1. Mechanism for herbicides and pesticides degradation

The mechanisms of herbicides and pesticides degradation by the ZnO nanoparticles and their composites have been investigated by researchers. When a light from sun or artificial source strikes the ZnO, its

e^- in CB and h^+ in VB are produced. The creation of the e^- and h^+ allow the process of oxidation and reduction processes to occur at surface of semiconductor photocatalysts. Thus, the mechanism of MP, PDM and TFL photocatalytic degradation by ZnONSt was studied. When irradiated by visible light, e^- are produced in CB while h^+ are produced in VB of the photocatalyst. The e^- generated in the presence of O₂ produced abundant O₂⁻ radical, while the h^+ generates highly reactive $\cdot$ OH radicals with higher oxidizing potentials. The generated ROS notably attack the pollutants and cause their degradation. For the MP degradation, the PNP and DMTPA are further degraded by the $\cdot$ OH to form the final products (Veerakumar et al., 2021). Metal nanoparticles deposited on ZnO surface are known to improve photocatalytic activity of the semiconductor material. Thus, the Pd and Ag deposited on the surface of the ZnONSt enhanced its capability to trap the traps the photogenerated e^- in a Schottky barrier by preventing it from returning to the surface of the ZnONSt. As such, the Pd and Ag as dopants acted as sink of e^- that enhanced the interfacial charge-transfer between the ZnONSt and the metals and helped in prolonging the e^-/h^+ pairs recombination. (Lee et al., 2017). The effect of the ZnONSt, Pd and Ag for the MP degradation are represented by the eqn. 33–39.





Thus, the proposed mechanism for the degradation was demonstrated in Fig. 11(e). Upon visible light irradiation, the photoexcitation of charges occurs. The transfer of e^- the ZnONSt to either Pt or Ag present on the surface of the photocatalyst. In such case, the frequent recombination of the charges is avoided and the catalytic efficiency of the Pd@ZnONSt and Ag@ZnONSt are greater than that of the pristine ZnONSt. The MP photocatalytic degradation is initiated by the P–O–C bonds cleavage which is subsequently oxidized to form the phosphate ion and carbon dioxide and other oxidation products. The mechanism of carbaryl degradation using ZnO/AC was also studied (Rungsawang et al., 2024). The AC has been shown to serve as a carrier collector of the photogenerated species. It also served as reinforcement for the adsorption of the herbicide which assist the photocatalytic process. Thus, during the excitation process, the e^- from CB of the ZnO are transferred to CB of the AC. Concurrently, the h^+ from VB of ZnO are transferred to VB of AC. This transfer behavior prolonged the e^-/h^+ pairs lifetimes and suppressed their recombination. The process facilitates the generation of the ROS which continuously attack the pollutant and its degradation and complete mineralization to CO_2 and H_2O (Rungsawang et al., 2024).

4.6. PAHs degradation

Polycyclic aromatic hydrocarbons (PAHs) are one of the ubiquitous organic presents in wastewater and other environmental matrices. They are formed from incomplete combustion of petroleum and petrochemical substances and are released into the environment as a result of anthropogenic activities such as industrial production, emission of vehicles, and runoff from paved surfaces (Lü et al., 2021, Xie et al., 2023). When discharged into the water bodies, PAHs exhibit varying degrees of toxicity in the ecosystem, depending on the extent of exposure, concentration level and their chemical structure. Due to their persistent nature, they are transported into the environment, and they undergo bioaccumulation in the tissues of organisms, cause adverse effect to aquatic organisms, plants, and animals (Garba et al., 2023, Zhong et al., 2022). Some PAHs are classified as carcinogenic, mutagenic, posing higher degree of risks to both human health. Due to their chemical structure and low water solubility, they are persistent in the environment for extended periods (Costa et al., 2020). They adsorbed in sediments and organic matter which resulted in their bioaccumulation in the body of aquatic organisms and disrupt their lives (Zhao et al., 2019). High concentration of PAHs in fishes, invertebrates, and other aquatic species caused reduction in the rate of growth, developmental abnormalities, and impaired reproduction. Chronic exposure to PAHs in humans has been linked to respiratory ailments, skin irritation, reproductive disorders, and an increased risk of certain cancers (Shi et al., 2022, Hoai et al., 2022).

Considering their toxicity and resistance in the environment, remediation techniques are needed to mitigate their effects and possibly eliminate them from the environment. Understanding the PAHs toxicological properties of vital for the implementation of designing efficient remediation strategies for complying with regulatory standards are crucial steps in mitigating the adverse effects of PAHs contamination in the environment (Zango et al., 2020). They are resistance to photolysis and traditional techniques of bioremediation, coagulation and flocculation may not effective and environmentally sustainable for their remediation (da S. Medeiros et al., 2022). Thus, various wastewater remediation processes such as the physical techniques (e.g., filtration, adsorption) (Zango et al., 2021), chemical techniques (oxidation, photo-Fenton, persulfate and photochemical) treatment processes have been employed for the PAHs remediation. The success of photocatalytic degradation technique for PAHs remediation has been widely recognized (Adamu et al., 2023). Various photocatalysts have been employed

and proven successful for the complete mineralization of the PAHs.

ZnO is among the most vastly exploited metal oxide nanoparticles for the degradation of PAHs. It has shown higher efficiency for the and photocatalytic degradation of both parent and substituted PAHs (Nguyen et al., 2020). First, the PAHs get adsorbed on the ZnO surface which resulted in an increased in the local concentration of the molecules of the PAHs near the surface of catalyst. This facilitated the interaction betwixt the ZnO active sites and PAHs molecules which promotes the decomposition activity in presence of UV or visible light. The PAHs adsorption onto the ZnO improved its proximity with the generated ROS during the degradation process as compared to its freely dispersion in the solution (Martínez-Vargas et al., 2019). The photocatalytic degradation of naphthalene was investigated by ZnO nanoparticle prepared using low temperature method (Sliem et al., 2022). The photocatalytic test was carried out in aqueous ethanol using UV lamp with light intensity of $1 - 2 \text{ W/cm}^2$, pH of 12 and temperature of 25°C . The photocatalytic degradation has been affected by the dosage of ZnO with the best degradation performance achieved at the lower dosage of 222 mg/L . The UV light generates the photon that facilitates the movement of electrons from ZnO valence band to its CV which cause the degradation of the naphthalene (Sliem et al., 2022).

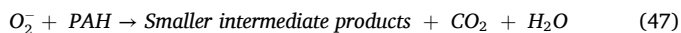
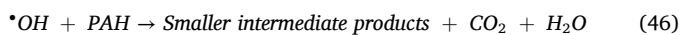
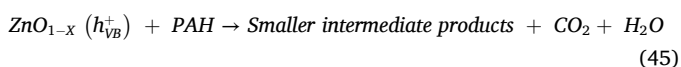
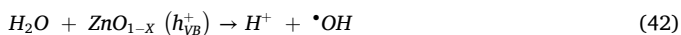
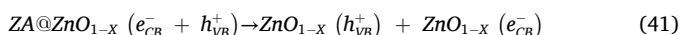
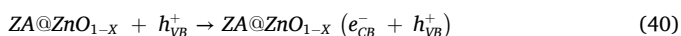
However, when modified to form composites, the performance of the materials is greater than the pristine form due to synergy of the contributing components. For instance, zeolite A (ZA) has been a unique three-dimensional micropores aluminosilicate material with good application in organic pollutant adsorption. Its core composite with oxygen-deficient ZnO nanosheet (core-shell ZA@ZnO_{1-x}) has shown superior efficiency as photocatalyst for decomposition of different PAHs (Manna and Sen, 2023). Despite the two catalysts can be activated by visible light, the performance of core-shell ZA@ZnO_{1-x} is much greater than that of ZnO_{1-x} . Within the visible light irradiation of 120 min, core-shell ZA@ZnO_{1-x} composite has achieved decomposition efficacy of 96%, 95.1%, and 93% for fluorene, phenanthrene and anthracene, respectively (Manna and Sen, 2023). The photocatalytic performance of pristine and Fe-doped ZnO/PVA nanofiber composite was also investigated for naphthalene degradation (Sekar et al., 2018). Underneath visible light illumination and without the photocatalyst, only 36% of naphthalene degradation was recorded. The degradation efficiency increased to 58 and 70%, in the presence of ZnO and Fe-ZnO nanoparticles, respectively. However, when Fe-doped ZnO/PVA nanofiber was used, the efficiency of the decomposition increased to 81 and 96% for the uncalcined and calcined samples, respectively. It was established that the Fe-doping narrowed the bandgap and provide oxygen vacancies that trapped the electrons and holes as well prevent their recombination. Table S3 contained summary of pristine and modified ZnO for the PAHs degradation.

4.6.1. Mechanism of PAHs degradation

Researchers have evaluated the mechanism of PAHs degradation by the ZnO nanoparticles. The semiconducting properties and higher surface area of the photocatalyst served as a backbone for its photocatalytic activity. Direct oxidation of PAHs takes place in the presence of ZnO nanoparticles via e^- transfer processes. Upon UV and visible light exposure, the ZnO generates ROS such as hydroxyl radicals ($\cdot\text{OH}$). The ROS are the major key players for the cleavage of the PAHs molecular structure which initiate the oxidation reactions that results breakdown and decomposition of molecules to fewer toxic species. Hence, researchers have investigated the photocatalytic decomposition of PAHs by the ZnO nanoparticles. The procedure for naphthalene degradation was described by Sing et al. When a UV light was shunned on the ZnO, its VB e^- jumps to CB, resulting in formation of h^+ on VB. The e^- on the ZnO surface combined with O_2 and H^+ in the medium to form H_2O_2 which breakdown to OH^- and $\cdot\text{OH}$ radicals. Similarly, in the presence of H_2O , $\cdot\text{OH}$ radicals are produced by the h^+ which attacked the PAHs molecules and caused their breakdown (Singh et al., 2013). The efficiency of anthracene degradation by the ZnO nanoparticles was also

shown to accelerates by the higher concentration of H_2O_2 which facilitated the OH radicals formation through either trapping the e^- or self-decomposition (Sliem et al., 2019).

The photocatalytic degradation of PAHs by modified ZnO photocatalysts possessed better surface activities compared to the pristine form. For instance, C-atom doped ZnO has demonstrated better efficiency for the PAHs degradation (Xue et al., 2018). Its bandgap was narrower by 0.19 eV in comparison to the crystal of pure ZnO. On irradiation by sunlight, the h^+ on the C-ZnO surface generates $\cdot\text{OH}$ radicals via oxidizing H_2O and OH^- , while the e^- generated $\cdot\text{O}_2^-$ by reaction with the absorbed O_2 . Meanwhile, the e^- on the surface of the excited PAHs is migrated to the C-ZnO CB and is captured by the O_2 to generates $\cdot\text{O}_2^-$ radicals (Xue et al., 2018). Mechanism of PAHs degradation by core-shell ZA@ZnO_{1-x} was also proposed (Manna and Sen, 2023). The generation of photoexcited e^- and h^+ occurred at CB and VB of the material upon visible light excitation (eq. 40). The core ZA in the nanocomposite potentially prevents the e^-/h^+ recombination by mediating the e^- to its vacant site (eq. 41). The production of $\cdot\text{OH}$ and $\cdot\text{O}_2^-$ radicals takes place at VB and CB due to photooxidation-reduction reaction as represented by the Eqs. (42) and (43). On the other hand, ZnO_{1-x} possessed higher porosity than the ZA. Thus, it traps the PAHs without blocking the micropores of the ZA which acts trappers of the e^- (eq. 44). Thus, the $\cdot\text{OH}$ radicals and the h^+ attack the PAHs either directly and indirectly, which causes they oxidation and subsequent degradation as highlighted by the eq. (45) and (46), respectively. The $\cdot\text{O}_2^-$ also contributed in the degradation of the PAHs into smaller intermediates (eq. 47). The final products for the degradation being the CO_2 and H_2O molecules (Manna and Sen, 2023).



The synergistic effect of MOF modified ZnO nanocomposite (ZnO-

MIL-101(Cr)) was also investigated for phenanthrene degradation (Adamu et al., 2024). The ZnO-MIL-101(Cr) was able to degrade over 98% of the PAH within 150 min of visible light irradiation. The photocatalytic decomposition pathway was highlighted in Fig.12. The e^- on the surface of photocatalyst was excited by the visible light illumination which generates h^+ in its VB. The e^- oxidized the O_2 to generate the $\cdot\text{O}_2^-$ radicals which formed $\text{HO}_2\cdot$ radical upon protonation and subsequently transformed to the H_2O_2 . The H_2O_2 substantiated the formation which $\cdot\text{OH}$ radicals that facilitated the cleavage of aromatic rings which further formed intermediates and subsequent degradation to CO_2 and H_2O (Adamu et al., 2024).

4.7. Degradation of other organic pollutants

ZnO has gained immense attention from the researchers in the field of environmental science and engineering due to photocatalytic efficiency. It has potential physicochemical and semiconducting properties and tunable surface morphologies for emerging and micropollutants remediation from environmental water sources. Thus, it has been prominent for decomposition of various organic pollutants due to its efficient adsorption of visible and ultraviolet light and its lower bandgap. Apart from the famous organic pollutants, the materials have been utilized for other toxic organic compounds such as poly and perfluoroalkyl substances (PFAS) (Dehghani et al., 2022), and wide spectrum of organic molecules that contaminate the environmental waters (Khady et al., 2022, Fathalian et al., 2024). Upon exposure to the sunlight or other light from artificial source, the ZnO nanoparticles is potentially excited and produced ROS such as $\cdot\text{OH}$, $\cdot\text{O}_2^-$, OH^- and other intermediate species which are highly reactive for attacking the organic molecule and oxidizing them to less harmful substances. The process of photocatalytic degradation has been promising for remediation of wide range of the organic species from environmental wastewaters. The technique has been efficient for addressing the issue of environmental pollution.

4.7.1. PFAS degradation

The poly- and perfluoroalkyl compounds such as perfluoroalkyl carboxylic acids (PFCAs) are among the most toxic organic pollutants that are vastly traced in environmental wastewater samples. They are a group of synthetic chemical substances that are widely recruited for various industrial applications such as in the production of surfactants, flame retardants, waterproof clothing, fire forms, oil-repellent and in making consumer products such as food packaging (Wang et al., 2005, Wang and Burghaus, 2005). They possessed high stability and unique chemical features due to their predominant C-F bonds. The PFAS have been detected in environmental wastewaters and are known to be persistent, bio accumulative, and toxic to the living organisms. They are

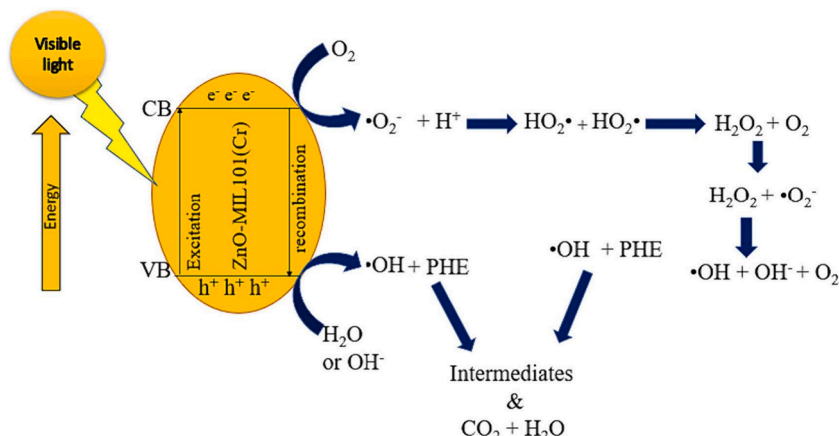


Fig. 12. Proposed mechanism of phenanthrene degradation by ZnO-MIL-101(Cr) photocatalyst. Reproduced from (Adamu et al., 2024).

classified as endocrine disruptors in humans, causing various ailments such as immunotoxicity, thyroid and kidney diseases and behavioral disorders (Wang et al., 2005, Tang and Luo, 2013). As such, much environmental concern has been raised concerning the substances PFAS in the environment due to their harmful and potential health impacts to plants, animals, and humans. They accumulate in the environment and are resistant to photolysis and conventional wastewater remediation techniques (Barisci and Suri, 2021). As such, efforts have been put to regulate, monitor, and eliminate the toxic compounds from the environmental waters. Advanced oxidation techniques, particularly photocatalysis has been widely recognized due to its efficiency for the remediation of the PFAS.

Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) have been the most iconic and widely detected PFCAs in the environmental waters. Their photocatalytic degradation has been widely investigated (Leung et al., 2022). The photocatalytic degradation of PFOA has been studied using ZnO nanoparticles and its composites. Yang et al., evaluated the efficacy of flower-shaped Bi₅O₇I/ZnO n-n heterojunction microspheres (BOI_{0.04}-BHZA-400) synthesized via solvothermal technique and calcined at 400 °C for decomposition of PFOA visible light irradiation (Yang et al., 2021). Under optimum condition of initial PFOA concentration of 0.5 g/L, pH of 4.0, photocatalyst dosage of 0.5 g/L, and irradiation time of 6 hours, the photocatalytic degradation efficiency was 91%. Higher dosage of the photocatalyst caused agglomeration and irradiated light scattering which decrease the efficiency of the process. Thus, the mechanism of the process has been proposed by calculating the bandgap of the material which was 2.24 and 3.33 eV for the Bi₅O₇I and ZnO, respectively (Fig. 13), while the calculated bandgap of the Bi₅O₇I/ZnO n-n heterojunction was 2.64 eV. Thus, upon visible light illumination, excitation of Bi₅O₇I occurred which generates e⁻/h⁺ pairs. The e⁻ from the Bi₅O₇I surface are transferred to the ZnO under the influence of electric field that occurred at the n-n heterojunction region of composite. However, since the ZnO has VB potential which is more positive compared to that of the Bi₅O₇I, the h⁺ from the Bi₅O₇I could not be transferred to the ZnO. As such, the CB of the ZnO only contained the photoinduced e⁻, whereas the VB of the Bi₅O₇I maintained its h⁺. Thus, the n-n heterojunction Bi₅O₇I/ZnO possessed excellent photocatalytic activity due to the e⁻/h⁺ pairs effective separations. The O₂ are transformed to [•]O₂⁻ radicals by the e⁻ in the CB, while the H₂O get oxidized by the h⁺ in the VB of the Bi₅O₇I to form the [•]OH radicals. The overall degradation of the PFOA was facilitated by the synergy of the e⁻ and h⁺ as highlighted by the eq. (48 – 52) as depicted in the Fig. 13 (Yang et al., 2021).

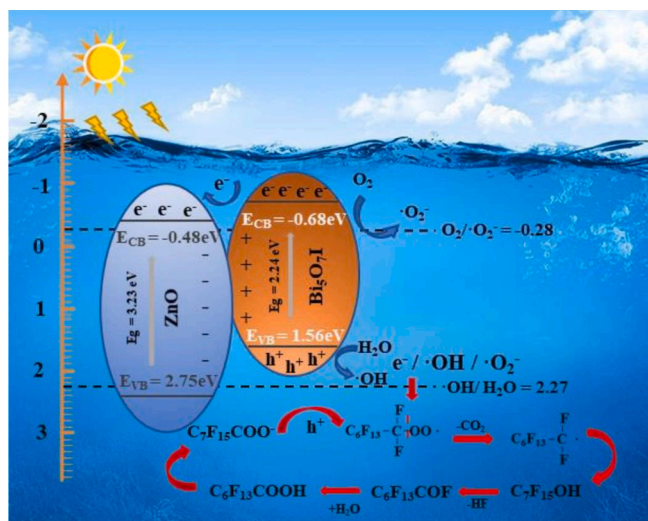
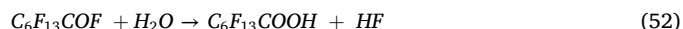
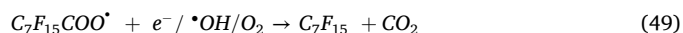


Fig. 13. Proposed mechanism of perfluorooctanoic acid degradation by Bi₅O₇I/ZnO heterojunction photocatalyst. Reproduced from (Yang et al., 2021).



4.7.2. Naphthol degradation

Naphthol also called hydroxynaphthalene, is a group of organic compounds originated from naphthalene, which is an aromatic bicyclic hydrocarbon widely employed as intermediates to produce industrial chemical substances such as pigments, dyes, and other important organic compounds. They are known for the capability to form colored complexes with metal ions, making them useful for coloring textiles, plastics, and other materials. The naphthol contained hydroxyl (-OH) group which is attached to the naphthalene ring (Abdelhameed et al., 2020). The important ones include 1-naphthol and 2-naphthol which are isomeric compounds (Nakane et al., 2024). Despite their industrial applications, they are widely detected in environmental waters. When present in water at higher concentration, they are highly toxic and cause various adverse effects to the environment and living organisms (Nakane et al., 2024). As such, it is crucial to monitor their presence in and eliminate them from the wastewater.

