


 Cite this: *RSC Adv.*, 2025, 15, 49852

# ZnO based photocatalysts for pesticides degradation

 Haji Muhammad,<sup>abc</sup> Maliha Hanif,<sup>d</sup> Mustafa Tuzen,<sup>\*a</sup> Asma Siddiqui,<sup>c</sup> Nazish Kousar,<sup>c</sup> Afzal Shah <sup>\*e</sup> and Mohammad Reza Afshar Mogaddam <sup>fg</sup>

The widespread application of pesticides in modern agriculture has significantly boosted crop production; however, their inherent toxicity, persistence, and resistance to conventional cleanup methods have led to serious environmental and public health concerns. Advanced oxidation processes (AOP), especially those utilizing visible light for photocatalysis, have recently emerged as promising eco-friendly alternatives for the degradation of pesticides. In particular, zinc oxide (ZnO) based nanophotocatalysts have garnered considerable attention due to their wide band gap (~3.37 eV), strong oxidative capability, high electron mobility, low electron–hole recombination rates, and natural antibacterial properties, which enhance their photocatalytic activity under sunlight. This review provides a comprehensive overview of recent progress in ZnO-mediated photocatalytic degradation of pesticides, focusing on synthesis methods, structural modifications such as doping and defect engineering, and material hybridization aimed at improving photocatalytic efficiency. Furthermore, the study critically examines the influence of key factors, including catalyst concentration, surface morphology, and particle size, on degradation performance. This review aims to offer a thorough understanding of the versatility of ZnO as a tunable photocatalyst for mitigating pesticide contamination in wastewater by combining mechanistic insights with experimental observations. This integration not only highlights the potential of ZnO in this context but also establishes a foundation for creating scalable and eco-friendly remediation approaches.

 Received 19th October 2025  
 Accepted 6th December 2025

DOI: 10.1039/d5ra08016a

[rsc.li/rsc-advances](https://rsc.li/rsc-advances)

## 1. Introduction

Pesticides play a vital role in modern agriculture, serving as indispensable tools for farmers to manage and mitigate weeds and control pests in farming practices. They play a significant role in combating insect-borne diseases and are also believed to greatly enhance agricultural productivity by reducing crop losses, improving yield, and ensuring the quality of food, all while being a cost-effective solution for farmers.<sup>1</sup> The application of pesticides on crops is estimated to be 3.5 million tons every year at a global scale. Despite the fact that approximately 1% of pesticides are effectively used to target and manage pests on the

intended crops, the vast majority of these chemicals end up affecting non-target plants or dispersing into the environment. This unintended distribution leads to significant contamination of soil, water, and air, posing serious risks to ecosystems and public health.<sup>2</sup> Consequently, the widespread use of pesticides disrupts food webs in both terrestrial and aquatic ecosystems, as the chemicals and their byproducts are often resistant to biodegradation, leading to persistent environmental contamination.<sup>3</sup> Additionally, these agrochemicals contribute to a reduction in biodiversity, a decrease in pollinator populations, harm to native soil microorganisms, and the disturbance of nesting habitats.<sup>4</sup>

Moreover, pesticide exposure is linked to a variety of health problems, affecting individuals in environmental, community, and occupational settings. These health issues can manifest as both acute and chronic effects, including cancer, genetic mutations, neurotoxicity,<sup>5</sup> and developmental disorders.<sup>6</sup> It is estimated that annually, more than a million agricultural workers show signs of pesticide poisoning.<sup>7</sup> As a result, the breakdown of pesticides and their residues is crucial. Many research efforts focus on techniques to minimize pesticide levels in the environment, particularly in soil and water, employing methods such as membrane filtration, surface adsorption, and biological degradation. However, these

<sup>a</sup>Chemistry Department, Faculty of Science and Arts, Tokat Gaziosmanpaşa University, 60250 Tokat, Turkey. E-mail: mustafa.tuzen@gop.edu.tr

<sup>b</sup>Department of Chemistry, University of Karachi, Karachi, 75270, Pakistan

<sup>c</sup>Department of Chemistry, Federal Urdu University of Arts, Sciences and Technology, Karachi 75300, Pakistan

<sup>d</sup>Department of Biotechnology, Federal Urdu University of Arts, Sciences and Technology, Karachi 75300, Pakistan

<sup>e</sup>Department of Chemistry, Quaid-i-Azam University, Islamabad 45320, Pakistan. E-mail: afzals\_gau@yahoo.com

<sup>f</sup>Food and Drug Safety Research Center, Pharmaceutical Sciences Institute, Tabriz University of Medical Sciences, Tabriz, Iran

<sup>g</sup>Research Center of New Material and Green Chemistry, Khazar University, 41 Mehseti Street, Baku AZ1096, Azerbaijan



approaches may have limitations when faced with high levels of contamination.<sup>8</sup>

Nanoparticles have garnered significant attention for their potential in pesticide degradation, with ZnO nanoparticles being particularly notable due to their abundance, stability, high reactivity, large surface area, excellent photosensitivity, and cost-effectiveness.<sup>9</sup> Furthermore, zinc oxide (ZnO) photocatalysts can be easily immobilized on various substrates, enhancing their applicability in diverse water treatment processes.<sup>10</sup> These advantageous characteristics drive researchers to innovate and create advanced ZnO hybrid photocatalysts with improved photo-efficiency, aimed at effectively breaking down hazardous pollutants such as pesticides.

Therefore, in view of the aforesaid, this review employed a narrative literature approach, primarily sourcing scientific publications, review articles, and reports from online databases such as Google Scholar, ScienceDirect, Springer, PubMed, and Scopus. Key terms included “ZnO photocatalysis”, “pesticide degradation”, “nanoparticle remediation”, and “environmental impact of pesticides”. While studies published in peer-reviewed journals over the past 10 to 15 years were prioritized, the review did not impose strict inclusion or exclusion criteria. It aims to provide a comprehensive understanding of ZnO-mediated photocatalytic pesticide degradation by integrating both theoretical and experimental findings, alongside relevant earlier research that contributes valuable context or mechanistic insights. Only English-language publications specifically addressing ZnO-based photocatalytic pesticide breakdown were considered, while patents, conference abstracts, and non-peer-reviewed materials were excluded. Moreover, this manuscript was proofread and edited for clarity and language enhancement using ChatGPT; OpenAI. The authors assume full responsibility for all content and ensure the accuracy and integrity of the work.

## 2. Environmental fate and impact of pesticides

Pesticides are man-made chemical substances that include nematicides, herbicides, fungicides, acaricides, insecticides, and molluscicides. These compounds are employed to control, eliminate, reduce, or repel organisms that are detrimental to crops or cause damage. Their absence would result in a startling 78% loss in fruit productivity, a 54% decrease in vegetable production, and a 32% decrease in cereal production.<sup>11</sup> Interestingly, pesticide use skyrocketed during World War II as a result of the increased need for food by a growing population. Initially, synthetic pesticides were primarily designed to eliminate mosquitoes, particularly those that carry malaria.<sup>12</sup> But after the 1950s, global pesticide production has seen growth at an average annual rate of approximately 11%, escalating from 0.2 million tons (ref. 13) to over 5 million tons by the year 2000.<sup>14</sup> Whereas annually, around 3 billion kilograms of pesticides are utilised globally.<sup>15</sup>

Likewise, synthetic pesticides have been used by humans since 1940; ever since, they vary in chemical, physical, and other

characteristics from one category to another. Hence, it is important to classify them according to their properties and study them within their specific category. At present, pesticides can be broadly categorized in two ways: (a) based on the type of pest they target (Fig. 1) and (b) according to their chemical composition (Table 1).

However, the overuse of pesticides poses a significant risk to non-target organisms, as nearly 98% of all sprayed pesticides, whether directly or indirectly, impact them. Evidence suggests that soil and water quality deteriorate due to pesticide accumulation. Moreover, pesticide accumulation can lead to a decrease in soil respiration up to 35%. Existing literature indicates that nearly 90% of water sources in agricultural areas are polluted with pesticides.<sup>26</sup>

What is more, in the presence of various existing persistent pollutants (industrial compounds, natural solvents, and cleansing agents), water-soluble pesticides are causing great trouble. Poor management, particularly in on-farm handling, is the primary contributor to pesticide contamination in the ecosystem.<sup>27</sup> There are many different sources of pesticide contamination, such as industrial manufacturing processes, the discharge from agricultural activities like container cleaning, spraying, and washing contaminated crops, soil degradation, atmospheric deposition, and many more, which potentially lead to environmental contamination through processes like bioaccumulation.<sup>28</sup> So basically, the persistent pesticides reach the environment by either direct or indirect means. What's more, pesticide pollution originates from two main categories of sources: point sources (specific) and non-point sources, also known as diffuse sources. This includes scenarios like the pesticide's transfer from various surface water sources, leading to water pollution, which affects both aquatic and land ecosystems. Along with other sources, agriculture is a major contributor to diffuse pollution, which is caused by activities without specific release points.<sup>29</sup> On a global and regional level, non-point source pollution is a major environmental challenge and is acknowledged as a major contributor to the deterioration of water quality. According to reports, non-point source pollution has affected between 30% and 50% of surface water bodies globally.<sup>30</sup>

Overview of pesticides and their environmental impact revealed that the excessive use of pesticides ultimately leads to their accumulation in soils, then either eliminates microorganisms that are essential for many biological processes, like nutrient uptake or organic matter breakdown, or inhibits their activity, which leads to lower soil fertility.<sup>31</sup> These inadequately and excessively used products can also harm non-targeted organisms because only a small portion (1–3%) of the pesticides being used reach their targets. The dispersal of contaminants to non-target areas occurs irrespective of any natural barriers, and because of multiple transport pathways, it can be difficult to track the contamination.<sup>32</sup> Preliminary findings show that aquatic organisms are seriously endangered due to the presence of pesticides in waterbodies. Fish communities experience behavioural and physiological changes, and aquatic plants suffer from lower oxygen levels in the water.<sup>33</sup> Additionally, pesticides affect terrestrial fauna populations, including



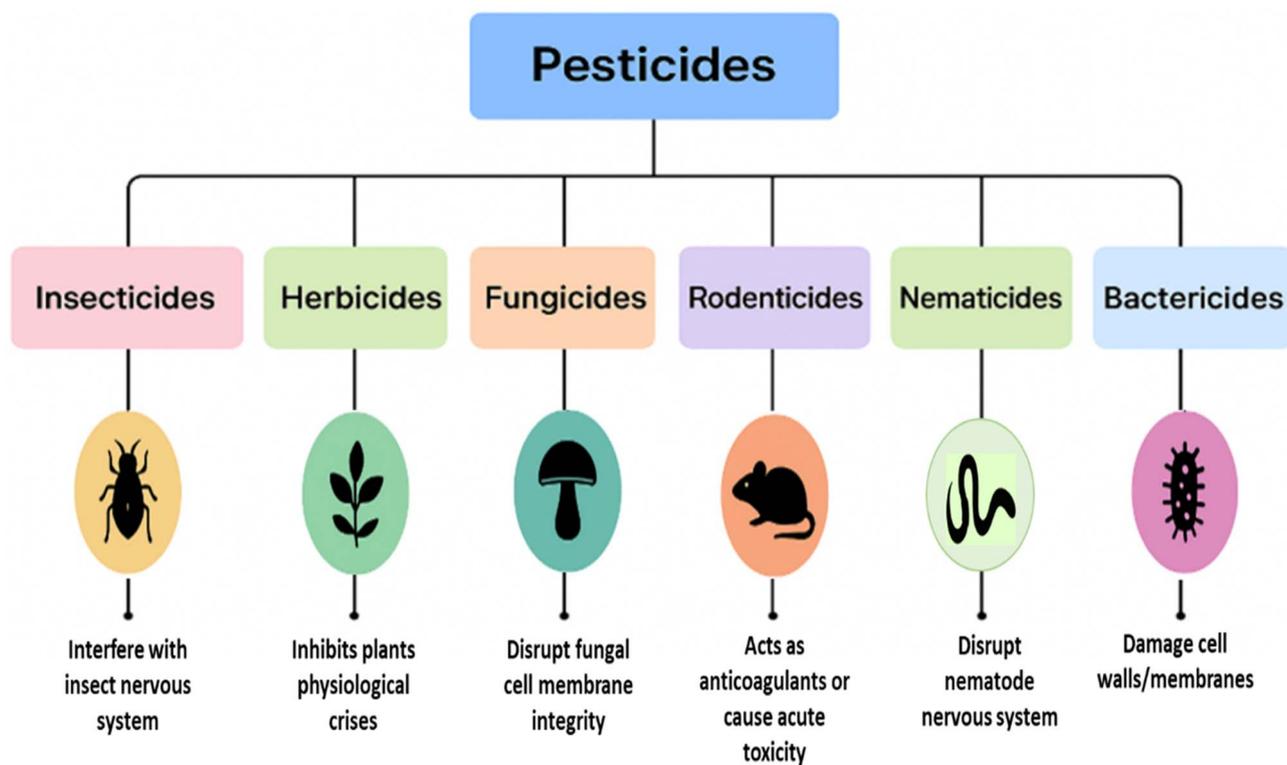


Fig. 1 Classification of pesticides based on the targeted pest.