Photocatalytic degradation played significant role in the naphthol remediation from the environmental waters. The use of ZnO and its K-doped composite (K-ZnO) has been reported for the degradation of 2-naphthol under sunlight illumination (Elmorsi, 2017). According to the report, the K-ZnO possessed larger BET surface area and higher efficiency for harnessing the visible light compared to the pristine ZnO. Thus, and optimum 1-naphthol degradation of 95% was achieved under the experimental condition of 12 mg/L as the naphthol initial concentration, 0.5 g/L photocatalyst dosage, pH of 10.5, atmospheric temperature of 37 °C, and illumination time of 70 min. The mechanism of the degradation process has been investigated which demonstrated the influence of [•]OH radicals and h⁺ for the pollutant degradation (Elmorsi, 2017). Prior, the degradation of the pollutant was studied by different metal-oxide nanoparticles including TiO₂, WO₃, CeO₂, CdO, ZnO among others (Karunakaran et al., 2010). Of the materials studied, only ZnO was able to achieve 100% degradation of pollutant within 60 min of visible light illumination. Its degradation efficiency was demonstrated by achieving 100% degradation during reusability. Thus, it has been recommended for the degradation of the naphthol (Karunakaran et al., 2010).

Table S4 summarizes the various findings reported on exploitation of ZnO nanoparticles and its composites for organic pollutants degradation. The promising performance of the materials towards the degradation of perfluorooctanoic acid, perfluorooctane sulfonates, naphthol, benzene, toluene and other organic compounds have been highlighted.

5. Ecological and environmental risks of nanoparticles

ZnO and ZnO-based nanoparticles have been widely applied in various technological areas, including medicine, dyeing, agriculture, energy storage materials, and wastewater treatment (Dejene, 2024). However, their increased use has raised concerns about their environmental impact. In agricultural applications, ZnO nanomaterials can alter soil microbial diversity and function. They can inhibit beneficial microorganisms involved in N₂ fixation, organic matter decomposition, and plant-microbe symbiosis, which can result in detrimental consequences for soil health and crop productivity (Haruna and Yahaya, 2021, Magdy Abdo et al., 2024). Indeed, ZnO can leach into aquatic

environments through industrial discharge, wastewater, or accidental release. The nanoparticles generate reactive oxygen species under UV irradiation, inducing oxidative stress in aquatic organisms. Reports have shown their toxicity to algae, fish, and invertebrates, leading to cell damage, reproductive failure, and mortality (Anbarasu et al., 2024, Mandal et al., 2024). These nanoparticles can also bioaccumulate in aquatic organisms, potentially entering the food chain. Although zinc is an essential element, excessive exposure disrupts enzymatic processes and causes toxic effects in higher trophic levels.

ZnO NPs are prone to aggregation, dissolution, and surface modification under environmental conditions. Their transformation into soluble Zn^{2+} ions increase their bioavailability and toxicity. The interaction of ZnO nanoparticles with organic matter or other pollutants may result in further environmental risks. The lack of standardized protocols for assessing nanoparticle toxicity limits the ability to predict their long-term environmental effects. Their nano-sized properties and complex behaviors under varying environmental conditions pose significant challenges for risk evaluation and regulation (Irede et al., 2024). Finally, to minimize environmental risks, small quantities of ZnO and ZnO-based materials should be produced. Safer synthesis methods, such as green approaches, biodegradable coatings, and recycling strategies, should also be adopted (Al-darwesh et al., 2024). Ultimately, more research is needed to develop comprehensive guidelines for the application and disposal of ZnO and ZnO-based nanomaterials.

6. The importance of modeling in photocatalytic processes

The application of modeling in photocatalytic degradation and environmental remediation has significantly advanced our understanding of pollutant removal processes, including kinetic studies, adsorption isothermal evaluations, etc. For instance, such modeling can demonstrate the role of adsorption in photocatalytic degradation, which is crucial for optimizing the removal of contaminants. Furthermore, machine learning techniques have emerged as powerful tools in this domain, enabling researchers to predict the effectiveness of photocatalytic processes and optimize conditions such as catalyst dosage and light intensity, thereby enhancing degradation rates through data-driven approaches. Additionally, computational modeling has been pivotal in explaining the complex interactions within photocatalytic systems, employing methods like multiscale modeling to bridge quantum mechanical calculations with kinetic models, ultimately guiding the design of more efficient photocatalysts and treatment systems. These advancements underscore the critical role of theoretical frameworks in facilitating practical applications of photocatalysis in industrial full-scale plants.

Based on the previous studies, the exploitation of the following items in studies related to ZnO nanoparticles-based photocatalysts, and their usage for organic pollutants decomposition and CO_2 conversion, should be considered:

- (i) Langmuir-Hinshelwood (L-H) model: L-H model is widely used to describe photocatalytic degradation kinetics, providing insights into reaction mechanisms and key parameters (H.D. Tran et al., 2023). This model and its modified versions have been applied to various pollutants and photocatalysts, including ZnO-based photocatalysts (Kadhim et al., 2023). However, more sophisticated variants of the L-H model have been developed to account for complex processes such as catalyst excitation, electron-hole pair recombination, and reactive oxygen species production (Ateia et al., 2020). For example, in 2022, the Langmuir-Hinshelwood-Hougen-Watson (LHHW) model has been used to study the photodegradation properties of green-synthesized ZnO nanoparticles, considering both adsorption and reaction steps (Villarreal et al., 2022). These models are crucial for understanding photocatalytic processes, optimizing

performance, and designing larger-scale reactors for pollutant degradation.

- (ii) Response Surface Methodology (RSM): RSM has emerged as a powerful tool for optimizing photocatalytic processes involving ZnO nanoparticles for pollutant degradation CO_2 conversion. RSM enables researchers to evaluate the effects of multiple variables simultaneously, such as catalyst dosage, pollutant concentration, and pH, on degradation efficiency (Aziri et al., 2024), helping them to enhance their understanding of parameter interactions affecting photocatalytic activity. Various experimental designs, including factorial, Doehlert, Box-Behnken, and central composite designs, have been employed to model and optimize photocatalytic treatment processes for diverse pollutants (Hasanpour et al., 2021). Recent studies have applied RSM to optimize the synthesis and performance of advanced nano-composite photocatalysts, such as $\text{Fe}_3\text{O}_4\text{-SiO}_2\text{/ZnO}$, for selective pollutant degradation. In fact, RSM is valuable in identifying optimal conditions for maximizing degradation efficiency and providing predictive models for photocatalytic processes within specified parameter ranges (Mokhtari et al., 2024).
- (iii) Kinetic modeling in real-world applications: In real-world applications, kinetic modeling has been crucial for assessing the feasibility of photocatalytic systems in treating real wastewaters or industrial CO_2 conversion. For example, a study investigated the use of $\text{Ag/g-C}_3\text{N}_4\text{/ZnO/Fe}_3\text{O}_4$ for degrading organic contaminants in industrial effluents (Raha and Ahmaruzzaman, 2022). In addition of Langmuir-Hinshelwood model, by employing kinetic models such as pseudo-first-order and pseudo-second-order kinetics, researchers could accurately describe the degradation behavior of various organic pollutants or CO_2 conversion under light irradiation. Such studies show the importance of modeling in predicting treatment efficiency and guiding scale-up processes for practical applications.
- (iv) Bayesian modeling techniques: These techniques have attracted much attention in environmental management and decision support over the past decade. These methods allow for the incorporation of prior knowledge, experimental data, and uncertainty quantification in model predictions. Bayesian approaches have been applied to various environmental challenges, including water quality analysis, pollution management, and habitat suitability modeling (Forio et al., 2023). In photocatalytic processes, Bayesian methods have been used to model the degradation of water pollutants and optimize operational conditions (Al Haiqi et al., 2020).

Modeling techniques significantly enhance the researchers' understanding and their ability for optimization of photocatalytic processes for both pollutant degradation and CO_2 conversion. Previous studies show that integrating appropriate modeling techniques can enhance the robustness of photocatalytic processes, providing valuable insights into reaction mechanisms and facilitating the development of more efficient and sustainable pollutant management strategies.

7. Prospects and challenges

The review presents a comprehensive overview of a promising area of research with significant implications for environmental sustainability. The article's structure, encompassing the synthesis, modification, and applications of ZnO and ZnO-based nanoparticles, is quite logical and well-defined. Nonetheless, it acknowledges there are existing challenges to consider and suggests future research directions needed to be explored. However, the review holds significant prospects due to its focus on a critical area of research. This includes the following potentials-

- i. **Fill a Knowledge Gap:** Provide a comprehensive and up-to-date overview of green synthesis techniques, modification strategies, and applications of ZnO nanoparticles for CO₂ conversion and organic pollutant degradation. In addition, the review highlights areas where further research is needed to optimize the performance and practical application of ZnO nanoparticles.
- ii. **Addressing Global Challenges:** The review directly contributes to finding solutions for climate change involving CO₂ conversion and degradation of organic pollutants.
- iii. **Promoting Sustainability:** By emphasizing green synthesis methods, the review aligns with the growing demand for environmentally friendly technologies. This would contribute to the development of environmentally friendly and cost-effective technologies for addressing global challenges such as climate change and water pollution.
- iv. **Advance Scientific Understanding:** Deepens the understanding of the underlying mechanisms involved in CO₂ conversion and organic pollutant degradation processes using ZnO-based materials.
- v. **Driving Innovation:** The exploration of ZnO nanoparticle modifications can inspire new approaches for enhancing catalytic performance and expanding applications.
- vi. **Policy and Industry:** The review can provide valuable insights for policymakers and industry stakeholders to develop supportive regulations and invest in related research. This could go a long way in developing sustainable policies and evidence-based guided investment towards development of the field.

The field of ZnO nanoparticles is interesting and promising, however, the review encountered the following challenges:

General perspectives of ZnO nanoparticles

- i. **Terminology and Standardization:** Inconsistencies in terminology and experimental methodologies across different studies can hinder data comparison and analysis.
- ii. **Defining "Green Synthesis":** Establishing clear criteria for what constitutes "green synthesis" can be controversial since it remains subjective.
- iii. **Photocatalytic Activity:** In-depth research is required on the challenges associated with CO₂ conversion and organic pollutant degradation using ZnO-based nanomaterials, such as low solar light utilization and catalyst stability that still defy its scalable applications.

Modifications of ZnO Nanoparticles

- i. **Intricacy of Modification Techniques:** The diverse range of modification techniques (bimetallic, carbon-based, organic polymers) introduces complexity in comparing and evaluating their effectiveness.
- ii. **Synergistic Effects:** Understanding the interplay between ZnO and different modifiers to achieve optimal performance requires intricate analysis.
- iii. **Characterization Challenges:** Characterizing the structure and properties of modified ZnO nanoparticles remains technically demanding and resource intensive.

CO₂ Conversion and Organic Pollutants Degradation

- i. **Mechanism Complexity:** Elucidating the precise mechanisms involved in CO₂ conversion and organic pollutant degradation using ZnO nanoparticles is often challenging due to the intricate reaction pathways.
- ii. **Performance Metrics:** Establishing reliable and comparable performance metrics for different studies remain difficult due to varying experimental conditions and evaluation criteria.

- iii. **Scale-Up Challenges:** Bridging the gap between laboratory-scale experiments and industrial-scale applications poses significant hurdles in terms of process optimization and economic feasibility.
- iv. **Environmental Impact:** Assessing the potential environmental impact of ZnO nanoparticles and their modifications requires careful consideration of factors such as toxicity, bioaccumulation, and fate in the environment.
- v. **Comparative Analysis:** Comparing the performance of ZnO-based catalysts for different pollutant types is quite challenging due to variations in experimental conditions and evaluation criteria.
- vi. **Regulatory Hurdles:** Navigating the complex regulatory landscape for nanomaterials remains time-consuming and may hinder the commercialization of ZnO-based technologies.

Overall Challenges

- i. **Data Heterogeneity:** The vast amount of research on ZnO nanoparticles leads to inconsistencies in experimental conditions, making data comparison and analysis difficult.
- ii. **Mechanism Complexity:** Understanding the exact mechanisms involved in CO₂ conversion and organic pollutant degradation by ZnO nanoparticles is complex and requires further investigation.
- iii. **Scalability and Cost-Effectiveness:** Translating laboratory-scale findings to industrial-scale applications faces challenges related to scalability and cost-effectiveness.
- iv. **Environmental Impact:** Although focusing on green synthesis, further studies should also consider the potential environmental impact of ZnO nanoparticles and their modifications.
- v. **Regulatory Framework:** The development and commercialization of ZnO-based technologies has been continuously hindered by the lack of clear regulatory frameworks.

Future directions

- i. **In-depth Mechanism Exploration:** Further studies should explore deeply into the mechanisms of CO₂ conversion and organic pollutant degradation, providing clear explanations and visual representations for practical optimization and scalability.
- ii. **Comparative Analysis:** A comparative analysis of different ZnO modification strategies based on performance metrics would enhance and deepen understanding of the performance of ZnO nanoparticles.
- iii. **Economic and Environmental Assessment:** Incorporating economic and environmental impact assessments of ZnO-based technologies would provide a holistic perspective.

6. Conclusion

This review has comprehensively explored the multifaceted landscape of ZnO nanoparticles, encompassing their green synthesis, diverse modifications, and catalytic applications in CO₂ conversion and organic pollutant degradation. The unique properties of ZnO, including its large bandgap, excellent electron mobility, and biocompatibility, have rendered it a promising candidate for addressing pressing environmental challenges.

Green synthesis methodologies, utilizing biological entities, have emerged as sustainable alternatives to conventional chemical methods for ZnO nanoparticle production. These approaches not only minimize the environmental footprint but also impart specific functionalities to the synthesized nanoparticles. Moreover, the modification of ZnO with various materials, such as metals, carbon-based structures, and organic polymers, has proven to be an effective strategy for augmenting its catalytic performance. Thus, the potential of ZnO and its derivatives for CO₂ conversion into valuable chemicals is evident. While challenges related to selectivity and energy efficiency persist, advancements in

perceiving underlying mechanisms and the development of novel catalyst designs hold promise for future discoveries.

In the context of organic pollutant degradation, ZnO-based photocatalysts have demonstrated remarkable efficacy in removing an ample range of contaminants from water and air. The capability of ZnO to build reactive oxygen species underneath light irradiation facilitates the mineralization of recalcitrant pollutants, including dyes, pharmaceuticals, phenols, pesticides, herbicides, PAHs, and PFAS. However, factors such as catalyst stability, reusability, and the formation of potentially harmful intermediates require careful consideration.

In conclusion, ZnO nanoparticles represent a versatile platform for developing sustainable solutions to environmental challenges. Continuous research and developing efforts are essential to optimize their performance, address scalability issues, and ensure their safe and effective implementation. By combining green synthesis that curtail the use of chemicals, innovative modifications of the ZnO nanoparticles for the composites formation significantly help in tuning the optical features, band gap of the material and enhancing its intrinsic properties for the target applications. Through deep understanding of the catalytic mechanisms, the full potential of ZnO nanoparticles can be harnessed for a cleaner and healthier environment, particularly in the real-world systems of sustainable environmental remediation and practical implementation of CO₂ conversion for the fuels generation.

CRedit authorship contribution statement

Zakariyya Uba Zango: Supervision, Formal analysis, Data curation, Conceptualization. **Abdurrahman Garba:** Writing – original draft, Investigation. **Fatimah Bukola Shittu:** Writing – original draft, Investigation. **Saifullahi Shehu Imam:** Writing – original draft, Validation, Investigation. **Abdurrahshid Haruna:** Writing – original draft, Software, Data curation. **Muttaqa Uba Zango:** Writing – original draft, Investigation. **Ismael A. Wadi:** Writing – original draft, Visualization, Validation. **Usman Bello:** Software, Formal analysis. **Haruna Adamu:** Writing – review & editing, Supervision, Project administration. **Basem E. Keshta:** Writing – original draft, Validation. **Dmitry Olegovich Bokov:** Writing – original draft, Validation. **Omirserik Baigenzhenov:** Writing – original draft. **Ahmad Hosseini-Bandegharai:** Writing – review & editing, Supervision, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

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Data availability

No data was used for the research described in the article.

References

- Aaga, G.F., Fereja, W.M., Tolcha, D.N., Labena, A.A., 2023. Croton macrostachyus leaf extract mediated synthesis of highly efficient ZnO NPs and ZnO/bentonite nanocomposites for photocatalytic degradation of organic dyes under solar irradiation. *J. Environ. Chem. Eng.* 11, 110982.
- Abanades, S., 2022. Redox cycles, active materials, and reactors applied to water and carbon dioxide splitting for solar thermochemical fuel production: a review. *Energies* (Basel) 15, 7061. <https://doi.org/10.3390/en15197061>.
- Abdelhameed, R.M., Abu-elghait, M., El-shahat, M., 2020. Enhancement the biological and visible-light photocatalytic activity. *J. Environ. Chem. Eng.* 8, 104107. <https://doi.org/10.1016/j.jece.2020.104107>.
- Abdulhusain, Z.H., Alshamsi, H.A., Salavati-Niasari, M., 2021. Facile synthesis of Au/ZnO/RGO nanohybrids using 1,8-diamino-3,6-dioxaoctan as novel functional agent for photo-degradation water treatment. *J. Mater. Res. Technol.* 15, 6098–6112. <https://doi.org/10.1016/j.jmrt.2021.11.038>.
- Abebe, B., Murthy, H.C.A., 2022. Insights into ZnO-based doped porous nanocrystal frameworks. *RSC. Adv.* 12, 5816–5833.
- Abegunde, S.M., Olasehinde, E.F., Adebayo, M.A., 2024. Green synthesis of ZnO nanoparticles using Nauclea latifolia fruit extract for adsorption of Congo red. *Hybrid Adv.* 5, 100164. <https://doi.org/10.1016/j.hybadv.2024.100164>.
- Abisha, P., J. C.G., Sonia, S., 2024. Hierarchical synthesis of binary ZnO@MWCNTs heterogeneous photocatalyst derived from porous Zn metal organic framework (MOF) template: Study on the effective photodegradation of Congo red (CR) dye. *Curr. Appl. Phys.* 60, 79–91. <https://doi.org/10.1016/j.cap.2024.02.003>.
- Abou-Elyazed, A.S., Shaban, A.K.F., Osman, A.I., Heikal, L.A., Mohamed, H.F.M., Hassan, W.M.I., El-Nahas, A.M., Keshta, B.E., Hamouda, A.S., 2024. Comparative catalytic efficacy of cost-effective MIL-101(Cr) based PET waste for biodiesel production. *Curr. Res. Green Sustain. Chem.*, 100401.
- Abuqamar, S.F., El-saadony, M.T., Alkafaas, S.S., Elsalahaty, M.I., Elkafas, S.S., Mathew, B.T., Aljasm, A.N., Alhammadi, H.S., Salem, H.M., El-mageed, T.A.A., Zaghloul, R.A., Mosa, W.F.A., Ezzat, A., Elrys, A.S., Saad, A.M., Alsaeed, F.A., Eltarabily, K.A., 2024. Ecological impacts and management strategies of pesticide pollution on aquatic life and human beings. *Mar. Pollut. Bull.* 206, 116613. <https://doi.org/10.1016/j.marpolbul.2024.116613>.
- Adamu, U.A., Hana, N., Abu, H., Zango, Z.U., Sambudi, N.S., Iqbal, A., Hussin, M.H., Hamidun, T.S., 2023. Low-temperature synthesis and characterization of porous chromium terephthalate MIL-101(Cr) and its photocatalytic degradation of phenanthrene. *Korean J. Chem. Eng.* 40, 1–14. <https://doi.org/10.1007/s11814-023-1408-0>.
- Adamu, U.A., Bakar, N.H.H.A., Iqbal, A., Sambudi, N.S., Zango, Z.U., 2024a. The role of bio-inspired ZnO nanoparticles in the modification of MIL101(Cr) properties for visible light degradation of phenanthrene. *Catal. Commun.* 187, 106905. <https://doi.org/10.1016/j.catcom.2024.106905>.
- Adamu, H., Haruna, A., Zango, Z.U., Garba, Z.N., Musa, S.G., Yahaya, S.M., IbrahimTafida, U., Bello, U., Danmallam, U.N., Akinpelu, A.A., Ibrahim, A.S., Sabo, A., Aljunid Merican, Z.M., Qamar, M., 2024b. Microplastics and co-pollutants in soil and marine environments: sorption and desorption dynamics in unveiling invisible danger and key to ecotoxicological risk assessment. *Chemosphere* 362, 142630. <https://doi.org/10.1016/j.chemosphere.2024.142630>.
- Ahmad, W., Kalra, D., 2020. Green synthesis, characterization and anti microbial activities of ZnO nanoparticles using Euphorbia hirta leaf extract. *J. King Saud Univ. - Sci.* 32, 2358–2364. <https://doi.org/10.1016/j.jksus.2020.03.014>.
- Ahmad, A.R.D., Imam, S.S., Adnan, R., Da Oh, W., Latip, A.F.A., Ahmad, A.A.D., 2023. Fenton degradation of ofloxacin antibiotic using calcium alginate beads impregnated with Fe₃O₄-montmorillonite composite. *Int. J. Biol. Macromol.* 229, 838–848.
- Ahmad, A., Khawar, M.R., Ahmad, I., Javed, M.H., Ahmad, A., Rauf, A., Younas, U., Nazir, A., Choi, D., Karami, A.M., 2024. Green synthesis of ZnO nanocubes from Ceropegia omissa H. Huber extract for photocatalytic degradation of bisphenol A under visible light to mitigate water pollution. *Environ. Res.* 249. <https://doi.org/10.1016/j.envres.2023.118093>.
- Ahmed, S., Annu, S.A.Chaudhry, Ikram, S., 2017. A review on biogenic synthesis of ZnO nanoparticles using plant extracts and microbes: a prospect towards green chemistry. *J. Photochem. Photobiol. B Biol.* 166, 272–284. <https://doi.org/10.1016/j.jphotobiol.2016.12.011>.
- Akbari, M., Sharifnia, S., 2017. Synthesis of ZnS/ZnO nanocomposite through solution combustion method for high rate photocatalytic conversion of CO₂ and CH₄. *Mater. Lett.* 194, 110–113. <https://doi.org/10.1016/j.matlet.2017.02.020>.
- Akkari, M., Aranda, P., Belver, C., Bedia, J., Amara, A.B.H., Ruiz-Hitzky, E., 2018. Reprint of ZnO/sepiolite heterostructured materials for solar photocatalytic degradation of pharmaceuticals in wastewater. *Appl. Clay Sci.* 160, 3–8.
- Al Abri, R., Al Marzouqi, F., Kuvarega, A.T., Meetani, M.A., Al Kindy, S.M.Z., Karthikeyan, S., Kim, Y., Selvaraj, R., 2019. Nanostructured cerium-doped ZnO for photocatalytic degradation of pharmaceuticals in aqueous solution. *J. Photochem. Photobiol. A Chem.* 384, 112065.
- Al Haiqi, O., Nour, A.H., Ayodele, B.V., Bargaa, R., 2020. Bayesian regularization-trained multi-layer perceptron neural network predictive modelling of phenol degradation using ZnO/Fe₂O₃ photocatalyst. *J. Phys. Conf. Ser.* 52058.
- Al-darwesh, M.Y., Ibrahim, S.S., Mohammed, M.A., 2024. A review on plant extract mediated green synthesis of zinc oxide nanoparticles and their biomedical applications. *Results. Chem.* 7. <https://doi.org/10.1016/j.rechem.2024.101368>.
- Alavi, M., Nokhodchi, A., 2021. Synthesis and modification of bio-derived antibacterial Ag and ZnO nanoparticles by plants, fungi, and bacteria. *Drug Discov. Today*. 26, 1953–1962. <https://doi.org/10.1016/j.drudis.2021.03.030>.
- Alegría, M., Aliaga, J., Cortes, P., Villarroel, R., Ballesteros, L., Donoso, J.P., Magon, C.J., González, G., Benavente, E., 2024. Copper doped hybrid 2D ZnO-stearic acid nanocomposite for boosting photocatalytic degradation of organic pollutants under simulated solar light. *Ceram. Int.* 50, 41866–41878. <https://doi.org/10.1016/j.ceramint.2024.08.040>.
- Amir, M., Fazal, T., Iqbal, J., Din, A.A., Ahmed, A., Ali, A., Razzaq, A., Ali, Z., Rehman, M.S.U., Park, Y.-K., 2022. Integrated adsorptive and photocatalytic degradation of pharmaceutical micropollutant, ciprofloxacin employing biochar-ZnO composite photocatalysts. *J. Ind. Eng. Chem.* 115, 171–182.
- Anandhi, P., Harikrishnan, S., Mahalingam, S., Jawahar Senthil Kumar, V., Lai, W.C., Rahaman, M., Kim, J., 2024. Efficient and stable supercapacitors using rGO/ZnO nanocomposites via wet chemical reaction. *Inorg. Chem. Commun.* 166. <https://doi.org/10.1016/j.inoche.2024.112675>.