beneficial insects, whose numbers may significantly decrease when broad-spectrum insecticides are applied.<sup>34</sup> Alternatively, the accumulation of pesticides in birds' and mammals' tissues has been responsible for a decline in their population because of the adverse effects on the nervous systems. It causes behavioural changes that can lead to death.<sup>35</sup> Through contaminated feed, water, or direct touch, farm animals are also exposed to pesticides, which can have detrimental effects. Multiple studies report that acute toxicity, immune system weakness, reproductive issues, and organ damage are all possible outcomes of pesticide exposure in farm animals (Table 2). Even at low concentrations, prolonged exposure might cause long-term health problems such as hormone imbalances and decreased productivity. Pesticide residues that bioaccumulate in animal tissues can also endanger human health by way of the food chain.

In a similar manner, humans can be adversely affected by pesticides through direct exposure to them during agricultural activities (Fig. 2). Because pesticides came into contact with humans *via* household vegetation, or having occupational-related farming, as well as indirectly through the food chain and environmental contamination.<sup>36</sup> Exposure of humans to pesticides conveys a significant health risk, with both acute effects and chronic effects on health. Numerous health consequences result from these effects, including acute and long-term neurotoxicity from fungicides, insecticides, and fumigants; lung damage from the pesticide paraquat; infant methemoglobinemia from nitrate seeping into groundwater; and chemical injuries like burns from pesticide exposure, such

as anhydrous ammonia.<sup>37</sup> Furthermore, a variety of cancers have been linked to pesticide exposure, including hematopoietic cancers, cancers of the digestive tract, cancers of the reproductive system, bladder cancer, breast cancer, and lung cancer.<sup>38</sup> Cholinergic effects include the possibility of immunologic abnormalities<sup>39</sup> and adverse effects on reproductive and developmental processes.<sup>40</sup> Moreover, pesticides can have an impact on health even if a person is not showing any serious signs of illness. People who get exposure often report difficulty in localizing sensations while their muscle strength is reduced.<sup>41</sup> The causes of diseases that may arise from exposure to pesticides can vary depending on a number of factors. These variables include the kind of pesticide applied, the exposure method and duration, and the general health of the person. Pesticides undergo various processes after entering the bodies of animals or humans, which include metabolism, excretion, storage, and accumulation in adipose tissues<sup>42</sup> as shown in Table 3.

### 3. Conventional method of pesticide remediation

Currently, various remediation methods are utilised for addressing the water<sup>58</sup> and soil<sup>59</sup> contamination with pesticides. If one technology proves ineffective, combining multiple methods becomes necessary to achieve satisfactory outcomes. Therefore, numerous techniques have been suggested and implemented over time to eliminate persistent pollutants.



Table 1 Classification of pesticides based on chemical groups and relevance to ZnO-mediated photocatalysis<sup>a</sup>

Chemical group	Examples	Structure type	Relevance to ZnO photocatalysis	Ref.
Organochlorines	DDT, aldrin, endosulfan, chlordane, heptachlor	Chlorinated aromatic hydrocarbons, high stability	Persistent organic pollutants require prolonged photocatalytic exposure to break C–Cl bonds	16
Organophosphates	Malathion, parathion, chlorpyrifos, diazinon	Phosphorothioates or phosphates, aliphatic or aromatic	Degrade relatively quickly; P–O and P–S bonds cleaved under UV/visible light	17
Carbamates	Carbaryl, aldicarb, carbofuran, methomyl	Carbamate esters of aromatic/aliphatic amines	ZnO photocatalysis breaks carbamate linkages, reducing toxicity	18
Pyrethroids	Permethrin, cypermethrin, deltamethrin	Cyclopropane carboxylate esters	Degrade into less toxic acids and alcohols under photocatalytic conditions	19
Neonicotinoids	Imidacloprid, thiamethoxam, acetamiprid	Chloronicotinyl or nitroguanidine derivatives	Water-soluble; susceptible to oxidative degradation in aqueous ZnO systems	20
Phenoxy herbicides	2,4-D, MCPA, mecoprop	Chlorinated phenoxyacetic acids	Aromatic rings and –COOH groups are readily attacked by OH <sup>•</sup>	21
Triazines	Atrazine, simazine, propazine	Nitrogen-containing heterocyclic aromatic rings	Photocatalysis disrupts the triazine ring structure and dechlorinates	22
Bipyridyl herbicides	Paraquat, diquat	Bipyridinium salts	Strongly absorb visible light; photocatalysis reduces toxicity <i>via</i> demethylation and ring cleavage	23
Fumigants	Methyl bromide, aluminium phosphide	Simple halides or phosphides	Easily decomposed into non-toxic products under photocatalytic oxidation	24
Rodenticides	Warfarin, brodifacoum	Coumarin derivatives	Aromatic and lactone structures oxidised under UV/visible photocatalysis	25

<sup>a</sup> DDT = dichlorodiphenyltrichloroethane. 2,4-D = 2,4-dichlorophenoxyacetic acid. MCPA = 2-methyl-4-chlorophenoxyacetic acid.