- Anbarasu, M., Martin, T.M., Priya, P., Sivamurugan, V., Kumar, M.S.K., Shaik, M.R., Kari, Z.A., Guru, A., 2024. Assessing the impact of Ag-ZnO nanoparticle on the induction of oxidative stress, hematological, and molecular changes in zebrafish (*Danio rerio*) and McCoy fibroblast cell lines. *Aquac. Int.* 32, 5373–5392. <https://doi.org/10.1007/s10499-024-01611-3>.
- Ani, I.J., Akpan, U.G., Olutoye, M.A., Hameed, B.H., 2018. Photocatalytic degradation of pollutants in petroleum refinery wastewater by TiO₂- and ZnO-based photocatalysts: recent development. *J. Clean. Prod.* 205, 930–954.
- Ara, H., Rafatullah, M., Ahmed, K., Faisal, M., Ali, M., Jeon, B., 2022. Photocatalytic activity of graphene oxide/zinc oxide nanocomposite derived from rice husk for the degradation of phenanthrene under ultraviolet-visible light. *J. Water Process Eng.* 47, 102714. <https://doi.org/10.1016/j.jwpe.2022.102714>.
- Arora, N., Thangavelu, K., Karanikolos, G.N., 2020. Bimetallic nanoparticles for antimicrobial applications. *Front. Chem.* 8, 1–22. <https://doi.org/10.3389/fchem.2020.00412>.
- Arslan, H., Eskinaya, O., Bilici, Z., Dizge, N., Balakrishnan, D., 2022. Comparison of Cr (VI) adsorption and photocatalytic reduction efficiency using leonardite powder. *Chemosphere* 300, 134492.
- Ashford, B., Tu, X., 2017. Non-thermal plasma technology for the conversion of CO₂. *Curr. Opin. Green Sustain. Chem.* 3, 45–49.
- Ateia, M., Alalm, M.G., Awfa, D., Johnson, M.S., Yoshimura, C., 2020. Modeling the degradation and disinfection of water pollutants by photocatalysts and composites: a critical review. *Sci. Total Environ.* 698, 134197.
- Azadi, E., Zinatizadeh, A.A., Yazdani, D., Sillanpää, M., Joshaghani, M., 2024. The photodegradation of oxytetracycline by Degussa P25-TiO₂/FeO/ZnO ternary chain heterojunction in the presence of persulfate under visible light irradiation: the optimization and kinetic study. *Inorg. Chem. Commun.* 166, 112600.
- Aziri, S., Bozetime, H., Meziame, S., Allam, D., Berkane, N., Bakri, R., Amrane, A., 2024. Screening and optimization of the most influencing factors during the photodegradation of Rhodamine B by zinc oxide photocatalyst: application of Plackett–Burman and central composite designs. *React. Kinet. Mech. Catal.* 1–20.
- Azizi, A., Kazemi, M., 2024. Green synthesis of zinc oxide magnetic nanocomposite via zinc electroplating effluent: its characterization and application as a photocatalyst. *Results Opt.*, 100698.
- Bae, K.-L., Kim, J., Lim, C.K., Nam, K.M., Song, H., 2017. Colloidal zinc oxide-copper (I) oxide nanocatalysts for selective aqueous photocatalytic carbon dioxide conversion into methane. *Nat. Commun.* 8, 1156.
- Bakhsh, E.M., Bilal, M., Ali, M., Ali, J., Wahab, A., Akhtar, K., Fagieh, T.M., Danish, E.Y., Asiri, A.M., Khan, S.B., 2022. Synthesis of activated carbon from trachycarpus fortunei seeds for the removal of cationic and anionic dyes. *Materials* (Basel) 15. <https://doi.org/10.3390/ma15061986>.
- Bandoh, C.K., Danu, B.Y., Agorku, E.S., Ampompong, F.K., Nkum, R.K., 2024. The effect of cobalt-doped ZnO-g-C₃N₄ heterostructures on photocatalytic degradation of eosin yellow dye in water under simulated solar light. *Results Mater.* 21, 100515.
- Barani, M., Masoudi, M., Mashreghi, M., Makhdoomi, A., Eshghi, H., 2021. Cell-free extract assisted synthesis of ZnO nanoparticles using aquatic bacterial strains: biological activities and toxicological evaluation. *Int. J. Pharm.* 606. <https://doi.org/10.1016/j.ijpharm.2021.120878>.
- Barisci, S., Suri, R., 2021. Electrooxidation of short- and long-chain perfluoroalkyl substances (PFASs) under different process conditions. *J. Environ. Chem. Eng.* 9, 105323. <https://doi.org/10.1016/j.jece.2021.105323>.
- Basavarajappa, P.S., Patil, S.B., Ganganagappa, N., Reddy, K.R., Raghu, A.V., Reddy, C. V., 2020. Recent progress in metal-doped TiO₂, non-metal doped/codoped TiO₂ and TiO₂ nanostructured hybrids for enhanced photocatalysis. *Int. J. Hydrogen Energy* 45, 7764–7778. <https://doi.org/10.1016/j.ijhydene.2019.07.241>.
- Basit, A., Yu, H., Wang, L., Uddin, M.A., Wang, Y., Awan, K.M., Keshta, B.E., Malik, M.O., 2024. Recent advances in wet surface tissue adhesive hydrogels for wound treatment. *Eur. Polym. J.* 216, 113260. <https://doi.org/10.1016/j.eurpolymj.2024.113260>.
- Bhaskar, A.R., Bhame, S., 2024. Journal of Environmental Chemical Engineering A review on ZnO and its modifications for photocatalytic degradation of prominent textile effluents: synthesis, mechanisms, and future directions. *J. Environ. Chem. Eng.* 12, 112553. <https://doi.org/10.1016/j.jece.2024.112553>.
- Bhatt, P., Joshi, S., Urper Bayram, G.M., Khatri, P., Simsek, H., 2023. Developments and application of chitosan-based adsorbents for wastewater treatments. *Environ. Res.* 226, 115530. <https://doi.org/10.1016/j.envres.2023.115530>.
- Borysiewicz, M.A., 2019. ZnO as a functional material, a review. *Crystals* (Basel) 9. <https://doi.org/10.3390/cryst9100505>.
- Brindhadevi, K., Kim, P.T., Alsalmi, M.S., Abd, O.H., Naveena, T., Lee, J., Bharathi, D., 2024. Deciphering the photocatalytic degradation of polyaromatic hydrocarbons (PAHs) using hausmannite (Mn₃O₄) nanoparticles and their efficacy against bacterial biofilm. *Chemosphere* 349, 140961. <https://doi.org/10.1016/j.chemosphere.2023.140961>.
- Bristhi, R.S., Ahsan Habib, M., Ara, M.H., Rezaul Karim, K.M., Khairul Islam, M., Naime, J., Hasan Rumon, M.M., Rayhan Khan, M.A., 2024. Green synthesis of ZnO NPs using aqueous extract of *Epipremnum aureum* leave: photocatalytic degradation of Congo red. *Results. Chem.* 7. <https://doi.org/10.1016/j.rchem.2024.101441>.
- Buasakun, J., Srilaong, P., Rattanakom, R., Duangthongyou, T., 2021. Synthesis of heterostructure of zn@mof-46(Zn) to improve the photocatalytic performance in methylene blue degradation. *Crystals* (Basel) 11. <https://doi.org/10.3390/cryst11111379>.
- G. Cappelletti, S. Mostoni, V. Pifferi, D. Meroni, L. Falciola, S. Ardizzone, O-toluidine photodetoxification by bismuth doped ZnO nanopowders, (2015).
- Cervantes-Gaxiola, M.E., Vázquez-González, F.A., Ríos-Iribe, E.Y., Méndez-Herrera, P.F., Leyva, C., 2024. Effect of pH on the green synthesis of ZnO nanoparticles using Sorghum bicolor seed extract and their application in photocatalytic dye degradation. *Mater. Lett.* 372. <https://doi.org/10.1016/j.matlet.2024.136982>.
- Chakravorty, A., Roy, S., 2024. A review of photocatalysis, basic principles, processes, and materials. *Sustain. Chem. Environ.* 8, 100155. <https://doi.org/10.1016/j.sceenv.2024.100155>.
- Chauhan, P.S., Kant, R., Rai, A., Gupta, A., Bhattacharya, S., 2019. Facile synthesis of ZnO/GO nanoflowers over Si substrate for improved photocatalytic decolorization of MB dye and industrial wastewater under solar irradiation. *Mater. Sci. Semicond. Process.* 89, 6–17. <https://doi.org/10.1016/j.mssp.2018.08.022>.
- Chopra, L., 2022. Photocatalytic activity of zinc oxide for dye and drug degradation: a review. *Mater. Today Proc.* 52, 1653–1656.
- Costa, J.A.S., Sarmento, V.H.V., Romão, L.P.C., Paranhos, C.M., 2020. Removal of polycyclic aromatic hydrocarbons from aqueous media with polysulfone/MCM-41 mixed matrix membranes. *J. Memb. Sci.* 601. <https://doi.org/10.1016/j.memsci.2020.117912>.
- Cui, W., Kang, X., Zhang, X., Cui, X., 2019. Gel-like ZnO/Zr-MOF(bpy) nanocomposite for highly efficient adsorption of Rhodamine B dye from aqueous solution. *J. Phys. Chem. Solids* 134, 165–175. <https://doi.org/10.1016/j.jpcs.2019.06.004>.
- Cursaru, L.M., Valsan, S.N., Puscasu, M.E., Tudor, I.A., Zarnescu-Ivan, N., Vasile, B.S., Piticescu, R.M., 2021. Study of zn-cnt nanocomposites in high-pressure conditions. *Materials* (Basel) 14. <https://doi.org/10.3390/ma14185330>.
- da S. Medeiros, D.C.C., Chelme-Ayala, P., Benally, C., Al-Anzi, B.S., Gamal El-Din, M., 2022. Review on carbon-based adsorbents from organic feedstocks for removal of organic contaminants from oil and gas industry process water: Production, adsorption performance and research gaps. *J. Environ. Manage.* 320, 115739. <https://doi.org/10.1016/j.jenvman.2022.115739>.
- da Trindade, L.G., Borba, K.M.N., Trench, A.B., Zanchet, L., Teodoro, V., Pontes, F.M.L., Longo, E., Mazzo, T.M., 2021. Effective strategy to coupling Zr-MOF/ZnO: Synthesis, morphology and photoelectrochemical properties evaluation. *J. Solid State Chem.* 293, 121794. <https://doi.org/10.1016/j.jssc.2020.121794>.
- Dar, R.A., Naikoo, G.A., Srivastava, A.K., Hassan, I.U., Karna, S.P., Giri, L., Shaikh, A.M. H., Rezakazemi, M., Ahmed, W., 2022. Performance of graphene-zinc oxide nanocomposite coated-glassy carbon electrode in the sensitive determination of para-nitrophenol. *Sci. Rep.* 12, 1–14. <https://doi.org/10.1038/s41598-021-03495-2>.
- Darwesh, O.M., Matter, I.A., Al-Balakocy, N.G., Abo-Elkasem, M.I., 2024. Circular economy reinforcement through molecular fabrication of textile wastes with microbial synthesized ZnO nanoparticles to have multifunctional properties. *Sci. Rep.* 14. <https://doi.org/10.1038/s41598-024-66430-1>.
- Das, D., Sahu, P., 2024. ZnO/Ag₂O/g-C₃N₄ composite heterostructures with AgO-induced superior visible light photocatalytic activity via unique bi-phasic dye-degradation phenomena. *Opt. Mater. (Amst.)* 147, 114596. <https://doi.org/10.1016/j.optmat.2023.114596>.
- Das, A., Patra, M., Kumar P, M., Bhagavathiachari, M., Nair, R.G., 2021. Role of type II heterojunction in ZnO–In₂O₃ nanodiscs for enhanced visible-light photocatalysis through the synergy of effective charge carrier separation and charge transport. *Mater. Chem. Phys.* 263, 124431. <https://doi.org/10.1016/j.matchemphys.2021.124431>.
- Davoodi, Y., Shafeeyan, M.S., 2024. Tailoring photocatalytic performance through Fe-doped TiO₂/ZnO for effective remediation of organic contaminants. *Water Resour. Ind.* 31. <https://doi.org/10.1016/j.wri.2024.100239>.
- Dehghani, M., Naseri, M., Nadeem, H., Holl, M.M.B., Batchelor, W., 2022. Sunlight-driven photocatalytic per- and polyfluoroalkyl substances degradation over zinc oxide/cellulose nanofiber catalyst using a continuous flow reactor. *J. Environ. Chem. Eng.* 10, 108686. <https://doi.org/10.1016/j.jece.2022.108686>.
- Dejene, B.K., Geletaw, T.M., 2023. A review of plant-mediated synthesis of zinc oxide nanoparticles for self-cleaning textiles. *Res. J. Text. Appar.* <https://doi.org/10.1108/RJTA-12-2022-0154>.
- Dejene, B.K., 2024. Exploring the potential of ZnO nanoparticle-treated fibers in advancing natural fiber reinforced composites: a review. *J. Nat. Fibers* 21. <https://doi.org/10.1080/15440478.2024.2311304>.
- Dhandapani, P., Prakash, A.A., AlSalhi, M.S., Maruthamuthu, S., Devanesan, S., Rajasekar, A., 2020. Ureolytic bacteria mediated synthesis of hairy ZnO nanostructure as photocatalyst for decolorization of dyes. *Mater. Chem. Phys.* 243. <https://doi.org/10.1016/j.matchemphys.2020.122619>.
- Dharmana, G., Nadiklatla, S.K., Gurugubelli, T.R., Viswanadham, B., 2024. Enhanced photo-catalytic degradation of mb dye over hydrothermal grown-up of ZnO/SnO₂ catalyst. *J. Chem.* 2024. <https://doi.org/10.1155/2024/9135923>.
- Didaskalou, C., A. B.Sibel Buyuktiyaki, Rustem Kecili, B., Fonte, a.G.S.Claudio P., 2017. Valorisation of agricultural waste with adsorption/nanofiltration hybrid process: from materials to sustainable process design. *Green. Chem.* 19, 3116–3125. <https://doi.org/10.1039/c7gc00912g>.
- Ding, F., Yang, D., Tong, Z., Nan, Y., Wang, Y., Zou, X., Jiang, Z., 2017. Graphitic carbon nitride-based nanocomposites as visible-light driven photocatalysts for environmental purification. *Environ. Sci. Nano.* 4, 1455–1469. <https://doi.org/10.1039/c7en00255f>.
- Dong, S., Zhang, D., Cui, H., Huang, T., 2019. ZnO/porous carbon composite from a mixed-ligand MOF for ultrasensitive electrochemical immunosensing of C-reactive protein. *Sensors Actuators, B Chem.* 284, 354–361. <https://doi.org/10.1016/j.snb.2018.12.150>.
- Durmaz, F., Hussaini, A.A., Mirza, S., Atasagun, B., Ulukus, D., Yildirim, M., 2024. Supercritical CO₂ directional-assisted green synthesis of ZnO nanoparticles obtained from *Euphorbia stricta* L. for functional applications. *Inorg. Chem. Commun.* 167. <https://doi.org/10.1016/j.inoche.2024.112737>.
- Ehsan, M., Waheed, A., Ullah, A., Kazmi, A., Ali, A., Raja, N.I., Mashwani, Z., Sultana, T., Mustafa, N., Ikram, M., Li, H., 2022. Review article plant-based bimetallic silver-zinc

- oxide nanoparticles : a comprehensive perspective of synthesis. *Biomed. Appl. Future Trends* 2022.
- El Golli, A., Fendrich, M., Bazzanella, N., Dridi, C., Miotello, A., Orlandi, M., 2021. Wastewater remediation with ZnO photocatalysts: green synthesis and solar concentration as an economically and environmentally viable route to application. *J. Environ. Manage.* 286, 112226.
- El Hassani, K., Beakou, B.H., Anouar, A., 2018. Analysis of adsorption of azo dye onto NiAl-CO₃ using Box-Behnken design approach and desirability function. *J. Mater. Environ. Sci.* 9, 520–527.
- Elankathirselvan, K., Fathima H. A., K. P., Al-Ansari, M.M., 2024. Synthesis and characterization of *Pyrus communis* fruit extract synthesized ZnO NPs and assessed their anti-diabetic and anti-microbial potential. *Environ. Res.* 258. <https://doi.org/10.1016/j.envres.2024.119450>.
- Eleryan, A., Güner, E.K., Hassaan, M., El-Nemr, M.A., Ragab, S., El Nemr, A., 2024. Mandarin biochar-CO-TETA was utilized for Acid Red 73 dye adsorption from water, and its isotherm and kinetic studies were investigated. *Sci. Rep.* 14, 13021.
- Elhalil, A., Elmoubarki, R., Farnane, M., Machrouhi, A., Mahjoubi, F.Z., Sadiq, M., Qourzal, S., Abdennouri, M., Barka, N., 2019. Novel Ag-ZnO-La₂O₃CO₃ photocatalysts derived from the Layered Double Hydroxide structure with excellent photocatalytic performance for the degradation of pharmaceutical compounds. *J. Sci. Adv. Mater. Devices.* 4, 34–46.
- Elmorsi, T.M., 2017. Toward visible-light responsive photocatalysts: nano-potassium doping zinc oxide (K-ZnO) for degradation of 2-naphthol. *Phys. Chem.* 7, 42–53. <https://doi.org/10.5923/j.pc.20170702.03>.
- Esfandian, H., Cherati, M., Rostamnejad, Khatirian, M., 2024. Electrochemical behavior and photocatalytic performance of chlorpyrifos pesticide decontamination using Ni-doped ZnO-TiO₂ nanocomposite. *Inorg. Chem. Commun.* 159. <https://doi.org/10.1016/j.inoche.2023.111750>.
- Fadhila, F.R., Umar, A., Chandren, S., Apriandanu, D.O.B., Yulizar, Y., 2024. Biosynthesis of CoCr₂O₄/ZnO nanocomposites using *Basella alba* L. leaves extracts with enhanced photocatalytic degradation of malachite green in aqueous media. *Chemosphere* 352. <https://doi.org/10.1016/j.chemosphere.2024.141215>.
- Fathalian, F., Moghadamzadeh, H., Hemmati, A., Ghaemi, A., 2024. Efficient CO₂ adsorption using chitosan, graphene oxide, and zinc oxide composite. *Sci. Rep.* 14, 3186.
- Fauzi, A.A., Jalil, A.A., Hassan, N.S., Aziz, F.F.A., Azami, M.S., Hussain, I., Saravanan, R., Vo, D.-V.N., 2022. A critical review on relationship of CeO₂-based photocatalyst towards mechanistic degradation of organic pollutant. *Chemosphere* 286, 131651. <https://doi.org/10.1016/j.chemosphere.2021.131651>.
- Forio, M.A.E., Moltchanova, E., Goethals, P.L.M., 2023. Application of Bayesian modeling in environmental management. *Front. Environ. Sci.* 10, 1128055.
- Fu, H., Xu, T., Zhu, S., Zhu, Y., 2008. Photocorrosion inhibition and enhancement of photocatalytic activity for ZnO via hybridization with C60. *Environ. Sci. Technol.* 42, 8064–8069. <https://doi.org/10.1021/es801484x>.
- Gębka, K., Beldowski, J., Beldowska, M., 2016. The impact of military activities on the concentration of mercury in soils of military training grounds and marine sediments. *Environ. Sci. Pollut. Res.* 23, 23103–23113. <https://doi.org/10.1007/s11356-016-7436-0>.
- Gao, D., Zhang, Y., Zhou, Z., Cai, F., Zhao, X., Huang, W., Li, Y., Zhu, J., Liu, P., Yang, F., Wang, G., Bao, X., 2017. Enhancing CO₂ electroreduction with the metal-oxide interface. *J. Am. Chem. Soc.* 139, 5652–5655. <https://doi.org/10.1021/jacs.7b00102>.
- Gao, D., Zhao, P., Lyu, B., Li, Y., Hou, Y., Ma, J., 2020. Carbon quantum dots decorated on ZnO nanoparticles: An efficient visible-light responsive antibacterial agents. *Appl. Organomet. Chem.* 34, 1–9. <https://doi.org/10.1002/aoc.5665>.
- Garba, A., Nasri, N.S., Basri, H., Ismail, R., Majid, Z., Abdul, Hamza, U.D., Mohammed, J., 2016. Adsorptive removal of phenol from aqueous solution on a modified palm shell-based carbon: fixed-bed adsorption studies. *Desalin. Water Treat.* 57, 29488–29499. <https://doi.org/10.1080/19443994.2016.1184187>.
- Garba, Z.N., Haruna, A., Tanimu, A., Bello, B.Z., Zango, Z.U., 2023. Recent progress in the preparation, characterization, and applications of modified halloysite nanotubes as adsorbents for wastewater treatment. *Korean J. Chem. Eng.* 40, 1–21. <https://doi.org/10.1007/s11814-023-1440-0>.
- Gaur, J., Vikrant, K., Kim, K.H., Kumar, S., Pal, M., Badru, R., Masand, S., Momoh, J., 2023. Photocatalytic degradation of Congo red dye using zinc oxide nanoparticles prepared using *Carica papaya* leaf extract. *Mater. Today Sustain.* 22. <https://doi.org/10.1016/j.mtsust.2023.100339>.
- Gawade, V.V., Gavade, N.L., Shinde, H.M., Babar, S.B., Kadam, A.N., Garadkar, K.M., 2017. Green synthesis of ZnO nanoparticles by using *Calotropis procera* leaves for the photodegradation of methyl orange. *J. Mater. Sci. Mater. Electron.* 28, 14033–14039. <https://doi.org/10.1007/s10854-017-7254-2>.
- Gayathri, P.V., Rayaroth, M.P., Aravindakumar, C.T., Pillai, D., Joseph, S., 2023. Sunlight-induced decontamination of water from emerging pharmaceutical pollutants using ZnO nanoparticles. *Chemosphere* 343, 140265.
- Geioushy, R.A., Hegazy, I.M., El-Sheikh, S.M., Fouad, O.A., 2022. Construction of 2D MoS₂/ZnO heterojunction as superior photocatalyst for highly efficient and selective CO₂ conversion into liquid fuel. *J. Environ. Chem. Eng.* 10, 107337. <https://doi.org/10.1016/j.jece.2022.107337>.
- Geng, Z., Kong, X., Chen, W., Su, H., Liu, Y., Cai, F., Wang, G., Zeng, J., 2018. Oxygen vacancies in ZnO nanosheets enhance CO₂ electrochemical reduction to CO. *Angew. Chemie - Int. Ed.* 57, 6054–6059. <https://doi.org/10.1002/anie.201711255>.
- Geng, K., He, T., Liu, R., Dalapati, S., Tan, K.T., Li, Z., Tao, S., Gong, Y., Jiang, Q., Jiang, D., 2020. Covalent organic frameworks: design, synthesis, and functions. *Chem. Rev.* 120, 8814–8933. <https://doi.org/10.1021/acs.chemrev.9b00550>.
- Gordijo, J.S., Rodrigues, N.M., Martins, J.B.L., 2023. CO₂ and CO capture on the ZnO surface: a GCMC and electronic structure study. *ACS. Omega* 8, 46830–46840.
- Gu, X., Yan, Q., Wei, Y., Luo, Y., Sun, Y., Zhao, D., Ji, F., Xu, X., 2019. Visible-light-responsive photocatalyst with a microsphere structure: preparation and photocatalytic performance of CQDs@BiOCl. *J. Mater. Sci. Mater. Electron.* 30, 16321–16336. <https://doi.org/10.1007/s10854-019-02003-7>.
- M.M. Gui, L.-L. Tan, W.-J. Ong, S.-P. Chai, A.R. Mohamed, CO₂ photocatalytic reduction: photocatalyst choice and product selectivity, 2015. 10.1007/978-3-319-11906-9_3.
- Gui, Y.-H., Tu, Y.-S., Guo, H.-S., Qin, X.-Y., Tian, K., Qin, X.-M., Guo, D.-J., Guo, X., 2024. Microwave-assisted efficient synthesis of ZnO nanospheres for low temperature NO₂ gas sensor. *Mater. Sci. Eng. B.* 299, 117031.
- Guo, Q., Fu, L., Yan, T., Tian, W., Ma, D., Li, J., Jiang, Y., Wang, X., 2020. Improved photocatalytic activity of porous ZnO nanosheets by thermal deposition graphene-like g-C₃N₄ for CO₂ reduction with H₂O vapor. *Appl. Surf. Sci.* 509, 144773. <https://doi.org/10.1016/j.apsusc.2019.144773>.
- Gurushantha, K., Renuka, L., Anantharaju, K.S., Vidya, Y.S., Nagaswarupa, H.P., Prashantha, S.C., Nagabhushana, H., 2017. Photocatalytic and photoluminescence studies of ZnO/ZnO nanocomposite for LED and waste water treatment applications. *Mater. Today Proc.* 4, 11747–11755.
- Guzmán, H., Salomone, F., Bensaid, S., Castellino, M., Russo, N., Hernández, S., 2022. CO₂ conversion to alcohols over Cu/ZnO catalysts: prospective synergies between electrocatalytic and thermocatalytic routes. *ACS Appl. Mater. Interfaces.* 14, 517–530. <https://doi.org/10.1021/acsmi.1c15871>.
- Habisreutinger, S.N., Schmidt-Mende, L., Stolarczyk, J.K., 2013. Photocatalytic reduction of CO₂ on TiO₂ and other semiconductors. *Angew. Chemie - Int. Ed.* 52, 7372–7408. <https://doi.org/10.1002/anie.201207199>.
- Haladu, S.A., Elsayed, K.A., Manda, A.A., Ibrahim Gaya, U., Almessiere, M.A., Hafez, M. A., 2025. ZnO submicron spheres doped with Eu nanoparticles prepared by laser ablation for efficient photocatalytic degradation of an organic dye. *Opt. Laser Technol.* 180. <https://doi.org/10.1016/j.optlastec.2024.111498>.
- Hamed, H., Moradi, S., Hudson, S.M., Tonelli, A.E., 2018. Chitosan based hydrogels and their applications for drug delivery in wound dressings: a review. *Carbohydr. Polym.* 199, 445–460. <https://doi.org/10.1016/j.carbpol.2018.06.114>.
- Hameed, H., Waheed, A., Sharif, M.S., Saleem, M., Afreen, A., Tariq, M., Kamal, A., Al-onazi, W.A., Al Farraj, D.A., Ahmad, S., Mahmoud, R.M., 2023. Green synthesis of zinc oxide (ZnO) nanoparticles from green algae and their assessment in various biological applications. *Micromachines. (Basel)* 14. <https://doi.org/10.3390/mi14050928>.
- Hamidon, T.S., Garba, Z.N., Zango, Z.U., Hussin, M.H., 2024. Biopolymer-based beads for the adsorptive removal of organic pollutants from wastewater: Current state and future perspectives. *Int. J. Biol. Macromol.* 269, 131759. <https://doi.org/10.1016/j.ijbiomac.2024.131759>.
- Hanafi, M.F., Sapawe, N., 2024. Enhanced photocatalytic degradation of phenol using mesoporous zinc nanoparticles catalyst. In: *AIP Conf. Proc.* AIP Publishing.
- Haq, S., Afsar, H., Ben Ali, M., Almalki, M., Albogami, B., Hedfi, A., 2021. Green synthesis and characterization of a ZnO-ZrO₂ heterojunction for environmental and biological applications. *Crystals (Basel)* 11, 1502.
- Haruna, A., Yahaya, S.M., 2021. Recent advances in the chemistry of bioactive compounds from plants and soil microbes: a review. *Chem. Africa.* 4, 231–248. <https://doi.org/10.1007/s42250-020-00213-9>.
- Haruna, A., Abdulkadir, I., Idris, S.O., 2018. Visible light induced photodegradation of methylene blue in sodium doped bismuth barium ferrite nanoparticle synthesized by sol-gel method. *Avicenna J. Environ. Heal. Eng.* 5, 120–126. <https://doi.org/10.15171/ajehe.2018.16>.
- Haruna, A., Abdulkadir, I., Idris, S.O., 2020. Photocatalytic activity and doping effects of BiFeO₃ nanoparticles in model organic dyes. *Heliyon.* 6. <https://doi.org/10.1016/j.heliyon.2020.e03237>.
- Haruna, A., Chong, F.K., Ho, Y.C., Merican, Z.M.A., 2022. Preparation and modification methods of defective titanium dioxide-based nanoparticles for photocatalytic wastewater treatment—a comprehensive review. *Environ. Sci. Pollut. Res.* 29, 70706–70745. <https://doi.org/10.1007/s11356-022-22749-8>.
- Haruna, A., Merican, Z., Merican, A., Basyaruddin, M., Rahman, A., Gani, S., Al-yaari, A., 2023a. Fabrication of PW11Zn@MOF-808 and its catalytic activity for oxidative desulfurization of fuel oil: kinetics, thermodynamics and mechanism. *J. Solid State Chem.* 326, 124232. <https://doi.org/10.1016/j.jssc.2023.124232>.
- Haruna, A., Merican, Z.M.A., Musa, S.G., Rahman, M.B.A., 2023b. MOF-808(Zr)-supported with Keggin Polyoxometalates as an efficient oxidative desulfurization catalyst. *J. Taiwan Inst. Chem. Eng.* 147. <https://doi.org/10.1016/j.jtice.2023.104919>.
- Haruna, A., Zango, Z.U., Tanimu, G., Izuagie, T., Musa, S.G., Garba, Z.N., Merican, Z.M. A., 2024. A critical review on recent trends in metal-organic framework-based composites as sustainable catalysts for environmental applications. *J. Environ. Chem. Eng.* 12, 113542. <https://doi.org/10.1016/j.jece.2024.113542>.
- Hasanah, A.U., Gareso, P.L., Rauf, N., Tahir, D., 2023. Photocatalytic performance of zinc oxide and metal-doped zinc oxide for various organic pollutants. *ChemBioEng Rev* 10, 698–710. <https://doi.org/10.1002/cben.202300004>.
- Hasanpour, M., Motahari, S., Jing, D., Hatami, M., 2021. Statistical analysis and optimization of photodegradation efficiency of methyl orange from aqueous solution using cellulose/zinc oxide hybrid aerogel by response surface methodology (RSM). *Arab. J. Chem.* 14, 103401.
- M. Hasanzadeh, Z. Ghaedrahmat, N. Kayedi, J. Haghighi, A. Azari, M. Afsharizadeh, Heliyon Persulfate-assisted heterogeneous photocatalytic degradation of furfural from aqueous solutions using TiO₂ – ZnO /biochar composite, *Heliyon.* 9 (2023) e21421. 10.1016/j.heliyon.2023.e21421.
- He, Y., Wang, Y., Zhang, L., Teng, B., Fan, M., 2015. High-efficiency conversion of CO₂ to fuel over ZnO/g-C₃N₄ photocatalyst. *Appl. Catal. B Environ.* 168–169, 1–8. <https://doi.org/10.1016/j.apcatb.2014.12.017>.