Traditional approaches for eliminating these pollutants include membrane filtration,<sup>60</sup> surface trapping,<sup>61</sup> ozonolysis, air stripping, skimming, photolysis, and Fenton oxidation processes.<sup>62</sup> Biodegradation, particularly through microbial action, is also found to be a versatile and effective strategy for remediating pesticide-contaminated sites due to the capability of microbes to function even in harsh environmental conditions.<sup>63</sup> However,

this method is both time-consuming and inefficient, with limitations in its applicability. Likewise, processes like sedimentation, membrane technologies, and chemical filtration entail significant operational expenses and result in the generation of highly poisonous secondary pollutants that enter nature.<sup>64</sup> In addition, various physicochemical techniques such as reverse osmosis, carbon adsorption, adsorption, nano-

Table 2 Pesticide impacts on farm animals

Pesticide class	Adverse effects in farm animals	Ref.
Carbamates	Neuromuscular weakness; potential residues in milk/eggs if misuse	43
Pyrethroids	Dermal/respiratory irritation; stress; resistance issues in stable flies affecting cattle	44
Neonicotinoids	Potential residue transfer <i>via</i> feed; limited direct farm-animal toxicity at labelled uses, but monitor feed contamination	45
Phenoxy herbicides	Indirect effects <i>via</i> forage contamination, and if misused, may lead to milk residue risks ( <i>e.g.</i> , feed-to-milk pathway)	46
Organochlorine	Bioaccumulation in animals and milk, causing potential human exposure	47



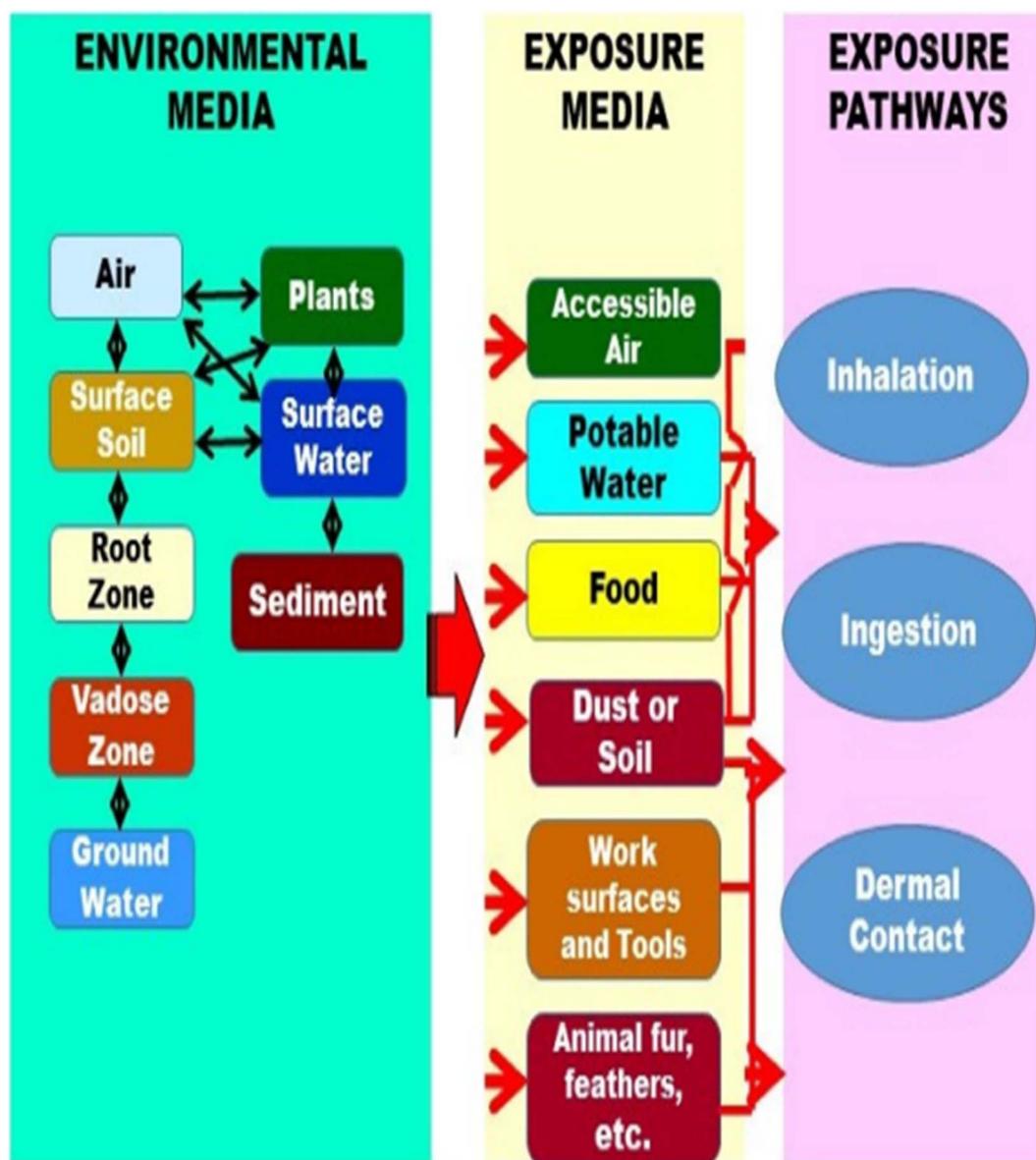


Fig. 2 Pathways of pesticides entry into the human body.<sup>15</sup> Reproduced from ref. 15 with permission from MDPI, copyright 2022.

filtration, distillation, adsorption, and ion exchange resins have also been utilised recently. Adsorption and coagulation are the processes that primarily concentrate pollutants, changing their phase, rather than eliminating or degrading them completely.<sup>65</sup> Therefore, these methods encounter significant challenges, including issues with disposal, membrane distortion, formation of sludge, operational handling, and various technical limitations.<sup>66</sup> In summary, the various physical, chemical, and biological methods employed for pesticide removal each possess distinct advantages and disadvantages. These characteristics influence their effectiveness based on factors such as the type of pollutant, its concentration, and the specific goals of the treatment, as illustrated in Fig. 3.

Since the majority of persistent pollutants are resistant to breakdown through conventional chemical and biological treatment approaches. The methods described above are

efficient, but they have limitations in terms of their effectiveness, applicability, cost, and time. Consequently, the inadequacy of current treatment processes for pesticide remediation has heightened the need for advanced technologies for treatment. So, scientists have explored alternative approaches to degrade persistent pesticides completely into eco-friendly substances, such as the advanced oxidation process (AOPs).