- Hegazy, I.M., Geioushy, R.A., El-Sheikh, S.M., Shawky, A., El-Sherbiny, S., Kandil, A.H. T., 2020a. Influence of oxygen vacancies on the performance of ZnO nanoparticles towards CO₂ photoreduction in different aqueous solutions. *J. Environ. Chem. Eng.* 8. <https://doi.org/10.1016/j.jece.2020.103887>.
- Hegazy, I.M., Geioushy, R.A., El-Sheikh, S.M., Shawky, A., El-Sherbiny, S., Kandil, A.H. T., 2020b. Influence of oxygen vacancies on the performance of ZnO nanoparticles towards CO₂ photoreduction in different aqueous solutions. *J. Environ. Chem. Eng.* 8, 103887.
- Hoai, P.T.T., Huong, N.T.M., Huong, P.T., Viet, N.M., 2022. Improved the light adsorption and separation of charge carriers to boost photocatalytic conversion of CO₂ by using silver doped ZnO photocatalyst. *Catalysts*. 12. <https://doi.org/10.3390/catal12101194>.
- Hong, L., Lin, J., Gao, D., Zheng, D., 2024. Molecular modeling of CO₂ affecting competitive adsorption within anthracite coal. *Sci. Rep.* 14, 7586.
- Hsueh, Y.H., Ke, W.J., Hsieh, C.T., Lin, K.S., Tzou, D.Y., Chiang, C.L., 2015. ZnO nanoparticles affect bacillus subtilis cell growth and biofilm formation. *PLoS One* 10. <https://doi.org/10.1371/journal.pone.0128457>.
- Hu, C., Hu, X., Li, R., Xing, Y., 2020. MOF derived ZnO/C nanocomposite with enhanced adsorption capacity and photocatalytic performance under sunlight. *J. Hazard. Mater.* 385, 121599. <https://doi.org/10.1016/j.jhazmat.2019.121599>.
- Huang, Z., Huang, G., 2023. Study on zinc-modified adsorbent for adsorption of trace CO₂ in electronic special gas BF₃. *Processes* 11, 1075.
- Hussain, M.Z., Pawar, G.S., Huang, Z., Tahir, A.A., Fischer, R.A., Zhu, Y., Xia, Y., 2019. Porous ZnO/Carbon nanocomposites derived from metal organic frameworks for highly efficient photocatalytic applications - a correlational study. *Carbon N. Y.* 146, 348–363. <https://doi.org/10.1016/j.carbon.2019.02.013>.
- Huynh, H.N.D., Nguyen, B.G.M., Dinh, T.M., Nguyen, N.M., Tran, C.K., Nguyen, T.T., Tran, N.H.T., La, H.P.P., Van Tran, T.T., Duy, L.T., 2024. Enhancing the performance of ZnO-based photodetectors by forming ZnO/(Cu: ZnO) core/shell nanorods. *ACS Appl. Electron. Mater.* 6, 1894–1903.
- Ichiji, E.O., Tichapondwa, S.M., Chirwa, E.M.N., 2022. Plasmonic effect and bandgap tailoring of Ag/Ag₂S doped on ZnO nanocomposites for enhanced visible-light photocatalysis. *Adv. Powder Technol.* 33, 103596. <https://doi.org/10.1016/j.appt.2022.103596>.
- Idris, D.S., Roy, A., 2023. Synthesis of bimetallic nanoparticles and applications—an updated review. *Crystals* (Basel) 13. <https://doi.org/10.3390/cryst13040637>.
- Idris, N.A., Yusoff, H.M., Idris, N.H., Badar, N., Elong, K., Muhamad, S.U., Yusoff, N.F.M., Wai, C.P., 2024. Green synthesis of zinc oxide nanoparticles using leaves extract of Mariposa Christia vespertilionis and its potential as anode materials in sodium-ion batteries (SIBs). *Arab. J. Sci. Eng.* 49, 623–635. <https://doi.org/10.1007/s13369-023-08300-y>.
- Irede, E.L., Awoyemi, R.F., Owolabi, B., Aworinde, O.R., Kajola, R.O., Hazeem, A., Raji, A. A., Ganiyu, L.O., Onukwuli, C.O., Onivefi, A.P., Ifijen, I.H., 2024. Cutting-edge developments in zinc oxide nanoparticles: synthesis and applications for enhanced antimicrobial and UV protection in healthcare solutions. *RSC. Adv.* 14, 20992–21034. <https://doi.org/10.1039/d4ra02452d>.
- Irshad, S., Salamat, A., Anjum, A.A., Sana, S., Saleem, R.S., Naheed, A., Iqbal, A., 2018. Green tea leaves mediated ZnO nanoparticles and its antimicrobial activity. *Cogent. Chem.* 4, 1469207. <https://doi.org/10.1080/23312009.2018.1469207>.
- Ishyaka, H.A., Ramli, A., Jumbri, K., Sambudi, N.S., Zango, Z.U., Saad, B., 2021. Adsorption and artificial neural network modelling of metolachlor removal by MIL-53(Al) metal-organic framework. In: *Adv. Robot. Autom. Data Anal. Sel. Pap. from ICITES 2020*. Springer Int. Publ, pp. 245–255.
- Ishyaka, H.A., Jumbri, K., Sambudi, N.S., Zango, Z.U., Abdullah, N., Saad, B., 2023. Optimizations and docking simulation study for metolachlor adsorption from water onto MIL-101(Cr) metal-organic framework. *Int. J. Environ. Sci. Technol.* 20, 277–292.
- Islam, T., Repon, M.R., Islam, T., Sarwar, Z., Rahman, M.M., 2023. Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions. *Environ. Sci. Pollut. Res.* 30, 9207–9242. <https://doi.org/10.1007/s11356-022-24398-3>.
- Jabbar, K.Q., Barzinjy, A.A., Hamad, S.M., 2022. Iron oxide nanoparticles: preparation methods, functions, adsorption and coagulation/flocculation in wastewater treatment. *Environ. Nanotechnol. Monit. Manag.* 17, 100661.
- F. Jahanbakhsh, B. Ebrahimi, Modified activated carbon with zinc oxide nanoparticles produced from used tire for removal of acid green 25 from aqueous solutions, 4 (2016) 8–13. <https://doi.org/10.11648/j.ajac.20160401.12>.
- Jha, S., Rani, R., Singh, S., 2023. Biogenic zinc oxide nanoparticles and their biomedical applications: a review. *J. Inorg. Organomet. Polym. Mater.* 33, 1437–1452. <https://doi.org/10.1007/s10904-023-02550-x>.
- Jia, Y., Han, H., Luo, Y., Wang, Q., Lee, B.W., Liu, C., 2023. SrTiO₃ nanosheets decorated with ZnFe₂O₄ nanoparticles as Z-scheme photocatalysts for highly efficient photocatalytic degradation and CO₂ conversion. *Sep. Purif. Technol.* 306, 122667.
- Jiang, J., Wang, H., Chen, X., Li, S., Xie, T., Wang, D., Lin, Y., 2017. Enhanced photocatalytic degradation of phenol and photogenerated charges transfer property over BiOI-loaded ZnO composites. *J. Colloid Interface Sci.* 494, 130–138. <https://doi.org/10.1016/j.jcis.2017.01.064>.
- Jiang, W., Loh, H., Low, B.Q.L., Zhu, H., Low, J., Heng, J.Z.X., Tang, K.Y., Li, Z., Loh, X. J., Ye, E., 2023a. Role of oxygen vacancy in metal oxides for photocatalytic CO₂ reduction. *Appl. Catal. B Environ.* 321, 122079.
- Jiang, Z., Liu, B., Yu, L., Tong, Y., Yan, M., Zhang, R., Han, W., Hao, Y., Shangguan, L., Zhang, S., Li, W., 2023b. Research progresses in preparation methods and applications of zinc oxide nanoparticles. *J. Alloys Compd.* 956. <https://doi.org/10.1016/j.jallcom.2023.170316>.
- Jin, C., Cheng, Y., Liu, W., Lv, Y., 2022. Preparation of ZnO-GO nanocomposites and their properties. *E3S Web Conf.* 341, 0–4. <https://doi.org/10.1051/e3sconf/202234101001>.
- Jing, H., Ji, L., Wang, Z., Guo, J., Lu, S., Sun, J., Cai, L., Wang, Y., 2021. Synthesis of znO nanoparticles loaded on biochar derived from spartina alterniflora with superior photocatalytic degradation performance. *Nanomaterials* 11. <https://doi.org/10.3390/nano11102479>.
- Jose, L.M., Raj, R.S.A., Sajan, D., Aravind, A., 2021. Adsorption and photocatalytic activity of biosynthesised ZnO nanoparticles using Aloe Vera leaf extract. *Nano Express* 2. <https://doi.org/10.1088/2632-959X/abeec6>.
- Josun, J., Sharma, P., Garg, V.Kumar, 2024. Optical and structural behavior of hydrothermally synthesized ZnO nanoparticles at various temperatures with NaOH molar ratios. *Results Opt.* 14. <https://doi.org/10.1016/j.rso.2023.100601>.
- Joy, A., Viswanathan, M.R., Vijayan, B.K., Silva, C.G., Basheer, I., Sugathan, S., Mohamed, P.A., Solaippan, A., Shereef, A., 2024. Solar photocatalysts: non-metal (C, N, and S)-doped ZnO synthesized through an industrially sustainable in situ approach for environmental remediation applications. *RSC. Adv.* 14, 21655–21667. <https://doi.org/10.1039/d4ra03492a>.
- Juma, A.K., Merican, Z.M.A., Haruna, A., 2024. Recent progress of MOF-based photocatalysts for environmental application and sustainability considerations. *Chem. Eng. Res. Des.* 208, 391–435. <https://doi.org/10.1016/j.cherd.2024.06.042>.
- Jun Wang, Z., Song, H., Pang, H., Ning, Y., Dao, T.D., Wang, Z., Chen, H., Weng, Y., Fu, Q., Nagao, T., Fang, Y., Ye, J., 2019. Photo-assisted methanol synthesis via CO₂ reduction under ambient pressure over plasmonic Cu/ZnO catalysts. *Appl. Catal. B Environ.* 250, 10–16. <https://doi.org/10.1016/j.apcatb.2019.03.003>.
- Jung, H.J., Koutavarapu, R., Lee, S., Kim, J.H., Choi, H.C., Choi, M.Y., 2018. Enhanced photocatalytic degradation of lindane using metal-semiconductor Zn/Ag and ZnO/Ag nanostructures. *J. Environ. Sci.* 74, 107–115. <https://doi.org/10.1016/j.jes.2018.02.014>.
- Kachere, A.R., Kakade, P.M., Kanwade, A.R., Dani, P., Mandlik, N.T., Rondiya, S.R., Dzade, N.Y., Jadhav, S.R., Bhosale, S.V., 2022. Zinc oxide graphene oxide nanocomposites: synthesis, characterization and their optical properties. *ES Mater. Manuf.* 16, 19–29. <https://doi.org/10.30919/esmm5f516>.
- Kadhim, M.J., Mahdi, M.A., Selman, A.M., Al-Ani, S.K.J., Hassan, J.J., Ahmed, N.M., 2023. The most important parameters that affect the photocatalytic activity of ZnO nanostructures against organic dyes: a review. *Iran. J. Catal.* 13.
- Kamal, A., Saba, M., Kamal, A., Batool, M., Asif, M., Al-Mohameed, A.M., Al Farraj, D.A., Habib, D., Ahmad, S., 2023. Bioinspired green synthesis of bimetallic iron and zinc oxide nanoparticles using mushroom extract and use against aspergillus niger; the most devastating fungi of the green world. *Catalysts*. 13. <https://doi.org/10.3390/catal13020400>.
- Kamyab, H., SaberiKamarposhti, M., Hashim, H., Yusuf, M., 2024. Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. *Carbon Lett.* 34, 265–289. <https://doi.org/10.1007/s42823-023-00647-4>.
- Karthik, K.V., Raghu, A.V., Reddy, K.R., Ravishanker, R., Sangeeta, M., Shetti, N.P., Reddy, C.V., 2022. Green synthesis of Cu-doped ZnO nanoparticles and its application for the photocatalytic degradation of hazardous organic pollutants. *Chemosphere* 287. <https://doi.org/10.1016/j.chemosphere.2021.132081>.
- Karunakaran, C., Narayanan, S., Gomathisankar, P., 2010. Photocatalytic degradation of 1-naphthol by oxide ceramics with added bacterial disinfection. *J. Hazard. Mater.* 181, 708–715. <https://doi.org/10.1016/j.jhazmat.2010.05.070>.
- Katiyar, A., Kumar, N., Shukla, R.K., Srivastava, A., 2020. Substrate free ultrasonic-assisted hydrothermal growth of ZnO nanoflowers at low temperature. *SN Appl. Sci.* 2, 1–7. <https://doi.org/10.1007/s42452-020-3186-1>.
- Kaur, M., Pal, B., Kaur, D., 2024. Modified Ag-ZnO coated graphene oxide ternary composite for superior photocatalytic degradation of crystal violet dye under visible light irradiation. *Diam. Relat. Mater.* 143. <https://doi.org/10.1016/j.diamond.2024.110935>.
- Keshta, B.E., Gemeay, A.H., 2022. Influence of synthesis and functionalization procedures of Fe₃O₄ NPs by mono- and diamino silane coupling agents on the adsorption efficiency of anionic dyes. *J. Hazardous, Toxic, Radioact. Waste* 26, 1–13. [https://doi.org/10.1061/\(asce\)hz.2153-5515.0000641](https://doi.org/10.1061/(asce)hz.2153-5515.0000641).
- Keshta, B.E., Yu, H., Wang, L., Uddin, M.A., El-Attar, H.G., Keshta, A.E., Gemeay, A.H., Hassan, F., Eid, S.M., 2024a. Cost-effective synthesis of MIL-101(Cr) from recyclable wastes and composite with polyaniline as an ion-to-electron transducer for potentiometric Pb²⁺ sensing. *Chem. Eng. J.* 485, 150049. <https://doi.org/10.1016/j.cej.2024.150049>.
- Keshta, B.E., Yu, H., Wang, L., El-Attar, H.G., El Aziz, F.A., Mahmoud, Y.A.G., Gemeay, A. H., Hassan, F., 2024b. Green preparation of antibacterial agents: MIL-101(Cr) synthesized from PET bottles recycling and its functionalization with silver nanoparticles. *Mater. Today Commun.* 38, 107731. <https://doi.org/10.1016/j.mtcomm.2023.107731>.
- Khalil, T.E., Elhusseiny, A.F., El-dissouky, A., Ibrahim, N.M., 2020. Functionalized chitosan nanocomposites for removal of toxic Cr (VI) from aqueous solution. *React. Funct. Polym.* 146, 104407. <https://doi.org/10.1016/j.reactfunctpolym.2019.104407>.
- Khan, I., Saeed, K., Khan, I., 2019. Nanoparticles: Properties, applications and toxicities. *Arab. J. Chem.* 12, 908–931. <https://doi.org/10.1016/j.arabjc.2017.05.011>.
- Khan, M.F., ul H. Bakhtiar, S., Zada, A., Raziq, F., Saleemi, H.A., Khan, M.S., Muhammad Ismail, P., Alguno, A.C., Capangpangan, R.Y., Ali, A., Hayat, S., Ali, S., Ismail, A., Zahid, M., 2022. Ag modified ZnO microsphere synthesis for efficient sonophotocatalytic degradation of organic pollutants and CO₂ conversion. *Environ. Nanotechnol. Monit. Manag.* 18, 100711. <https://doi.org/10.1016/j.enmm.2022.100711>.

- Khan, W.U., Ahmed, S., Dhoble, Y., Madhav, S., 2023. A critical review of hazardous waste generation from textile industries and associated ecological impacts. *J. Indian Chem. Soc.* 100. <https://doi.org/10.1016/j.jics.2022.100829>.
- Khdary, N.H., Alayyar, A.S., Alsarhan, L.M., Alshihri, S., Mokhtar, M., 2022. Metal oxides as catalyst/supporter for CO₂ capture and conversion, review. *Catalysts* 12, 300.
- Klienchen de Maria, V.P., Guedes de Paiva, F.F., Tamashiro, J.R., Silva, L.H.P., da Silva Pinho, G., Rubio-Marcos, F., Kinoshita, A., 2024. Advances in ZnO nanoparticles in building material: Antimicrobial and photocatalytic applications – Systematic literature review. *Constr. Build. Mater.* 417. <https://doi.org/10.1016/j.conbuildmat.2024.135337>.
- Kovács, Z., Márta, V., Gyulavári, T., Ágoston, Á., Baia, L., Pap, Z., Hernadi, K., 2022. Noble metal modified (002)-oriented ZnO hollow spheres for the degradation of a broad range of pollutants. *J. Environ. Chem. Eng.* 10, 1–12. <https://doi.org/10.1016/j.jece.2022.107655>.
- Kshirsagar, S.D., Shelake, S.P., Biswas, B., Ramesh, K., Gaur, R., Abraham, B.M., Sainath, A.V.S., 2024. U. Pal, Emerging ZnO semiconductors for photocatalytic CO₂ reduction to methanol. *Small*, 2407318.
- Kula, K., Klemes, J.J., Van Fan, Y., Varbanov, P.S., Gaurav, G.K., Jasiński, R., 2024. Environmental footprints and implications of converting GHG species to value-added chemicals: a review. *Rev. Chem. Eng.* 40, 457–480.
- Kumar, A., Ahmad, M.I., 2022. Role of defects in the electronic properties of Al doped ZnO films deposited by spray pyrolysis. *J. Mater. Sci.* 57, 7877–7895. <https://doi.org/10.1007/s10853-022-07136-5>.
- Kumar, S.G., Rao, K.S.R.K., 2017. Comparison of modification strategies towards enhanced charge carrier separation and photocatalytic degradation activity of metal oxide semiconductors (TiO₂, WO₃ and ZnO). *Appl. Surf. Sci.* 391, 124–148. <https://doi.org/10.1016/j.apsusc.2016.07.081>.
- Kumar, S., Pandit, V., Bhattacharyya, K., Krishnan, V., 2018. Sunlight driven photocatalytic reduction of 4-nitrophenol on Pt decorated ZnO-RGO nanoheterostructures. *Mater. Chem. Phys.* 214, 364–376. <https://doi.org/10.1016/j.matchemphys.2018.04.113>.
- Kumar, D., Singh, M.K., Mehata, M.S., 2022. Exploration of grown cobalt-doped zinc oxide nanoparticles and photodegradation of industrial dye. *Mater. Res. Bull.* 150. <https://doi.org/10.1016/j.materresbull.2022.111795>.
- Kumar, V., Kumar, D., Singh, V., Kaushik, N., Kaushik, A., Purohit, L.P., Kaushik, N.K., Sharma, S.K., 2024. Ag-catalyzed strain engineering in ZnO for tailoring defects towards bacterial inactivation and removal of organic dyes for environmental sustainability. *Colloids Surfaces A Physicochem. Eng. Asp.* 698, 134460.
- Kusiak-Nejman, E., Ćmielewska, K., Ekiert, E., Wanag, A., Kapica-Kozar, J., Pelech, I., Narkiewicz, U., Morawski, A.W., 2024. The comparison of photocatalytic reduction of CO₂ on ZnO photocatalysts at slightly acidic and alkaline pH towards the formation of valuable products. *Catal. Today*. 432. <https://doi.org/10.1016/j.cattod.2024.114599>.
- Lü, F., Bao, H., He, F., Qi, G., Sun, J., Zhang, S., Zhuo, L., Yang, H., Hu, G., Luo, J., 2021. Nitrogen dopant induced highly selective CO₂ reduction over lotus-leaf shaped ZnO nanorods. *Mater. Chem. Front.* 5, 4225–4230.
- Lakshmi, N.J., Anandakumar, S., Sampathkumar, V., Manoj, S., 2024. Synthesized ZnO nanoparticles using sorghum panicle for the photocatalytic degradation of pharmaceutical waste water. *Desalin. Water Treat.*, 100557.
- Lange, A.S., Pathan, A.S., Bhosale, S.V., Hase, Y.V., Gaje, T.R., Autade, V.B., Jadhkar, S.R., Arote, S.A., 2024. Studies on combustion synthesized ZnO and ZnO@ZrO₂ nanocomposites for dye contaminated wastewater treatment. *Next Sustain.* 4, 100053.
- Le Pivert, M., Poupart, R., Capochichi-Gnambodé, M., Martin, N., Leprince-Wang, Y., 2019. Direct growth of ZnO nanowires on civil engineering materials: smart materials for supported photodegradation. *Microsyst. Nanoeng.* 5, 1–7. <https://doi.org/10.1038/s41378-019-0102-1>.
- Lee, K.M., Lai, C.W., Ngai, K.S., Juan, J.C., 2016. Recent developments of zinc oxide based photocatalyst in water treatment technology: a review. *Water. Res.* 88, 428–448. <https://doi.org/10.1016/j.watres.2015.09.045>.
- Lee, W.J., Lim, J., Kim, S.O., 2017. Nitrogen dopants in carbon nanomaterials: defects or a new opportunity? *Small. Methods* 1. <https://doi.org/10.1002/smt.201600014>.
- Lee, H., Kannan, P., Al Shoaibi, A., Srinivasakannan, C., 2019. Phenol degradation catalyzed by metal oxide supported porous carbon matrix under UV irradiation. *J. Water Process Eng.* 31. <https://doi.org/10.1016/j.jwpe.2019.100869>.
- Lee, D.-E., Kim, M.-K., Danish, M., Jo, W.-K., 2023. State-of-the-art review on photocatalysis for efficient wastewater treatment: attractive approach in photocatalyst design and parameters affecting the photocatalytic degradation. *Catal. Commun.*, 106764.
- Lee, K.H., Farheen, R., Arshad, Z., Ali, M., Hassan, H., Alshareef, M., Dahshan, A., Khalid, U., 2024. Optimized Cu-doping in ZnO electro-spun nanofibers for enhanced photovoltaic performance in perovskite solar cells and photocatalytic dye degradation. *RSC Adv.* 14, 15391–15407.
- Lei, H., Nie, R., Wu, G., Hou, Z., 2015. Hydrogenation of CO₂ to CH₃OH over Cu/ZnO catalysts with different ZnO morphology. *Fuel* 154, 161–166. <https://doi.org/10.1016/j.fuel.2015.03.052>.
- Leung, S.C.E., Shukla, P., Chen, D., Eftekhari, E., An, H., Zare, F., Ghasemi, N., Zhang, D., Nguyen, N.T., Li, Q., 2022. Emerging technologies for PFOS/PFOA degradation and removal: a review. *Sci. Total Environ.* 827. <https://doi.org/10.1016/j.scitotenv.2022.153669>.
- Li, B., Liu, T., Wang, Y., Wang, Z., 2012. ZnO/graphene-oxide nanocomposite with remarkably enhanced visible-light-driven photocatalytic performance. *J. Colloid Interface Sci.* 377, 114–121. <https://doi.org/10.1016/j.jcis.2012.03.060>.
- Li, D., Huang, J.F., Cao, L.Y., Li, J.Y., Ouyang, H.B., Yao, C.Y., 2014. Microwave hydrothermal synthesis of Sr²⁺ doped ZnO crystallites with enhanced photocatalytic properties. *Ceram. Int.* 40, 2647–2653. <https://doi.org/10.1016/j.ceramint.2013.10.061>.
- Li, C., Wang, G., Gao, Y., Wang, C., Wen, S., Li, H., Wu, J., Shen, L., Guo, W., Ruan, S., 2019a. Highly efficient polymer solar cells based on low-temperature processed ZnO: Application of a bifunctional Au@CNTs nanocomposite. *J. Mater. Chem. C* 7, 2676–2685. <https://doi.org/10.1039/c8tc05653f>.
- Li, P., Zhu, S., Hu, H., Guo, L., He, T., 2019b. Influence of defects in porous ZnO nanoplates on CO₂ photoreduction. *Catal. Today*. 335, 300–305. <https://doi.org/10.1016/j.cattod.2018.11.068>.
- Li, P., Hu, H., Luo, G., Zhu, S., Guo, L., Qu, P., Shen, Q., He, T., 2020. Crystal facet-dependent CO₂ photoreduction over porous ZnO nanocatalysts. *ACS Appl. Mater. Interfaces*. <https://doi.org/10.1021/acsami.0c17596>.
- Li, M., Zhang, R., Zou, Z., Zhang, L., Ma, H., 2024. Optimizing physico-chemical properties of hierarchical ZnO/TiO₂ nano-film by the novel heating method for photocatalytic degradation of antibiotics and dye. *Chemosphere* 346, 140392.
- Lim, K., Hamid, M.A.A., Shamsudin, R., Al-Hardan, N.H., Mansori, I., Chiu, W., 2016. Temperature-driven structural and morphological evolution of zinc oxide nano-coalesced microstructures and its defect-related photoluminescence properties. *Materials* (Basel) 9. <https://doi.org/10.3390/ma9040300>.
- Lin, L., Yu, Z., Wang, X., 2019. Crystalline carbon nitride semiconductors for photocatalytic water splitting. *Angew. Chemie*. 131, 6225–6236. <https://doi.org/10.1002/ange.201809897>.
- Liu, X., Ye, L., Liu, S., Li, Y., Ji, X., 2016. Photocatalytic reduction of CO₂ by ZnO micro/nanomaterials with different morphologies and ratios of {0001} facets. *Sci. Rep.* 6, 38474. <https://doi.org/10.1038/srep38474>.
- Liu, X., Luo, J., Wang, H., Huang, L., Wang, S., Li, S., Sun, Z., Sun, F., Jiang, Z., Wei, S., Li, W.X., Lu, J., 2022. In situ spectroscopic characterization and theoretical calculations identify partially reduced ZnO1–x/Cu interfaces for methanol synthesis from CO₂. *Angew. Chemie - Int. Ed.* 61. <https://doi.org/10.1002/anie.202202330>.
- Liu, H., Wang, C., Ai, X., Wang, B., Bian, Y., Wang, Y., Hu, Z., Zhang, Z., 2023a. Single atom catalysts for organic pollutant degradation. *J. Environ. Chem. Eng.* 11, 110573. <https://doi.org/10.1016/j.jece.2023.110573>.
- Liu, R., Fu, X., Guo, Y., Zhang, J., Tian, W., 2023b. A study on Ag or Ce doped and co-doped ZnO for the photocatalytic degradation of RhB dye. *Vacuum*. 215, 112337.
- Liu, L., 2016. Controllable ZnO nanorod arrays@carbon fibers composites: towards advanced CO₂ photocatalytic reduction catalysts. *Ceram. Int.* 42, 12516–12520. <https://doi.org/10.1016/j.ceramint.2016.04.136>.
- Long, R., Li, Y., Liu, Y., Chen, S., Zheng, X., Gao, C., He, C., Chen, N., Qi, Z., Song, L., Jiang, J., Zhu, J., Xiong, Y., 2017a. Isolation of Cu atoms in Pd lattice: forming highly selective sites for photocatalytic conversion of CO₂ to CH₄. *J. Am. Chem. Soc.* 139, 4486–4492. <https://doi.org/10.1021/jacs.7b00452>.
- Long, N.V.D., Lee, J., Koo, K.-K., Luis, P., Lee, M., 2017b. Recent progress and novel applications in enzymatic conversion of carbon dioxide. *Energies* (Basel) 10, 473.
- Lu, Q., Rosen, J., Jiao, F., 2015. Nanostructured metallic electrocatalysts for carbon dioxide reduction. *ChemCatChem*. 7, 38–47. <https://doi.org/10.1002/cctc.201402669>.
- Luo, S., Liu, C., Zhou, S., Li, W., Ma, C., Liu, S., 2020. ZnO nanorod arrays assembled on activated carbon fibers for photocatalytic degradation: characteristics and synergistic effects. *Chemosphere* 261, 127731. <https://doi.org/10.1016/j.chemosphere.2020.127731>.
- Luque, P.A., Garrafa-Gálvez, H.E., García-Maró, C.A., Soto-Robles, C.A., 2022. Study of the optical properties of ZnO semiconductor nanoparticles using *Origanum vulgare* and its effect in Rhodamine B degradation. *Optik* (Stuttg) 258. <https://doi.org/10.1016/j.ijleo.2022.168937>.
- Luque-Morales, P.A., López-Peraza, A., Nava-Olivas, O.J., Amaya-Parra, G., Báez-López, Y.A., Orozco-Carmona, V.M., Garrafa-Gálvez, H.E., Chinchillas-Chinchillas, M.de J., 2021. ZnO semiconductor nanoparticles and their application in photocatalytic degradation of various organic dyes. *Materials* (Basel) 14. <https://doi.org/10.3390/ma14247537>.
- Ma, X., Zhang, B., Cong, Q., He, X., Gao, M., Li, G., 2016. Organic/inorganic nanocomposites of ZnO/CuO/chitosan with improved properties. *Mater. Chem. Phys.* 178, 88–97. <https://doi.org/10.1016/j.matchemphys.2016.04.074>.
- Ma, S., Deng, T., Li, Z., Zhang, Z., Jia, J., Li, Q., Wu, G., Xia, H., Yang, S., Liu, X., 2022. Photocatalytic hydrogen production on a sp²-carbon-linked covalent organic framework. *Angew. Chemie*. 134, e202208919.
- Ma, S., Min, J., Yang, C., Liao, C., Zhu, Y., Zhao, X., Zhou, Y., Li, X., Zhao, Q., Shih, K., 2024. Developing a low-carbon, scalable strategy for the conversion of spent batteries into metal-organic framework-74 for CO₂ capture. *Resour. Conserv. Recycl.* 209, 107707.
- Magdy Abdo, D., Nasr El-Shazly, A., Adel Hamza, M., 2024. Effect of acidic and basic leachants on the synthesis of ZnO nanoparticles from Egyptian zinc ore, their optical/surface characteristics and photocatalytic performance. *Mater. Lett.* 364. <https://doi.org/10.1016/j.matlet.2024.136377>.
- Mahmoudi, G., Sharifnia, S., Rahimpour, F., Hosseini, S.N., 2013. Photocatalytic conversion of CO₂ and CH₄ using ZnO coated mesh: effect of operational parameters and optimization. *Sol. Energy Mater. Sol. Cells*. 111, 31–40. <https://doi.org/10.1016/j.solmat.2012.12.017>.
- Mahmud, R.A., Ali, K.A., Putri, L.K., Morikawa, Y., Mohamed, A.R., 2023. ZnO with engineered surface defects as a competent photocatalyst for CO₂ photoreduction into valuable fuels under simulated solar light irradiation. *J. Environ. Chem. Eng.* 11, 109637.
- Majumder, S., Chatterjee, S., Basnet, P., Mukherjee, J., 2020. ZnO based nanomaterials for photocatalytic degradation of aqueous pharmaceutical waste solutions – a contemporary review. *Environ. Nanotechnology, Monit. Manag.* 14. <https://doi.org/10.1016/j.enmm.2020.100386>.