#### 4. Advanced oxidation process

To address the downsides of traditional treatment methods, scientists are exploring AOPs as a more effective way to remove pesticides from wastewater. AOP stands out as an exceptionally effective and advantageous method for purifying polluted water. It efficiently transforms pesticides or any other organic contaminants into water, carbon dioxide, and basic salts.<sup>67</sup> It



Table 3 Main classes of pesticide and their effect on human health

Pesticide class	Effect	Ref.
Organophosphate	Chronic central nervous system disorders, respiratory disorders, cardiovascular diseases, diabetes mellitus, cancer, infertility issues, impaired vision, Alzheimer's disease, cellular oxidative stress, Parkinson's disease, hypotension, <i>etc.</i>	48–50
Organochlorine	Cardiovascular disorders, hypertension, neurological disorders, hormone-related cancers (breast, prostate, lung, stomach), obesity, endocrine disruption, alterations in embryonic development, hematologic and hepatic changes, diabetes in overweight individuals, learning disabilities in children, hyperactivity disorder, and Parkinson's disease	51 and 52
Carbamate	Immunotoxicity, cholinergic poisoning, male infertility, endocrine disruption and inhibition of esterases, endoplasmic reticulum stress, <i>etc.</i>	53 and 54
Pyrethroids	Respiratory distress, nausea, tachycardia, apathy, metabolic acidosis, convulsions, anaphylactic shock, pulmonary edema, and oxidative stress. Risks to reproductive health and neurobehavioral, cancer, and the development of autism spectrum disorders in infants, <i>etc.</i>	55–57

employs a potent oxidant like hydroxyl radical ( $\text{OH}^\bullet$ ), possessing the second-highest oxidising power, approximately 2.8 eV less than fluorine. These radicals can interact with nearly all organic pollutants at rate constants ranging from  $10^6$  to  $10^9 \text{ mol L}^{-1} \text{ s}^{-1}$ .<sup>68</sup> This advanced technology is becoming more promising and an increasingly adopted method for addressing recalcitrant wastewater, containing a lot of organic matter and low pH levels. Moreover, this approach is employed to neutralise pathogens after secondary treatment.<sup>69</sup>

Generally, AOP involves activating semiconductor photocatalysts through light that leads to the formation of  $\text{OH}^\bullet$  that oxidizes pollutants. The reduction of adsorbed oxygen molecules generates oxygen radicals that help break down pollutants.<sup>70</sup> The indiscriminate characteristic of  $\text{OH}^\bullet$  renders them suitable for remediation in the environment.<sup>71</sup> Additional oxidative agents employed in AOP include ozone and superoxide radicals ( $\text{O}_2^{\bullet-}$ ).<sup>72</sup> The general classification of AOP can be seen in Fig. 4.

## 5. Photocatalysis

Within this sequence of procedures, photocatalysis, which relies on the use of a photocatalyst to absorb accelerated photons, is one of the most effective methods in the AOP. According to the Photocatalysis Industry Association of Japan, a photocatalyst is a substance that accelerates chemical reactions by utilizing an external energy source. One important application of photocatalysts is the degradation of harmful substances such as pesticides. By generating reactive free radicals, particularly  $\text{OH}^\bullet$ , photocatalysts can convert highly toxic pesticides into less harmful compounds.<sup>74</sup> This process begins

when the photocatalyst absorbs radiation with wavelengths longer than 290 nm. The absorbed energy excites electrons in the catalyst material, promoting them to a higher energy state. These excited electrons, along with the resulting positive “holes” left behind, can interact with surrounding molecules. The interaction leads to the formation of reactive species such as superoxide and  $\text{OH}^\bullet$ . These radicals then react with the active components of pesticides or other pollutants through oxidation–reduction reactions (Fig. 5), ultimately leading to their breakdown and the detoxification of water.<sup>75</sup>

Photocatalysts offer safety, cost-effectiveness, exceptional durability, chemical and biological inertness, insolubility in most scenarios, and the ability to be recycled and reused. They can be activated by both artificial light and sunlight.<sup>76</sup> However, there are several challenges in photocatalysis research that must be addressed before practical application. These include the inability to function effectively in solar radiation, issues with reactor design, limitations on catalyst reuse and recovery, lower quantum efficiency, and the potential production of toxic byproducts.<sup>77</sup> Another challenge in photocatalysis is the rapid recombination of photo-generated electron–hole pairs, which can hinder the efficiency of the process. This phenomenon, known as charge recombination, results in the release of electron energy as heat, ultimately terminating the reaction. To address this issue, doping with metal oxide nanomaterials is recommended. Doping helps prevent electron–hole recombination by introducing metal ions, thus extending the lifespan of electron–hole pairs enough to facilitate redox reactions at the catalyst surface.<sup>78</sup>

The photocatalysis process is of two kinds: homogeneous and heterogeneous. Homogeneous photocatalysis occurs when