- Malerba, M., Cerana, R., 2018. Recent advances of chitosan applications in plants. *Polymers* (Basel) 10, 1–10. <https://doi.org/10.3390/polym10020118>.
- Mandal, A.H., Ghosh, S., Adhurya, D., Chatterjee, P., Samajdar, I., Mukherjee, D., Dhara, K., Saha, N.C., Piccione, G., Multisanti, C.R., Saha, S., Faggio, C., 2024. Exploring the impact of zinc oxide nanoparticles on fish and fish-food organisms: a review. *Aquac. Reports* 36. <https://doi.org/10.1016/j.aqrep.2024.102038>.
- Manikanika, L., Chopra, Kumar, R., 2024. Combustion-synthesized ZnO-CeO₂ heterojunctions for advanced photocatalytic dye degradation. *Inorg. Chem. Commun.* 160, 111896. <https://doi.org/10.1016/j.inoche.2023.111896>.
- H.K. Mankomal, Synergistic effect of biochar impregnated with ZnO nano-flowers for effective removal of organic pollutants from wastewater, <https://www.Sciencedirect.com/Journal/Applied-Surface-Science-Advances>. 12 (2022) 2666–5239. <https://doi.org/10.1016/j.apsadv.2022.100339>.
- Manna, M., Sen, S., 2023. A novel oxygen-deficient core-shell Zn@ZnO_{1-x} nanocomposite for enhanced degradation of multiple polyaromatic hydrocarbons. *Appl. Surf. Sci.* 630, 157523. <https://doi.org/10.1016/j.apsusc.2023.157523>.
- Martínez-Vargas, B.L., Cruz-Ramírez, M., Díaz-Real, J.A., Rodríguez-López, J.L., Bacame-Valenzuela, F.J., Ortega-Borges, R., Reyes-Vidal, Y., Ortiz-Frade, L., 2019. Synthesis and characterization of n-ZnO/p-MnO nanocomposites for the photocatalytic degradation of anthracene. *J. Photochem. Photobiol. A Chem.* 369, 85–96. <https://doi.org/10.1016/j.jphotochem.2018.10.010>.
- Masekela, D., Hintsho-Mbita, N.C., Dlamini, L.N., Yusuf, T.L., Mabuba, N., 2024. Internal piezoelectric field produced by tri-component (FTO: Sb-ZnO/MoS₂) thin film for enhanced photocatalytic degradation of organic pollutants and antibacterial activity. *Mater. Today Commun.* 38, 108500.
- Matei, E., Şăulean, A.A., Răpă, M., Constandache, A., Predescu, A.M., Coman, G., Berbecaru, A.C., Predescu, C., 2023. ZnO Nanostructured Matrix As Nexus Catalysts For the Removal of Emerging Pollutants. Springer, Berlin Heidelberg. <https://doi.org/10.1007/s11356-023-30713-3>.
- Matinise, N., Fuku, X.G., Kaviyarasu, K., Mayedwa, N., Maaza, M., 2017. ZnO nanoparticles via Moringa oleifera green synthesis: physical properties & mechanism of formation. *Appl. Surf. Sci.* 406, 339–347. <https://doi.org/10.1016/j.apsusc.2017.01.219>.
- Matysiak, W., Zaborowska, M., 2019. Hybrid ZnO/ZnO-NPs nanofibres fabricated via electrospinning. *J. Achiev. Mater. Manuf. Eng.* 94, 5–12. <https://doi.org/10.5604/01.3001.0013.5116>.
- Meng, J., Chen, Q., Lu, J., Liu, H., 2019. Z-scheme photocatalytic CO₂ reduction on a heterostructure of oxygen-defective ZnO/reduced graphene oxide/UiO-66-NH₂ under visible light. *ACS Appl. Mater. Interfaces* 11, 550–562. <https://doi.org/10.1021/acsami.8b14282>.
- Meruvu, H., Vangalapati, M., Chaitanya Chippada, S., Bammidi, S.Rao, 2011. Synthesis and characterization of zinc oxide nanoparticles and its antimicrobial activity against bacillus subtilis and escherichia coli. *Rasayan J. Chem.* 4, 217–222.
- Minas, F., Chandravanshi, B.S., Leta, S., 2017. Chemical precipitation method for chromium removal and its recovery from tannery wastewater in Ethiopia. *Chem. Int.* 3, 291–305.
- Mirzaeifard, Z., Shariatinia, Z., Jourshabani, M., Rezaei Darvishi, S.M., 2020. ZnO photocatalyst revisited: effective photocatalytic degradation of emerging contaminants using S-doped ZnO nanoparticles under visible light radiation. *Ind. Eng. Chem. Res.* 59, 15894–15911.
- Mishra, J., Singh, G., Kaur, N., Ganguli, A.K., 2023. Role of linker molecules on morphology of tripodal ligands based functionalized ZnO nanoparticles and its effect on photocatalysis. *Inorg. Chem. Commun.* 148. <https://doi.org/10.1016/j.inoche.2022.110333>.
- Mohamed, R.M., Mkhali, I.A., Alhaddad, M., Basaleh, A., Alzahrani, K.A., Ismail, A.A., 2021. Enhanced CO₂ photocatalytic conversion into CH₃OH over visible-light-driven Pt nanoparticle-decorated mesoporous ZnO-ZnS S-scheme heterostructure. *Ceram. Int.* 47, 26779–26788. <https://doi.org/10.1016/j.ceramint.2021.06.086>.
- Mohammed, M.K.A., Shekargofar, M., 2021. Surface treatment of ZnO films with carbon nanotubes for efficient perovskite solar cells. *Sustain. Energy Fuels* 5, 540–548. <https://doi.org/10.1039/d0se01493a>.
- Mohd Adnan, M.A., Julkapli, N.Muht, Amir, M.N.I., Maamor, A., 2019. Effect on different TiO₂ photocatalyst supports on photodecolorization of synthetic dyes: a review. *Int. J. Environ. Sci. Technol.* 16, 547–566. <https://doi.org/10.1007/s13762-018-1857-x>.
- Mohtaram, M.S., Sabbaghi, S., Rasouli, J., Rasouli, K., 2024. Photocatalytic degradation of tetracycline using a novel WO₃-ZnO/AC under visible light irradiation: Optimization of effective factors by RSM-CCD. *Environ. Pollut.* 347, 123746.
- Mokhtari, S., Faghhihan, H., Pourshirband, N., Sharafi-Badr, P., 2024. Synthesis of Fe₃O₄-SiO₂/ZnO nanocomposite: a RSM study towards sulfasalazine photodegradation. *Inorg. Chem. Commun.*, 112002.
- Molla-Mahmoudi, M., Monazami-Tehrani, G., Hassani, M., Bahramzadeh, A.H., 2018. Investigating the effects of pharmaceutical wastes on the environment and human health (systematic review). *J. Saf. Promot. Inj. Prev.* 6.
- Moradi, S., Ali, S., Hayati, F., Akbar, A., Kakavandi, B., Bashardoust, P., Anvaripour, B., 2020. Performance and reaction mechanism of MgO/ZnO/Graphene ternary nanocomposite in coupling with LED and ultrasound waves for the degradation of sulfamethoxazole and pharmaceutical wastewater. *Sep. Purif. Technol.* 251, 117373. <https://doi.org/10.1016/j.seppur.2020.117373>.
- Mostafa, M.H., Elsway, M.A., Darwish, M.S.A., Hussein, L.I., Abdaleem, A.H., 2020. Microwave-Assisted preparation of Chitosan/ZnO nanocomposite and its application in dye removal. *Mater. Chem. Phys.* 248, 122914. <https://doi.org/10.1016/j.matchemphys.2020.122914>.
- Mubeen, K., Safeen, K., Irshad, A., Safeen, A., Ghani, T., Shah, W.H., Khan, R., Ahmad, K.S., Casin, R., Rashwan, M.A., Elansary, H.O., Shah, A., 2023. ZnO/CuSe composite-mediated bandgap modulation for enhanced photocatalytic performance against methyl blue dye. *Sci. Rep.* 13, 1–13. <https://doi.org/10.1038/s41598-023-46780-y>.
- Murugan, A., Thirumal, V., Kim, J., Siva, V., Kasinathan, P., Allothman, A.A., Mohammad, S., Selvakumar, K., 2024. Effective visible light-driven binary ZnO catalyst decorated on layered double hydroxides for simultaneous photocatalytic degradation of Ciprofloxacin and Ampicillin. *J. Taiwan Inst. Chem. Eng.* 161, 105495.
- Nagpal, K., Rauwel, E., Estephan, E., Soares, M.R., Rauwel, P., 2022. Significance of hydroxyl groups on the optical properties of ZnO nanoparticles combined with CNT and PEDOT: PSS. *Nanomaterials* 12, 3546.
- Nakane, R., Kiribayashi, R., Sunada, K., Mochizuki, Y., Isobe, T., Matsushita, S., Nagai, T., Ishiguro, H., Nakajima, A., 2024. Degradation of 2-naphthol in water and antibacterial/antiviral activity by Zn₂SnO₄, ZnSn(OH)₆ and Y₂Sn₂O₇. *Ceram. Int.* 50, 10797–10805. <https://doi.org/10.1016/j.ceramint.2023.12.395>.
- Nalwa, K., Thakur, A., Sharma, N., 2017. Synthesis of ZnO nanoparticles and its application in adsorption. *Adv. Mater. Proc.* 2, 697–703.
- Navidpour, A.H., Safaei, J., Johir, M.A.H., Ni, B.J., Dashti, A., Li, X., Zhou, J.L., 2024. Zinc oxide@citric acid-modified graphitic carbon nitride nanocomposites for adsorption and photocatalytic degradation of perfluorooctanoic acid. *Adv. Compos. Hybrid Mater.* 7, 1–20. <https://doi.org/10.1007/s42114-024-00867-w>.
- Nguyen, V., Thi, L.P., Van Le, Q., Singh, P., 2020. Chemosphere Tailored photocatalysts and revealed reaction pathways for photodegradation of polycyclic aromatic hydrocarbons (PAHs) in water, soil and other sources. *Chemosphere* 260, 127529. <https://doi.org/10.1016/j.chemosphere.2020.127529>.
- Nguyen, L.T.T., Vo, D.V.N., Nguyen, L.T.H., Duong, A.T.T., Nguyen, H.Q., Chu, N.M., Nguyen, D.T.C., Van Tran, T., 2022. Synthesis, characterization, and application of ZnFe₂O₄/ZnO nanoparticles for photocatalytic degradation of Rhodamine B under visible-light illumination. *Environ. Technol. Innov.* 25. <https://doi.org/10.1016/j.eti.2021.102130>.
- Nguyen, D.T.C., Nguyen, N.T.T., Nguyen, T.T.T., Van Tran, T., 2024. Recent advances in the biosynthesis of ZnO nanoparticles using floral waste extract for water treatment, agriculture and biomedical engineering. *Nanoscale Adv.* <https://doi.org/10.1039/d4na00133h>.
- Ningthoujam, R., Singh, Y.D., Babu, P.J., Tirkey, A., Pradhan, S., Sarma, M., 2022. Nanocatalyst in remediating environmental pollutants. *Chem. Phys. Impact.* 4, 100064. <https://doi.org/10.1016/j.chphi.2022.100064>.
- Nugraha, Iriany, Misran, E., 2023. Regeneration of spent bleaching earth using microwave assisted extraction method with hexane as solvent for the bleaching of crude palm oil. *J. Phys. Conf. Ser.* 2421. <https://doi.org/10.1088/1742-6596/2421/1/012007>.
- Nunes, D., Pimentel, A., Goncalves, A., Pereira, S., Branquinho, R., Barquinha, P., Fortunato, E., Martins, R., 2019. Metal oxide nanostructures for sensor applications. *Sens. Technol.* 34. <https://doi.org/10.1088/1361-6641/ab011e>.
- Nyamutswa, L.T., Zhu, B., Navaratna, D., Collins, S., Duke, M.C., 2018. Proof of concept for light conducting membrane substrate for UV-activated photocatalysis as an alternative to chemical cleaning. *Membranes* (Basel) 8. <https://doi.org/10.3390/membranes8040122>.
- Okonkwo, O., Biswas, P., 2021. Synthesis of novel catalysts for carbon dioxide conversion to products of value. *Catal. Clean Energy Environ. Sustain. Petrochemicals Refin. Process.* 2, 527–556.
- Omar, S., Omar, M., Attia, N.F., El-Subriti, G.M., Eltaweil, A., 2024. Rational engineering and fabrication of efficient nanophotocatalysts based on ZnO-SrO-CdS for pharmaceutical pollutants based wastewater degradation. *Surf. Interfaces* 45, 103817.
- Ong, C.B., Ng, L.Y., Mohammad, A.W., 2018. A review of ZnO nanoparticles as solar photocatalysts: synthesis, mechanisms and applications. *Renew. Sustain. Energy Rev.* 81, 536–551. <https://doi.org/10.1016/j.rser.2017.08.020>.
- Osman, A.I., Zhang, Y., Farghali, M., Rashwan, A.K., Eltaweil, A.S., Abd El-Monaem, E. M., Mohamed, I.M.A., Badr, M.M., Ihara, I., Rooney, D.W., Yap, P.S., 2024. Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: a review. *Environ. Chem. Lett.* 22, 841–887. <https://doi.org/10.1007/s10311-023-01682-3>.
- Palomino, R.M., Ramírez, P.J., Liu, Z., Hamlyn, R., Waluyo, I., Mahapatra, M., Orozco, I., Hunt, A., Simonovis, J.P., Senanayake, S.D., 2018. Hydrogenation of CO₂ on ZnO/Cu (100) and ZnO/Cu (111) catalysts: role of copper structure and metal-oxide interface in methanol synthesis. *J. Phys. Chem. B* 122, 794–800.
- Patil, S.S., Amarnath, C.A., Sukhdev, A., Saravanan, C., 2023. Investigation on integration of conducting polymers with Cu doped ZnO towards photocatalytic degradation of organic dye. *Opt. Mater. (Amst)* 146, 114575.
- Paul, D.R., Gautam, S., Panchal, P., Nehra, S.P., Choudhary, P., Sharma, A., 2020. ZnO-modified g-C₃N₄: a potential photocatalyst for environmental application. *ACS Omega* 5, 3828–3838. <https://doi.org/10.1021/acsomega.9b02688>.
- Petrovic, B., Gorbounov, M., Soltani, S.M., 2021. Influence of surface modification on selective CO₂ adsorption: a technical review on mechanisms and methods. *Microporous Mesoporous Mater.* 312, 110751.
- Petrovic, B., Gorbounov, M., Soltani, S.M., 2022. Impact of surface functional groups and their introduction methods on the mechanisms of CO₂ adsorption on porous carbonaceous adsorbents. *Carbon Capture Sci. Technol.* 3, 100045.
- Photo-oxidation, D., Yaqoob, A.A., Habibah, N., Serr, A., Nasir, M., Ibrahim, M., 2020. Advances and challenges in developing efficient graphene oxide-based ZnO photocatalysts for dye photo-oxidation. *Nanomaterials* 10, 932. <https://doi.org/10.3390/nano10050932>.
- Porcu, S., Secci, F., Ricci, P.C., 2022. Advances in hybrid composites for photocatalytic applications: a review. *Molecules* 27, 6828.
- Porrawatkul, P., Nuengmarcha, P., Kuyyogsuy, A., Pimsen, R., Rattanaburi, P., 2023. Effect of Na and Al doping on ZnO nanoparticles for potential application in