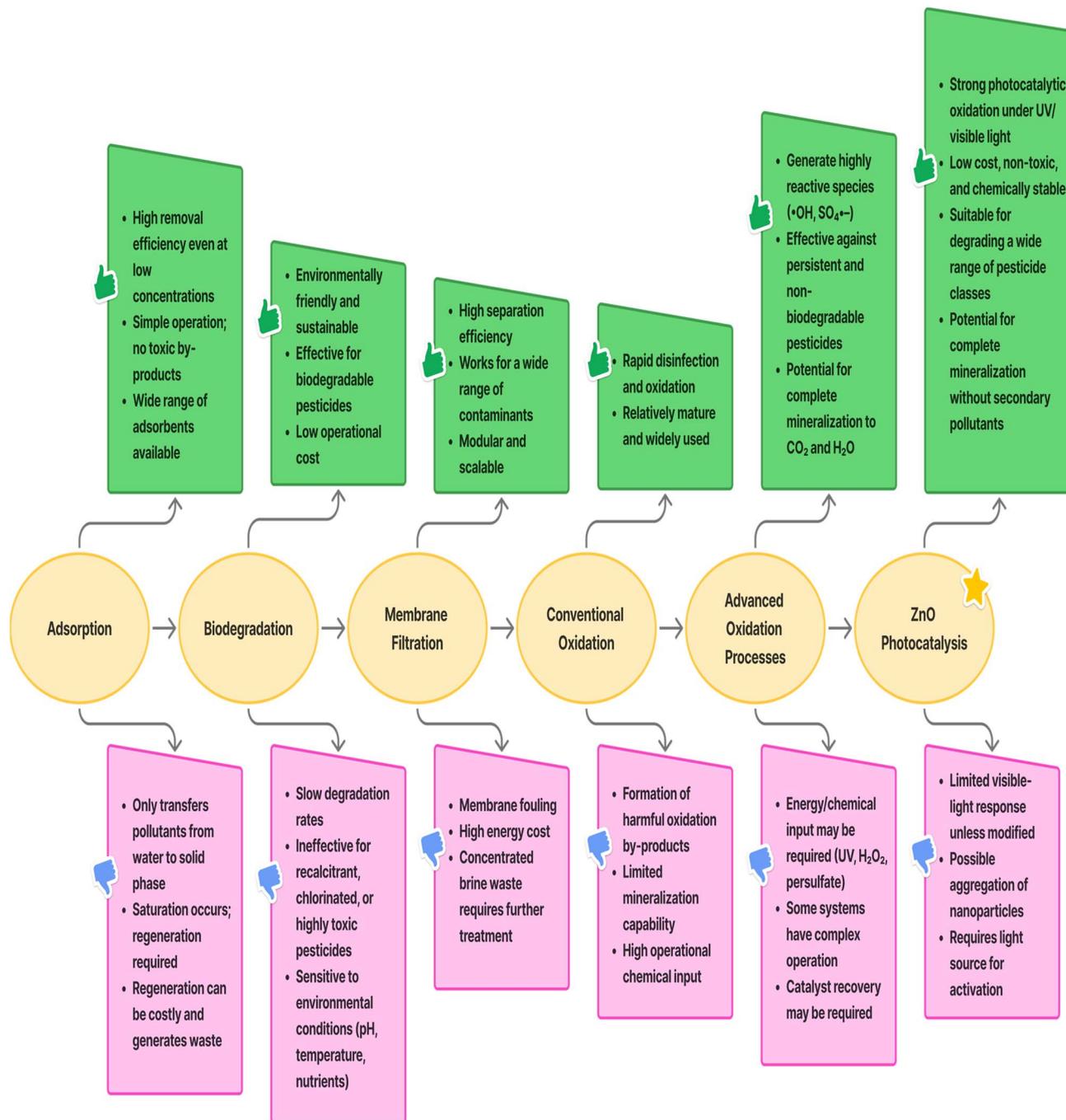


Fig. 3 Comparison of treatment methods for pesticide removal: distinct advantages and limitations associated with each approach.

a soluble catalyst and reactant are present in a single phase. The derived homogeneous solution contains photon promoters and active catalytic sites that function in two different ways. In the first technique, a photosensitizer is used to transfer electrons to the catalyst, creating an active site that triggers a reduction reaction. In the second technique, the catalyst acts as both a catalyst and a substance that absorbs light. When light incidence excites the catalyst electrons, they shift from the highest occupied molecular orbital to the lowest unoccupied molecular orbital, causing the catalyst to act as a good substance for redox

processes.<sup>80</sup> Transition metal complexes are the most widely used homogeneous photocatalyst due to their advantageous energy band gap properties and stability, while ozone is the second most commonly used catalyst.<sup>79,81</sup> The main disadvantage of a homogeneous photocatalyst system is that it is difficult to separate the photocatalyst from the solution since it is completely soluble.<sup>82</sup>

Heterogeneous photocatalysis refers to the enhancement of photoreactions in the presence of a catalyst.<sup>83</sup> The reaction involves the interaction of substances with multiple states.