- sunscreens. *J. Photochem. Photobiol. B Biol.* 240. <https://doi.org/10.1016/j.jphotobiol.2023.112668>.
- Prabhuraj, T., Prabhu, S., Dhandapani, E., Duraisamy, N., Ramesh, R., Kumar, K.A.R., Maadeswaran, P., 2021. Bifunctional ZnO sphere/r-GO composites for supercapacitor and photocatalytic activity of organic dye degradation. *Diam. Relat. Mater.* 120, 108592. <https://doi.org/10.1016/j.diamond.2021.108592>.
- Priyadarshini, S.S., Shubha, J.P., Shivalingappa, J., Adil, S.F., Kuniyil, M., Hatshan, M. R., Shaik, B., Kavalli, K., 2022. Photocatalytic degradation of methylene blue and metanil yellow dyes using green synthesized zinc oxide (ZnO) nanocrystals. *Crystals*. (Basel) 12. <https://doi.org/10.3390/cryst12010022>.
- Qi, K., Yu, J., 2020. Modification of ZnO-based photocatalysts for enhanced photocatalytic activity. *Interface Sci. Technol. Elsevier*, pp. 265–284.
- Qin, C., Wang, H., Yuan, X., Xiong, T., Zhang, J., Zhang, J., 2020. Understanding structure-performance correlation of biochar materials in environmental remediation and electrochemical devices. *Chem. Eng. J.* 382, 122977. <https://doi.org/10.1016/j.cej.2019.122977>.
- Qu, Y., Xu, X., Huang, R., Qi, W., Su, R., He, Z., 2020. Enhanced photocatalytic degradation of antibiotics in water over functionalized N,S-doped carbon quantum dots embedded ZnO nanoflowers under sunlight irradiation. *Chem. Eng. J.* 382, 123016. <https://doi.org/10.1016/j.cej.2019.123016>.
- Rachna, M., Rani, Shanker, U., 2019. Sunlight active ZnO@FeHCF nanocomposite for the degradation of bisphenol A and nonylphenol. *J. Environ. Chem. Eng.* 7, 103153. <https://doi.org/10.1016/j.jece.2019.103153>.
- Raha, S., Ahmaruzzaman, M., 2022a. A novel Ag/g-C₃N₄/ZnO/Fe₃O₄ nanohybrid superparamagnetic photocatalyst for efficient degradation of emerging pharmaceutical contaminant (Pantoprazole) from aqueous sources. *J. Environ. Chem. Eng.* 10, 108904.
- Raha, S., Ahmaruzzaman, M., 2022b. ZnO nanostructured materials and their potential applications: progress, challenges and perspectives. *Nanoscale Adv.* 4, 1868–1925. <https://doi.org/10.1039/d1na00880c>.
- Rahmati, E., Rafiee, Z., 2019. A biocompatible high surface area ZnO-based molecularly imprinted polymer for the determination of meloxicam in water media and plasma. *New J. Chem.* 43, 8492–8501. <https://doi.org/10.1039/c9nj01386e>.
- Ramalingam, G., Pachaiappan, R., Kumar, P.S., Dharani, S., Rajendran, S., Vo, D.V.N., Hoang, T.K.A., 2022. Hybrid metal organic frameworks as an Exotic material for the photocatalytic degradation of pollutants present in wastewater: a review. *Chemosphere* 288, 132448. <https://doi.org/10.1016/j.chemosphere.2021.132448>.
- Ramasubbu, V., Kumar, P.R., Mothi, E.M., Karuppasamy, K., Kim, H.S., Maiyalagan, T., Shajan, X.S., 2019. Highly interconnected porous TiO₂-Ni-MOF composite aerogel photoanodes for high power conversion efficiency in quasi-solid dye-sensitized solar cells. *Appl. Surf. Sci.* 496, 143646. <https://doi.org/10.1016/j.apsusc.2019.143646>.
- Rani, M., Rachna, U., Shanker, 2019. Mineralization of carcinogenic anthracene and phenanthrene by sunlight active bimetallic oxides nanocomposites. *J. Colloid Interface Sci.* 555, 676–688. <https://doi.org/10.1016/j.jcis.2019.08.016>.
- Rani, M., Rachna, U., Shanker, 2020. Metal oxide-chitosan based nanocomposites for efficient degradation of carcinogenic PAHs. *J. Environ. Chem. Eng.* 8, 103810. <https://doi.org/10.1016/j.jece.2020.103810>.
- Rani, M., Shanker, U., 2019. Sunlight mediated improved photocatalytic degradation of carcinogenic benz[a]anthracene and benzo[a]pyrene by zinc oxide encapsulated hexacyanoferrate nanocomposite. *J. Photochem. Photobiol. A Chem.*, 111861 <https://doi.org/10.1016/j.jphotochem.2019.111861>.
- Ranjbari, A., Kim, J., Yu, J., Kim, J., Park, M., Kim, N., Demeestere, K., Heynderickx, P. M., 2024. Effect of oxygen vacancy modification of ZnO on photocatalytic degradation of methyl orange: a kinetic study. *Catal. Today* 427, 114413.
- Ren, X., Gao, Y., Zheng, L., Wang, Z., Wang, P., Zheng, Z., Liu, Y., Cheng, H., Dai, Y., Huang, B., 2021. Oxygen vacancy enhancing CO₂ electrochemical reduction to CO on Ce-doped ZnO catalysts. *Surf. Interfaces*. 23, 100923. <https://doi.org/10.1016/j.surf.2020.100923>.
- Ribao, P., Corredor, J., Rivero, M.J., Ortiz, I., 2019. Role of reactive oxygen species on the activity of noble metal-doped TiO₂ photocatalysts. *J. Hazard. Mater.* 372, 45–51. <https://doi.org/10.1016/j.jhazmat.2018.05.026>.
- Rilda, Y., Kurniawan, S., Arief, S., 2015. Synthesis and modification of the morphology of zinc oxide (ZnO) nano particles with induced biopolymer chitosan. *Res. J. Pharm. Biol. Chem. Sci.* 6, 1511–1518.
- Rosen, J., Hutchings, G.S., Lu, Q., Rivera, S., Zhou, Y., Vlachos, D.G., Jiao, F., 2015. Mechanistic insights into the electrochemical reduction of CO₂ to CO on nanostructured Ag surfaces. *ACS Catal.* 5, 4293–4299. <https://doi.org/10.1021/acscatal.5b00840>.
- Roy, S., Darabdhara, J., Ahmaruzzaman, M., 2023. ZnO-based Cu metal-organic framework (MOF) nanocomposite for boosting and tuning the photocatalytic degradation performance. *Environ. Sci. Pollut. Res.* 30, 95673–95691. <https://doi.org/10.1007/s11356-023-29105-4>.
- Roy, T., Basak, N., Mainak, S., Das, S., Ali, S.I., Islam, E., Burkholderia, sp, 2024. EIKU21 mediated synthesis of biogenic ZnO nanoparticle-based pigment for development of antibacterial cotton fabric through nanocoating. *Biomass Convers. Biorefinery*. <https://doi.org/10.1007/s13399-024-05694-z>.
- Rungsawang, T., Krobthong, S., Paengpan, K., 2024. Synergy of functionalized activated carbon and ZnO nanoparticles for enhancing photocatalytic degradation of methylene blue and carbaryl. *Radiat. Phys. Chem.*, 111924 <https://doi.org/10.1016/j.radphyschem.2024.111924>.
- Sabri, M.A., Al Jitan, S., Bahamon, D., Vega, L.F., Palmisano, G., 2021. Current and future perspectives on catalytic-based integrated carbon capture and utilization. *Sci. Total Environ.* 790, 148081.
- Saeed, M., Marwani, H.M., Shahzad, U., Asiri, A.M., Rahman, M.M., 2024. Recent advances, challenges, and future perspectives of ZnO nanostructure materials towards energy applications. *Chem. Rec.* 24. <https://doi.org/10.1002/tcr.202300106>.
- Sakineh, S., Dehghanifard, E., Noorisepehr, M., 2019. Efficient clean-up of waters contaminated with diazinon pesticide using photo-decomposition of peroxy monosulfate by ZnO decorated on a magnetic core/shell structure. *J. Environ. Manage.* 250, 109472. <https://doi.org/10.1016/j.jenvman.2019.109472>.
- Sanakousar, F.M., Vidyasagar, C., Jiménez-Pérez, V.M., Prakash, K., 2022. Recent progress on visible-light-driven metal and non-metal doped ZnO nanostructures for photocatalytic degradation of organic pollutants. *Mater. Sci. Semicond. Process.* 140. <https://doi.org/10.1016/j.mssp.2021.106390>.
- Sanjeev, N.O., Valsan, A.E., 2024. Photocatalytic and antibacterial activity of green synthesized and immobilized zinc oxide nanoparticles for the removal of sulfadiazine and acetaminophen: effect of operational parameters and degradation pathway. *J. Environ. Chem. Eng.* 12, 112649. <https://doi.org/10.1016/j.jece.2024.112649>.
- Sarno, M., Ponticorvo, E., Pioletti, S., Nardiello, A.M., De Pasquale, S., Funicello, N., 2020. AuAg/ZnO nanocatalyst for CO₂ valorization and H₂ and CO electrochemical production. *J. CO₂ Util.* 39, 101179.
- Sathiyaseelan, A., Vishven Naveen, K., Zhang, X., Han, K., Wang, M.H., 2023. Research progress on chitosan-zinc oxide nanocomposites fabrication, characterization, biomedical and environmental applications. *Coord. Chem. Rev.* 496. <https://doi.org/10.1016/j.ccr.2023.215398>.
- Sayed, M., Xu, F., Kuang, P., Low, J., Wang, S., Zhang, L., Yu, J., 2021. Sustained CO₂-photoreduction activity and high selectivity over Mn, C-codoped ZnO core-triple shell hollow spheres. *Nat. Commun.* 12, 1–10. <https://doi.org/10.1038/s41467-021-25007-6>.
- Sayed, M.A., Mohamed, A., Ahmed, S.A., El-Sherbeen, A.M., Al Zoubi, W., Abukhadra, M.R., 2024. Enhanced photocatalytic degradation of Congo red dye into safe end-products over ZnO@ polyaniline/coal composite as low cost catalyst under visible light: pathways and ecotoxicity. *J. Photochem. Photobiol. A Chem.*, 115843.
- Schott, J.A., Wu, Z., Dai, S., Li, M., Huang, K., Schott, J.A., 2017. Effect of metal oxides modification on CO₂ adsorption performance over mesoporous carbon. *Microporous Mesoporous Mater.* 249, 34–41. <https://doi.org/10.1016/j.micromeso.2017.04.033>.
- Sedefoglu, N., 2024. Green synthesis of ZnO nanoparticles by Myrtus communis plant extract with investigation of effect of precursor, calcination temperature and study of photocatalytic performance. *Ceram. Int.* 50, 9884–9895. <https://doi.org/10.1016/j.ceramint.2024.01.387>.
- Sekar, A.D., Muthukumar, H., Chandrasekaran, N.I., Matheswaran, M., 2018. Photocatalytic degradation of naphthalene using calcined Fe-ZnO/PVA nanofibers. *Chemosphere* 205, 610–617. <https://doi.org/10.1016/j.chemosphere.2018.04.131>.
- K. Sekar, R. Doineau, S. Mayarambakam, B. Schmaltz, G. Poulin-Vittrant, Control of ZnO nanowires growth in flexible perovskite solar cells: a mini-review, *Heliyon*. (2024).
- Shah, M.A., Shibiru, A.L., Kumar, V., Srivastava, V.C., 2023. Carbon dioxide conversion to value-added products and fuels: opportunities and challenges: a critical review. *Int. J. Green Energy*. 1–20.
- Shakoor, M.H., Shakoor, M.B., Jilani, A., Ahmed, T., Rizwan, M., Dustgeer, M.R., Iqbal, J., Zahid, M., Yong, J.W.H., 2024. Enhancing the photocatalytic degradation of methylene blue with graphene oxide-encapsulated g-C₃N₄/ZnO ternary composites. *ACS Omega* 9, 16187–16195. <https://doi.org/10.1021/acsomega.3c10172>.
- Shan, S., Lv, Z., Wu, H., 2024. A novel readily recyclable Fe₃O₄/ZnO/loofah biochar composite for efficient degradation of organic pollutants under visible light. *Mater. Sci. Eng. B* 303, 117272. <https://doi.org/10.1016/j.mseb.2024.117272>.
- Shanmugam, J., Dhayalan, M., Savaas Umar, M.R., Gopal, M., Khan, M.A., Simal-Gandara, J., Cid-Samamed, A., 2022. Green synthesis of silver nanoparticles using allium cepa var. aggregatum natural extract: antibacterial and cytotoxic properties. *Nanomaterials* 12. <https://doi.org/10.3390/nano12101725>.
- Sharma, A., Hosseini-Bandegharai, A., Kumar, N., Kumar, S., Kumari, K., 2022. Insight into ZnO/carbon hybrid materials for photocatalytic reduction of CO₂: An in-depth review. *J. CO₂ Util.* 65, 102205. <https://doi.org/10.1016/j.jcou.2022.102205>.
- Sheydaei, M., Ayoubi-Feiz, B., Abbaszade-Fakhri, G., 2021. A visible-light active g-C₃N₄/Ce-ZnO/Ti nanocomposite for efficient photoelectrocatalytic pharmaceutical degradation: modelling with artificial neural network. *Process Saf. Environ. Prot.* 149, 776–785.
- Shi, C., Zhang, L., Shi, Z., Ma, J., Wang, Z., 2022. Cellulose template designed porous ZnO based catalysts with different valence copper for solar photocatalytic CO₂ conversion. *Ind. Crops Prod.* 186, 115223. <https://doi.org/10.1016/j.indcrop.2022.115223>.
- Shreya, A., Naik, H.S.B., Vishnu, G., Viswanath, R., Shivaraj, B., Shashank, M., Hareeshanika, S., 2024. Bifunctional applications of Facile Mg-doped ZnO nanoparticles fabricated via co-precipitation technique. *J. Inorg. Organomet. Polym. Mater.* <https://doi.org/10.1007/s10904-024-03073-9>.
- Siddiqi, K.S., ur Rahman, A., Tajuddin, A., Husen, 2018. Properties of zinc oxide nanoparticles and their activity against microbes. *Nanoscale Res. Lett.* 13. <https://doi.org/10.1186/s11671-018-2532-3>.
- Sikam, P., Takahashi, K., Roongcharoen, T., Jitwatanasirikul, T., Chitpakdee, C., Faungnawakij, K., Namuangruk, S., 2021. Effect of 3d-transition metals doped in ZnO monolayers on the CO₂ electrochemical reduction to valuable products: first principles study. *Appl. Surf. Sci.* 550, 149380.
- Sin, J.-C., Lam, S.-M., Satoshi, I., Lee, K.-T., Mohamed, A.R., 2014. Sunlight photocatalytic activity enhancement and mechanism of novel europium-doped ZnO hierarchical micro/nanospheres for degradation of phenol. *Appl. Catal. B Environ.* 148, 258–268.
- Singh, P., Mondal, K., Sharma, A., 2013. Reusable electrospun mesoporous ZnO nanofiber mats for photocatalytic degradation of polycyclic aromatic hydrocarbon

- dyes in wastewater. *J. Colloid Interface Sci.* 394, 208–215. <https://doi.org/10.1016/j.jcis.2012.12.006>.
- Singh, A., Rajput, V.D., Lalotra, S., Agrawal, S., Ghazaryan, K., Singh, J., Minkina, T., Rajput, P., Mandzhieva, S., Alexiou, A., 2024a. Zinc oxide nanoparticles influence on plant tolerance to salinity stress: insights into physiological, biochemical, and molecular responses. *Environ. Geochem. Health.* 46. <https://doi.org/10.1007/s10653-024-01921-8>.
- Singh, V., Sapehia, R., Dhiman, V., 2024b. Removal of methylene blue dye by green synthesized NiO/ZnO nanocomposites. *Inorg. Chem. Commun.* 162, 112267.
- Sliem, M.A., Youssef, A., Genidy, G., 2019. Photocatalytic degradation of anthracene in aqueous dispersion of metal oxides nanoparticles: Effect of different parameters. *J. Photochem. Photobiol. A Chem.* 371, 327–335. <https://doi.org/10.1016/j.jphotochem.2018.11.028>.
- Sliem, M.A., Salim, A.Y., MAbdelnaby, R., Mohamed, G.G., Amin, A.S., 2022. Photocatalytic degradation of naphthalene in aqueous dispersion of nanoparticles: effect of different parameters. *Benha J. Appl. Sci.* 7, 41–47. <http://bjas.journals.ekb.eg>.
- Sohail, M.F., Rehman, M., Hussain, S.Z., Huma, Z.e., Shahnaz, G., Qureshi, O.S., Khalid, Q., Mirza, S., Hussain, I., Webster, T.J., 2020. Green synthesis of zinc oxide nanoparticles by Neem extract as multi-facet therapeutic agents. *J. Drug Deliv. Sci. Technol.* 59. <https://doi.org/10.1016/j.jddst.2020.101911>.
- Soni, J., Revathi, D., Dhanraj, G., Ramasubburayan, R., 2024. Bioinspired green synthesis of ZnO nanoparticles by marine-derived *Streptomyces plicatus* and its multifaceted biomedical properties. *Microb. Pathog.* 193. <https://doi.org/10.1016/j.micpath.2024.106758>.
- Soo, X.Y.D., Lee, J.J.C., Wu, W.-Y., Tao, L., Wang, C., Zhu, Q., Bu, J., 2024. Advancements in CO₂ capture by absorption and adsorption: a comprehensive review. *J. CO₂ Util.* 81, 102727.
- Sousa, J.C.G., Ribeiro, A.R., Barbosa, M.O., Pereira, M.F.R., Silva, A.M.T., 2018. A review on environmental monitoring of water organic pollutants identified by EU guidelines. *J. Hazard. Mater.* 344, 146–162.
- Sreelakshmi, T., Prasad, A.R., Joseph, A., 2024. Synthesis, characterization, and effective removal of dye pollutants from water bodies using a new ZnO nanocomposite. *J. Indian Chem. Soc.* 101, 101183.
- Suba, S., Vijayakumar, S., Vidhya, E., Punitha, V.N., Nilavukkarasi, M., 2021. Microbial mediated synthesis of ZnO nanoparticles derived from *Lactobacillus* spp: characterizations, antimicrobial and biocompatibility efficiencies. *Sensors Int* 2. <https://doi.org/10.1016/j.sintl.2021.100104>.
- Sudha, D., Kumar, E.R., Shanjiya, S., Munshi, A.M., Al-Hazmi, G.A.A., El-Metwaly, N.M., Kirubavathy, S.J., 2023. Structural, optical, morphological and electrochemical properties of ZnO and graphene oxide blended ZnO nanocomposites. *Ceram. Int.* 49, 7284–7288. <https://doi.org/10.1016/j.ceramint.2022.10.192>.
- Sun, Q., Sun, Y., Zhou, M., Cheng, H., Chen, H., Dorus, B., Lu, M., 2022a. A 2D/3D g-C₃N₄/ZnO heterojunction enhanced visible-light driven photocatalytic activity for sulfonamides degradation. *Ceram. Int.* 48, 7283–7290. <https://doi.org/10.1016/j.ceramint.2021.11.289>.
- Sun, Y., Wu, J., Wang, Y., Li, J., Wang, N., Harding, J., Mo, S., Chen, L., Chen, P., Fu, M., 2022b. Plasma-catalytic CO₂ hydrogenation over a Pd/ZnO catalyst: in situ probing of gas-phase and surface reactions. *JACS.* Au 2, 1800–1810.
- Sun, Y., Zhang, W., Li, Q., Liu, H., Wang, X., 2023. Preparations and applications of zinc oxide based photocatalytic materials. *Adv. Sens. Energy Mater.* 2, 100069. <https://doi.org/10.1016/j.asens.2023.100069>.
- Swamy M. M., BS, S., C. M., S. P., ND, R., 2021. Bio-mediated synthesis of ZnO nanoparticles using Lantana Camara flower extract: Its characterizations, photocatalytic, electrochemical and anti-inflammatory applications. *Environ. Nanotechnol. Monit. Manag.* 15. <https://doi.org/10.1016/j.enmm.2021.100442>.
- Swathi, S., Babu, E.S., Yuvakkumar, R., Ravi, G., Chinnathambi, A., Alharbi, S.A., Velauthapillai, D., 2021. Branched and unbranched ZnO nanorods grown via chemical vapor deposition for photoelectrochemical water-splitting applications. *Ceram. Int.* 47, 9785–9790. <https://doi.org/10.1016/j.ceramint.2020.12.119>.
- Tang, Q.-L., Luo, Q.-H., 2013. Adsorption of CO₂ at ZnO: a surface structure effect from DFT+U calculations. *J. Phys. Chem. C* 117, 22954–22966.
- Tauqeer, H.M., Karczewska, A., Lewińska, L.K., Fatima, M., Khan, S.A., Farhad, M., Turan, V., Ramzani, P.M.A., Iqbal, M., 2020. Environmental concerns associated with explosives (HMX, TNT, and RDX), heavy metals and metalloids from shooting range soils: Prevailing issues, leading management practices, and future perspectives. *Handb. Bioremed. Physiol. Mol. Biotechnol. Interv.* 569–590. <https://doi.org/10.1016/B978-0-12-819382-2.00036-3>.
- Thang, N.Q., Sabbah, A., Chen, L.-C., Chen, K.-H., Thi, C.M., Van Viet, P., 2021. High-efficient photocatalytic degradation of commercial drugs for pharmaceutical wastewater treatment prospects: a case study of Ag/g-C₃N₄/ZnO nanocomposite materials. *Chemosphere* 282, 130971.
- Thi Bich Hop, D., Quoc Tuan, T., Van Quang, N., Tu, N., Le Tien, H., Tran, M.T., Quang Vinh, T., Cong Tu, N., Ngoc Bach, T., Dao, V.D., Thi Lan Huong, P., 2024. Enhanced visible-light photocatalytic degradation efficiency of Ce³⁺-doped ZnO nanoparticles synthesized by sol-gel method. *Ceram. Int.* 50, 17338–17353. <https://doi.org/10.1016/j.ceramint.2024.02.216>.
- Thirumavalavan, M., Sukumar, K., Sabarimuthu, S.Q., 2024. Trends in green synthesis, pharmaceutical and medical applications of nano ZnO: a review. *Inorg. Chem. Commun.* 169. <https://doi.org/10.1016/j.inoche.2024.113002>.
- Tran, G.T., Nguyen, N.T.H., Nguyen, N.T.T., Nguyen, T.T.T., Nguyen, D.T.C., Van Tran, T., 2023a. Formation, properties and applications of microalgae-based ZnO nanoparticles: a review. *J. Environ. Chem. Eng.* 11. <https://doi.org/10.1016/j.jece.2023.110939>.
- Tran, H.D., Nguyen, D.Q., Do, P.T., Tran, U.N.P., 2023b. Kinetics of photocatalytic degradation of organic compounds: a mini-review and new approach. *RSC. Adv.* 13, 16915–16925.
- Tran, D.-T., Nguyen, T.-H., Vu, P.-T., Dang, V.-Q., Van, H.-T., 2024. Cu-ZnO/CdS/rGO tertiary heterojunction for improved photocatalytic degradation of synthetic dyes using visible light. *J. Water Process Eng.* 57, 104687.
- Tseng, I.-H., Chang, W.-C., Wu, J.C.S., 2002. Photoreduction of CO₂ using sol-gel derived titania and titania-supported copper catalysts. *Appl. Catal. B Environ.* 37, 37–48.
- Turakulov, Z., Kamolov, A., Norkobilov, A., Variny, M., Diaz-Sainz, G., Gómez-Coma, L., Fallanza, M., 2024. Assessing various CO₂ utilization technologies: a brief comparative review. *J. Chem. Technol. Biotechnol.* 99, 1291–1307.
- Tyona, M.D., Osuji, R.U., Asogwa, P.U., Jambure, S.B., Ezema, F.I., 2017. Structural modification and band gap tailoring of zinc oxide thin films using copper impurities. *J. Solid State Electrochem.* 21, 2629–2638. <https://doi.org/10.1007/s10008-017-3533-3>.
- Uikey, P., Vishwakarma, K., 2016. Review of Zinc Oxide (ZnO) nanoparticles applications and properties. *Int. J. Emerg. Technol. Comput. Sci. Electron.* 21, 976–1353.
- Ullah, S., Shaban, M., Siddique, A., Zulfikar, A., Lali, N.S., Naeem-ul-Hassan, M., Irfan, M.I., Sher, M., Fayyaz ur Rehman, M., Hanbashi, A., Sabei, F.Y., Amin, H.M.A., Abbas, A., 2024. Greenly synthesized zinc oxide nanoparticles: an efficient, highly selective, cost-effective catalyst for dehydrogenation of formic acid and with improved antioxidant and phyto-toxic properties. *J. Environ. Chem. Eng.* 12, 113350. <https://doi.org/10.1016/j.jece.2024.113350>.
- Upadhyay, G.K., Purohit, L.P., Sharma, H., Jain, N., Sharma, S.K., 2025. Z-scheme based photoactive ZnO:TiO₂:CdO:g-C₃N₄ nanocomposites for advance oxidation process. *J. Mol. Struct.* 1319. <https://doi.org/10.1016/j.molstruc.2024.139366>.
- Van Hung, N., Nguyen, B.T.M., Nghi, N.H., Khieu, D.Q., 2021. Photocatalytic degradation of methylene blue by using ZnO/Longan seed activated carbon under visible-light region. *J. Inorg. Organomet. Polym. Mater.* 31, 446–459. <https://doi.org/10.1007/s10904-020-01734-z>.
- Veerakumar, P., Sangili, A., Saranya, K., Pandikumar, A., Lin, K., 2021. Palladium and silver nanoparticles embedded on zinc oxide nanostars for photocatalytic degradation of pesticides and herbicides. *Chem. Eng. J.* 410, 128434. <https://doi.org/10.1016/j.cej.2021.128434>.
- Vijayakumar, B.W., Shivaraj, Manjunatha, C., Abhishek, B., Nagaraju, G., Panda, P.K., 2020. Hydrothermal synthesis of ZnO nanotubes for CO gas sensing. *Sensors Int.* 1, 100018. <https://doi.org/10.1016/j.sintl.2020.100018>.
- Villarreal, R.C., Luque-Morales, M., Chinchillas-Chinchillas, M.J., Luque, P.A., 2022. Langmuir-Hinshelwood-Hougen-Watson model for the study of photodegradation properties of zinc oxide semiconductor nanoparticles synthesized by *Peumus boldus*. *Results. Phys.* 36, 105421.
- Vinayagam, M., Ramachandran, S., Ramya, V., Sivasamy, A., 2016. Photocatalytic degradation of orange G dye using ZnO/biomass activated carbon nanocomposite. *J. Environ. Chem. Eng.* <https://doi.org/10.1016/j.jece.2017.06.005>, 0–1.
- Vyas, S., 2020. A short review on properties and applications of zinc oxide based thin films and devices: ZnO as a promising material for applications in electronics, optoelectronics, biomedical and sensors. *Johnson Matthey Technol. Rev.* 64, 202–218. <https://doi.org/10.1595/205651320X15694993568524>.
- Waghchaure, R.H., Adole, V.A., Jagdale, B.S., 2022. Photocatalytic degradation of methylene blue, rhodamine B, methyl orange and Eriochrome black T dyes by modified ZnO nanocatalysts : a concise review. *Inorg. Chem. Commun.* 143, 109764. <https://doi.org/10.1016/j.inoche.2022.109764>.
- Wang, J., Burghaus, U., 2005. Adsorption dynamics of CO₂ on Zn-ZnO (0001): a molecular beam study. *J. Chem. Phys.* 122.
- Wang, J., Hokkanen, B., Burghaus, U., 2005. Adsorption of CO₂ on pristine Zn-ZnO (0 0 1) and defected Zn-ZnO (0 0 1): A thermal desorption spectroscopy study. *Surf. Sci.* 577, 158–166.
- Wang, X., Ahmad, M., Sun, H., 2017. Three-dimensional ZnO hierarchical nanostructures: solution phase synthesis and applications. *Materials (Basel)* 10, 1–24. <https://doi.org/10.3390/ma10111304>.
- Wang, H., Li, J., Wan, Y., Nazir, A., Song, X., Huo, P., Wang, H., 2023a. Synthesis of AgInS₂ QDs-MoS₂/GO composite with enhanced interfacial charge separation for efficient photocatalytic degradation of tetracycline and CO₂ reduction. *J. Alloys Compd.* 954, 170159.
- Wang, X., Yang, S., Jin, P., Peng, A., Zhao, X., Yang, K., He, J., 2023b. Highly efficient photocatalytic degradation of microcystin-LR with permonosulfate activated by visible-light over Z-scheme ZnO/g-C₃N₄: degradation pathways and mechanism. *J. Environ. Chem. Eng.* 11, 111088. <https://doi.org/10.1016/j.jece.2023.111088>.
- Wang, J., Meng, Q., Zhang, Q., 2023c. Aerosol-assisted synthesis of mesoporous Cu/ZnO-ZrO₂ catalyst with highly selective photothermal CO₂ reduction to methanol. *Dalt. Trans.* 52, 6019–6028.
- Wang, H., Xiao, Y., Qi, Y., Zhang, A., Du, J., Li, J., Guo, T., 2023d. Fabrication of ZnO nanosheets self-assembled by nanoparticles for accelerated electrocatalytic reduction of CO₂ to CO. *Fuel* 333, 126431.
- Wawrzynczyk, D., Cichy, B., Stęka, W., Nyk, M., 2018. The role of L-cysteine and introduced surface defects in reactive oxygen species generation by ZnO nanoparticles. *Dalt. Trans.* 47, 8320–8329.
- Woolerton, T.W., Sheard, S., Reisner, E., Pierce, E., Ragsdale, S.W., Armstrong, F.A., 2010. Efficient and clean photoreduction of CO₂ to CO by enzyme-modified TiO₂ nanoparticles using visible light. *J. Am. Chem. Soc.* 132, 2132–2133.
- Xie, G., Jin, R., Ren, P., Fang, Y., Zhang, R., Jun Wang, Z., 2023. Boosting CO₂ hydrogenation to methanol by adding trace amount of Au into Cu/ZnO catalysts. *Appl. Catal. B Environ.* 324, 122233. <https://doi.org/10.1016/j.apcatb.2022.122233>.
- Xie, G., Bai, X., Man, Y., Ren, P., Jin, R., Zhang, R., Ostrikov, K.K., Wang, Z., Jun, Yang, Q., 2024. High-performance Al-doped Cu/ZnO catalysts for CO₂

- hydrogenation to methanol: MIL-53(Al) source-enabled oxygen vacancy engineering and related promoting mechanisms. *Chem. Eng. J.* 480. <https://doi.org/10.1016/j.cej.2023.148195>.
- Xing, C., Ma, M., Chang, J., Ji, Z., Wang, P., Sun, L., Li, S., Li, M., 2023. Polyoxometalate anchored zinc oxide nanocomposite as a highly effective photocatalyst and bactericide for wastewater decontamination. *Chem. Eng. J.* 464. <https://doi.org/10.1016/j.cej.2023.142632>.
- Xu, J., Huang, Y., Zhu, S., Abbes, N., Jing, X., Zhang, L., 2021. A review of the green synthesis of ZnO nanoparticles using plant extracts and their prospects for application in antibacterial textiles. *J. Eng. Fiber. Fabr.* 16. <https://doi.org/10.1177/15589250211046242>.
- Xu, J.J., Lu, Y.N., Tao, F.F., Liang, P.F., Zhang, P.A., 2023. ZnO nanoparticles modified by carbon quantum dots for the photocatalytic removal of synthetic pigment pollutants. *ACS. Omega* 8, 7845–7857. <https://doi.org/10.1021/acsomega.2c07591>.
- Xue, Y.N., Zhang, J.Y., Tang, S., Liu, J.K., Yue, Y.B., Yang, X.H., 2018. Rapid degradation of unmanageable polycyclic aromatic hydrocarbons by a C-ZnO solid solution nanocatalyst. *New J. Chem.* 42, 4308–4316. <https://doi.org/10.1039/c7nj04855f>.
- Yadav, V.S.K., Purkait, M.K., 2016. Solar cell driven electrochemical process for the reduction of CO₂ to HCOOH on Zn and Sn electrocatalysts. *Sol. Energy* 124, 177–183.
- Yadav, R., Sinha, A.K., 2017. Titania cowrapped α -sulfur composite as a visible light active photocatalyst for hydrogen evolution using in situ methanol for CO₂ as a sacrificial agent. *ACS Sustain. Chem. Eng.* 5, 6736–6745. <https://doi.org/10.1021/acssuschemeng.7b00996>.
- Yadav, P., Manori, S., Chamoli, P., Shukla, R.K., 2024. Photocatalytic degradation of ternary dye mixture using RGO, γ -Fe₂O₃ and ZnO based binary and ternary nanocomposites. *Inorg. Chem. Commun.*, 112791.
- Yadeta Gemachu, L., Birhanu, A., Lealele, 2024. Green synthesis of ZnO, CuO and NiO nanoparticles using Neem leaf extract and comparing their photocatalytic activity under solar irradiation. *Green Chem. Lett. Rev.* 17. <https://doi.org/10.1080/17518253.2023.2293841>.
- Yamuna, A., Mandalam, A., Karthigaiselvi, A., Balasubramanian, M., Thiruparasakthi, B., Ravichandran, S., Mayavan, S., 2015. One-step synthesis of boron nitride carbon nanosheets containing zinc oxide for catalysis of the oxygen reduction reaction and degradation of organic dyes. In: *RSC. Adv.*, 5, pp. 69394–69399.
- Yang, Y., Ji, W., Li, X., Zheng, Z., Bi, F., Yang, M., Xu, J., Zhang, X., 2021. Insights into the degradation mechanism of perfluorooctanoic acid under visible-light irradiation through fabricating flower-shaped Bi₂O₃/ZnO n-n heterojunction microspheres. *Chem. Eng. J.* 420, 129934. <https://doi.org/10.1016/j.cej.2021.129934>.
- Yeganeh, M., Charkhloo, E., Reza, H., Esrafil, A., Gholami, M., 2022. Photocatalytic processes associated with degradation of pesticides in aqueous solutions : Systematic review and meta -analysis. *Chem. Eng. J.* 428, 130081. <https://doi.org/10.1016/j.cej.2021.130081>.
- Yu, J., Yang, H., Li, X., Chen, X., Li, W., Li, X., Zhang, C., 2025. MOF-on-MOF-derived hollow tubular ZnFe₂O₄/Er-ZnO heterojunctions for the efficient degradation of tetracycline by visible light photocatalysis. *Appl. Surf. Sci.* 684. <https://doi.org/10.1016/j.apsusc.2024.161634>.
- Yuan, Q., Yang, Y., Wu, W., Dai, X., Zhong, J., Jian, Y., Li, R., Wang, T., Yu, H., Xia, X., 2023. Synthesis of a novel TiO₂/HA/RGO composite material with photocatalytic activity for dye degradation. *Mater. Chem. Phys.* 304, 127847. <https://doi.org/10.1016/j.matchemphys.2023.127847>.
- Yusof, H., Mohd, Mohamad, R., Zaidan, U.H., Abdul Rahman, N.A., 2019. Microbial synthesis of zinc oxide nanoparticles and their potential application as an antimicrobial agent and a feed supplement in animal industry: a review. *J. Anim. Sci. Biotechnol.* 10. <https://doi.org/10.1186/s40104-019-0368-z>.
- Zanardo, D., Forghieri, G., Ghedini, E., Menegazzo, F., Giordana, A., Cerrato, G., Cattaruzza, E., Di Michele, A., Cruciani, G., Signoretto, M., 2023. Effect of the synthetic parameters over ZnO in the CO₂ photoreduction. *Molecules* 28. <https://doi.org/10.3390/molecules28124798>.
- Zango, Z.U., Sambudi, N.S., Jumbri, K., Abu Bakar, N.H.H., Abdullah, N.A.F., Negim, E.S. M., Saad, B., 2020. Experimental and molecular docking model studies for the adsorption of polycyclic aromatic hydrocarbons onto UiO-66(Zr) and NH₂-UiO-66 (Zr) metal-organic frameworks. *Chem. Eng. Sci.* 220, 115608. <https://doi.org/10.1016/j.ces.2020.115608>.
- Zango, Z.U., Ramli, A., Jumbri, K., 2021. UiO-66 and ZIF-8 metal-organic frameworks for acenaphthene adsorption. In: *Springer Proc. Complex.* Springer, Singapore, pp. 238–253. <https://doi.org/10.1007/978-981-16-4513-6>.
- Zango, Z.U., Dennis, J.O., Aljameel, A.I., Usman, F., Ali, M.K.M., Abdulkadir, B.A., Algessair, S., Aldaghri, O.A., Ibaouf, K.H., 2022a. Effective removal of methylene blue from simulated wastewater using ZnO-chitosan nanocomposites: optimization, kinetics, and isotherm studies. *Molecules* 27. <https://doi.org/10.3390/molecules27154746>.
- Zango, Z.U., Garba, A., Garba, Z.N., Zango, M.U., Usman, F., Lim, J., 2022b. Montmorillonite for adsorption and catalytic elimination of pollutants from wastewater: a state-of-the-art review. *Sustain* 14, 16441.
- Zango, Z.U., Ethiraj, B., Al-Mubaddel, F.S., Alam, M.M., Lawal, M.A., Kadir, H.A., Khoo, K.S., Garba, Z.N., Usman, F., Zango, M.U., Lim, J.W., 2023a. An overview on human exposure, toxicity, solid-phase microextraction and adsorptive removal of perfluoroalkyl carboxylic acids (PFCAs) from water matrices. *Environ. Res.* 231, 116102. <https://doi.org/10.1016/j.envres.2023.116102>.
- Zango, Z.U., Khoo, K.S., Garba, A., Kadir, H.A., Usman, F., Zango, M.U., Da Oh, W., Lim, J.W., 2023b. A review on superior advanced oxidation and photocatalytic degradation techniques for perfluorooctanoic acid (PFOA) elimination from wastewater. *Environ. Res.* 221, 115326. <https://doi.org/10.1016/j.envres.2023.115326>.
- Zango, Z.U., Khoo, K.S., Garba, A., Garba, Z.N., Danmallam, U.N., Aldaghri, O., Ibaouf, K.H., Ahmad, N.M., Binzowaimil, A.M., Lim, J.W., Bhattu, M., Ramesh, M. D., 2024a. A review on titanium oxide nanoparticles modified metal-organic frameworks for effective CO₂ conversion and efficient wastewater remediation. *Environ. Res.* 252, 119024. <https://doi.org/10.1016/j.envres.2024.119024>.
- Zarekarizi, F., Joharian, M., Morsali, A., 2018. Pillar-layered MOFs: functionality, interpenetration, flexibility and applications. *J. Mater. Chem. A* 6, 19288–19329. <https://doi.org/10.1039/c8ta03306d>.
- Zhang, H., Zong, R., Zhu, Y., 2009. Photocorrosion inhibition and photoactivity enhancement for zinc oxide via hybridization with monolayer polyaniline. *J. Phys. Chem. C* 113, 4605–4611. <https://doi.org/10.1021/jp810748u>.
- Zhang, H., Lv, X., Li, Y., Wang, Y., Li, J., 2010. P25-graphene composite as a high performance photocatalyst. *ACS. Nano* 4, 380–386. <https://doi.org/10.1021/nn901221k>.
- Zhang, J., Sun, J., Zhang, X., Zhao, Y., Zhang, S., 2011. The recent development of CO₂ fixation and conversion by ionic liquid. *Greenh. Gases Sci. Technol.* 1, 142–159.
- Zhang, Y., Chen, Z., Liu, S., Xu, Y.J., 2013. Size effect induced activity enhancement and anti-photocorrosion of reduced graphene oxide/ZnO composites for degradation of organic dyes and reduction of Cr(VI) in water. *Appl. Catal. B Environ.* 140–141, 598–607. <https://doi.org/10.1016/j.apcatb.2013.04.059>.
- Zhang, L., Li, N., Jiu, H., Qi, G., Huang, Y., 2015. ZnO-reduced graphene oxide nanocomposites as efficient photocatalysts for photocatalytic reduction of CO₂. *Ceram. Int.* 41, 6256–6262. <https://doi.org/10.1016/j.ceramint.2015.01.044>.
- Zhang, M., Lu, M., Lang, Z.L., Liu, J., Liu, M., Chang, J.N., Li, L.Y., Shang, L.J., Wang, M., Li, S.L., Lan, Y.Q., 2020a. Semiconductor/covalent-organic-framework Z-scheme heterojunctions for artificial photosynthesis. *Angew. Chemie - Int. Ed.* 59, 6500–6506. <https://doi.org/10.1002/anie.202000929>.
- Zhang, J., Fan, L., Zhao, F., Fu, Y., Lu, J., Zhang, Z., Teng, B., Huang, W., 2020b. Zinc oxide morphology-dependent Pd/ZnO catalysis in base-free CO₂ hydrogenation into formic acid. *ChemCatChem* 12, 5540–5547.
- Zhang, J., Fan, L., Zhao, F., Fu, Y., Lu, J.Q., Zhang, Z., Teng, B., Huang, W., 2020c. Zinc oxide morphology-dependent Pd/ZnO catalysis in base-free CO₂ hydrogenation into formic acid. *ChemCatChem* 12, 5540–5547. <https://doi.org/10.1002/cctc.202000934>.
- Zhao, J., Liu, B., Meng, L., He, S., Yuan, R., Hou, Y., Ding, Z., Lin, H., Zhang, Z., Wang, X., Long, J., 2019a. Plasmonic control of solar-driven CO₂ conversion at the metal/ZnO interfaces. *Appl. Catal. B Environ.* 256, 117823. <https://doi.org/10.1016/j.apcatb.2019.117823>.
- Zhao, J., Tian, W., Liu, S., Wang, Z., Du, Z., Xie, W., 2019b. Existence, removal and transformation of parent and nitrated polycyclic aromatic hydrocarbons in two biological wastewater treatment processes. *Chemosphere* 224, 527–537. <https://doi.org/10.1016/j.chemosphere.2019.02.164>.
- Zheng, Y., Liu, J., Cheng, B., You, W., Ho, W., Tang, H., 2019. Hierarchical porous Al₂O₃@ZnO core-shell microfibres with excellent adsorption affinity for Congo red molecule. *Appl. Surf. Sci.* 473, 251–260. <https://doi.org/10.1016/j.apsusc.2018.12.106>.
- Zheng, F., Queirós, J.M., Martins, P.M., de Luis, R.F., Fidalgo-Marijuan, A., Vilas-Vilela, J.L., Lancers-Méndez, S., Reguera, J., 2023a. Au-sensitized TiO₂ and ZnO nanoparticles for broadband pharmaceuticals photocatalytic degradation in water remediation. *Colloids Surfaces A Physicochem. Eng. Asp.* 671, 131594.
- Zheng, A.L.T., Abdullah, C.A.C., Chung, E.L.T., Andou, Y., 2023b. Recent progress in visible light-doped ZnO photocatalyst for pollution control. *Int. J. Environ. Sci. Technol.* 20, 5753–5772.
- Zheng, Z., He, J., Zhang, Z., Kumar, A., Khan, M., Lung, C.W., Lo, I.M.C., 2024. Magnetically recyclable nanophotocatalysts in photocatalysis-involving processes for organic pollutant removal from wastewater: current status and perspectives. *Environ. Sci. Nano* 11, 1784–1816.
- Zhong, Y., Wang, K., Guo, C., Kou, Y., Hassan, A., Lu, Y., Wang, J., Wang, W., 2022. Competition adsorption of malachite green and rhodamine B on polyethylene and polyvinyl chloride microplastics in aqueous environment. *Water Sci. Technol.* 86, 894–908.
- Zhou, M., Yang, P., Yuan, R., Asiri, A.M., Wakeel, M., Wang, X., 2017. Modulating crystallinity of graphitic carbon nitride for photocatalytic oxidation of alcohols. *ChemSusChem* 10, 4451–4456. <https://doi.org/10.1002/cssc.201701392>.
- Zhu, G., Wang, H., Yang, G., Chen, L., Guo, P., Zhang, L., 2015a. A facile synthesis of ZnO/CNT hierarchical microsphere composites with enhanced photocatalytic degradation of methylene blue. *RSC. Adv.* 89, 72476–72481. <https://doi.org/10.1039/c5ra11873e>, 2015.
- Zhu, B., Xia, P., Ho, W., Yu, J., 2015b. Isoelectric point and adsorption activity of porous g-C₃N₄ applied surface science isoelectric point and adsorption activity of porous g-C₃N₄. *Appl. Surf. Sci.* 344, 188–195. <https://doi.org/10.1016/j.apsusc.2015.03.086>.
- Zirak, M., Alehdaghi, H., Shakoori, A.M., 2021. Preparation of ZnO-carbon quantum dot composite thin films with superhydrophilic surface. *Mater. Technol.* 36, 72–80. <https://doi.org/10.1080/10667857.2020.1728863>.
- Zong, X., Jin, Y., Li, Y., Zhang, X., Zhang, S., Xie, H., Zhang, J., Xiong, Y., 2022. Morphology-controllable ZnO catalysts enriched with oxygen-vacancies for boosting CO₂ electroreduction to CO. *J. CO₂ Util.* 61, 102051. <https://doi.org/10.1016/j.jcou.2022.102051>.
- Zouhair, M., Tanji, K., Navio, J.A., Hidalgo, M.C., Jaramillo-Páez, C., Kherbeche, A., 2020. Preparation of ZnFe₂O₄/ZnO composite: effect of operational parameters for photocatalytic degradation of dyes under UV and visible illumination. *J. Photochem. Photobiol. A Chem.* 390, 112305.