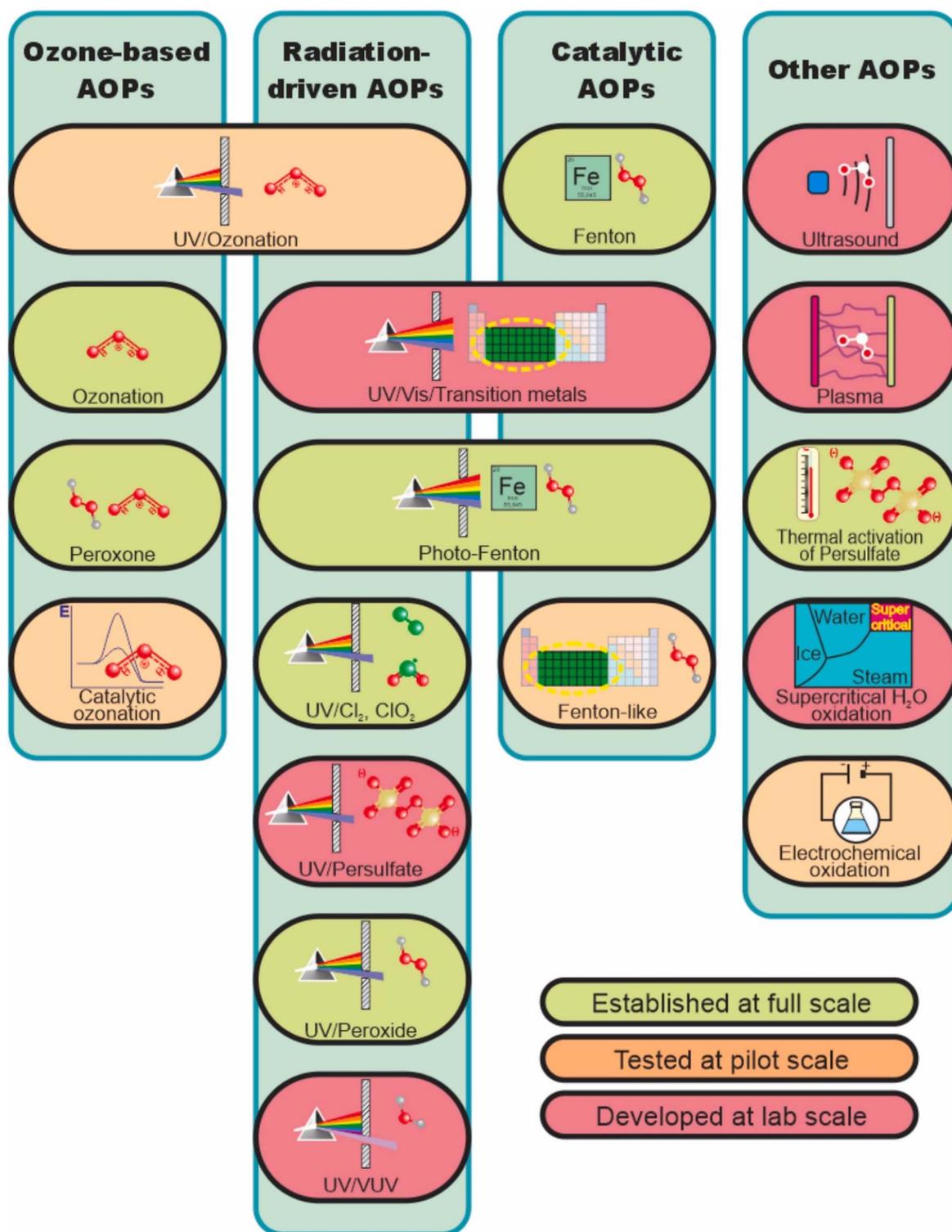


Fig. 4 Classification of AOPs. This figure has been reproduced with permission from ref. 73, Elsevier, copyright 2024.

Typically, a solid photocatalyst is used, and organic pollutants or compounds in the aqueous phase are exposed to the catalyst's surface for photo degradation.<sup>84</sup> Commonly used materials in heterogeneous photocatalysis include ZnO, ZnS, MnO<sub>2</sub>, WO<sub>3</sub>, MoO<sub>3</sub>, TiO<sub>2</sub>, SnO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, CdS, CeO<sub>2</sub>, and ZrO<sub>2</sub> (Table 4).

These materials are favoured due to their chemical and mechanical stability, as well as their inertness towards biological tissues. They have a low energy gap and possess properties like high porosity, large surface area, and both hydrophobic and hydrophilic interactions that make them well-suited for the



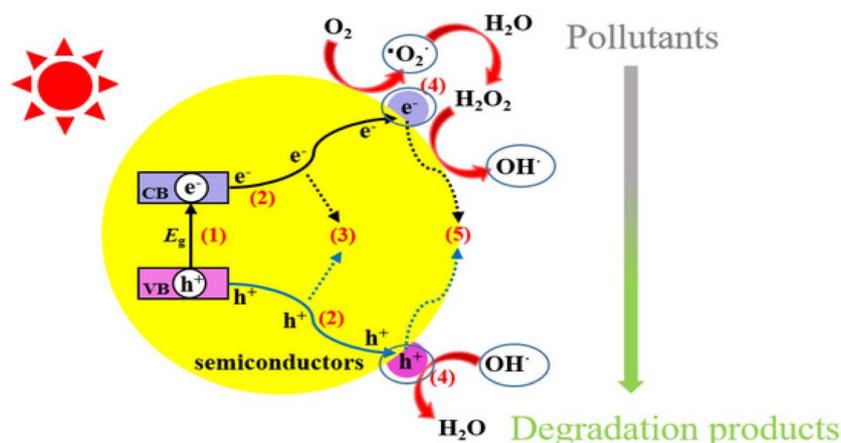


Fig. 5 Photocatalytic processes over a heterogeneous photocatalyst.<sup>79</sup> Reproduced from ref. 79 with permission from MDPI, copyright 2021.

Table 4 Band gap energies of a semiconductor

Semiconductor	Band gap (eV)	Ref.
ZnO	3.37	88
TiO	3.20	89
MnO <sub>2</sub>	1.38 or 1.41	90
Fe <sub>2</sub> O <sub>3</sub>	1.77 to 2.25	91
SnO <sub>2</sub>	3.66	92

photodegradation of persistent pesticides.<sup>85,86</sup> Heterogeneous photocatalysis is a complex process involving multiple stages to eliminate harmful substances from wastewaters. Generally, the process starts when light of sufficient energy strikes the catalyst's surface, and it is absorbed, causing an electron to move from the valence band (VB) to the conduction band (CB), leaving a hole in the valence band. This process generates an electron-hole pair called an exciton. A critical aspect of heterogeneous photocatalysis is to prevent the recombination of these electron-hole pairs and utilize excitons for a redox reaction to fully degrade toxic compounds into harmless minerals.<sup>87</sup>

Nanomaterials, which are known for their small size and unique properties, have emerged as a promising area of interest for effectively addressing various environmental pollutants, including organic pesticides. A diverse array of materials, including metal oxides (such as TiO<sub>2</sub>, ZnO, CuO, MgO), metal nanoparticles (like Au, Ag), bimetallic nanoparticles, bio-nanopolymers (such as alginate-Ag, ZnO-cellulose), adsorbents (including triggered charcoal, zeolites, calcite, clays, and other carbonaceous materials), as well as nanoparticles and nanocomposites, have been extensively utilized for pesticide remediation over decade.<sup>93</sup>

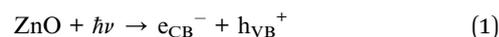
Typically, nano-based remediation technology utilizing nanomaterials as photocatalysts stands out as the most effective advanced oxidation method for addressing pesticides and further harmful pollutants. By using photo-excitation, the photocatalyst creates both electron-donating (reducing) and electron-accepting (oxidizing) species (Fig. 6), which have great potential as redox agents. Technology like nano-photocatalysis

follows the principles of green chemistry to remove harmful pollutants from the environment and human life. It achieves this by breaking down stubborn compounds (Fig. 6) into intermediary substances and eventually into harmless byproducts.<sup>94</sup>

## 6. ZnO and its nanomaterials as photocatalysts

Since visible light makes up the bulk of the solar spectrum, there is a rising need to use solar energy to combat water pollution, which has led to an increased focus on Visible Light Active (VLA) photocatalysts. An ideal photocatalyst should function under both UV and visible light, remain chemically stable, resist photo-corrosion, be environmentally safe, and remain cost-effective,<sup>96</sup> but to do so, factors such as surface area, porosity, crystalline structure, particle size, and band gap play a critical role.<sup>66</sup>

ZnO is classified as a II-VI semiconductor, characterized by a direct band gap of approximately 3.37 eV and an exciton binding energy of around 60 meV. It adopts a wurtzite hexagonal crystal structure, where the tetrahedral coordination of Zn<sup>2+</sup> and O<sup>2-</sup> ions leads to significant polarization, influencing its electronic band structure. The conduction band is primarily derived from the Zn 4s orbitals, while the valence band is formed from the O 2p orbitals. When exposed to UV light, ZnO facilitates the generation of electron-hole pairs, as illustrated in eqn (1):



In nanoscale ZnO, the phenomena of quantum confinement, the presence of surface states, and oxygen vacancies contribute to the formation of shallow donor levels. These factors enhance electron density, facilitate stronger adsorption, and promote efficient electron transfer to pesticide molecules. Additionally, when ZnO is synthesized using environmentally friendly or waste-derived methods, it aligns with green chemistry



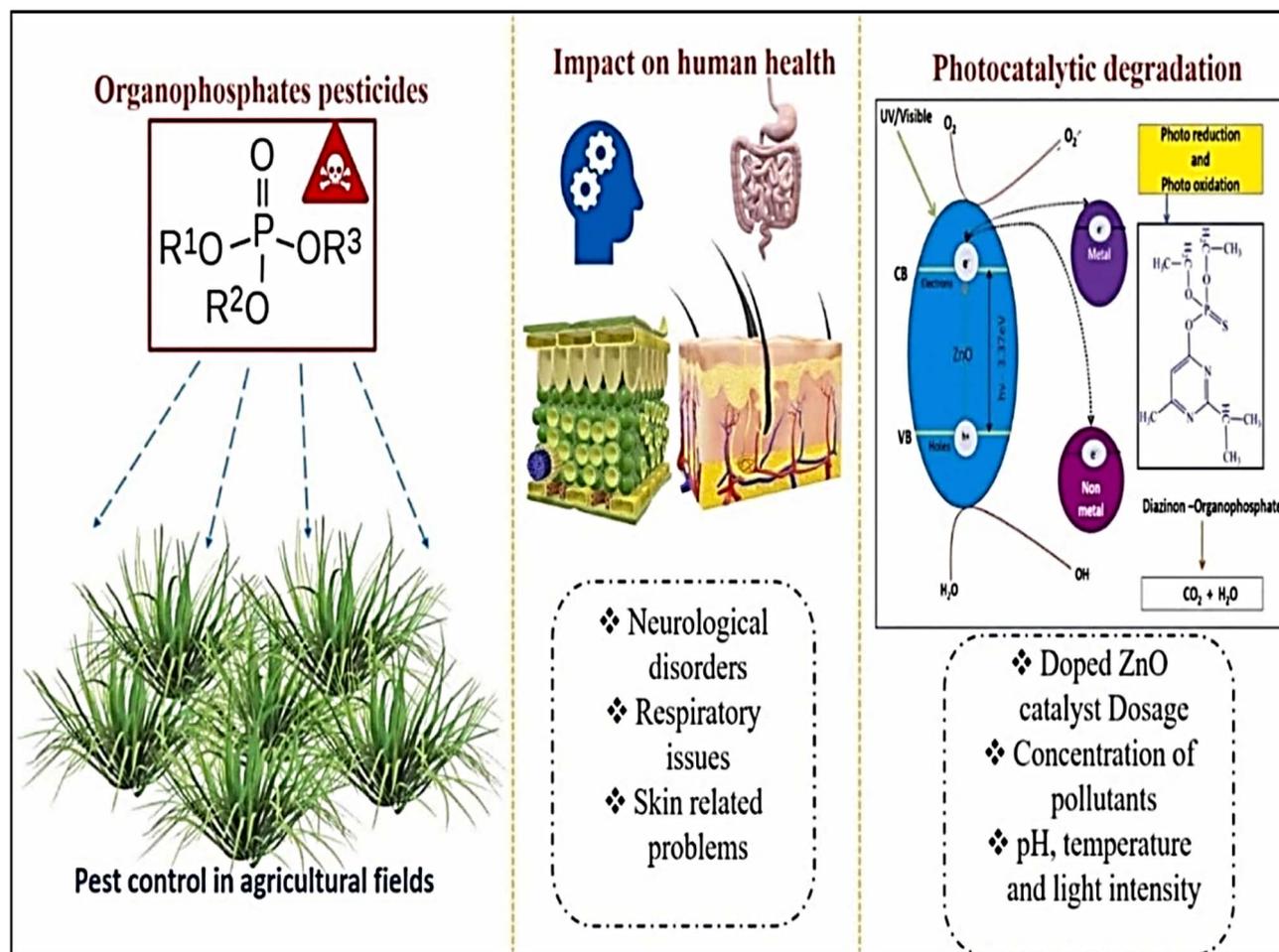


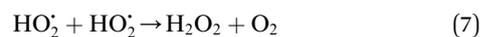
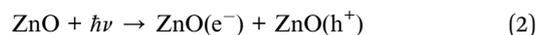
Fig. 6 Photocatalytic degradation of the health hazardous organophosphorus pesticides using ZnO coupled photocatalysts. This figure has been reproduced with permission from ref. 95, Elsevier, copyright 2024.

principles by reducing resource consumption and minimizing its environmental impact.

ZnO exhibits band edges of approximately  $-0.5$  eV for the conduction band and  $+2.7$  eV for the valence band relative to the NHE, facilitating the generation of both superoxide ( $\text{O}_2^{\cdot-}$ ) and hydroxyl radicals ( $\text{OH}^{\cdot}$ ). Under UV light excitation with wavelengths shorter than 380 nm, electrons are able to reduce  $\text{O}_2$  to  $\text{O}_2^{\cdot-}$ , while the holes oxidize water or  $\text{OH}^-$  to yield  $\text{OH}^{\cdot}$ , as depicted in Fig. 7. Reactive oxygen species exhibit a potent oxidative capacity, enabling them to break down pesticides, dyes, pharmaceuticals, and other enduring pollutants into benign products such as  $\text{CO}_2$  and  $\text{H}_2\text{O}$ .<sup>97</sup> The photocatalytic performance of ZnO is strongly influenced by band gap energy, charge carrier dynamics, and synthesis-dependent morphological factors.<sup>98</sup>

Similarly, at the surface of ZnO nanoparticles, upon visible light interaction, mechanistic changes start. The photoreaction begins when electron-hole pairs are generated that migrate across the nanoparticle surface. These pairs undergo oxidation and reduction reactions on the surface of the catalyst. Upon contact with water molecules, the holes produce hydroxyl ions ( $\text{OH}^-$ ) and convert into hydroxyl radicals  $\text{OH}^{\cdot}$ . Electrons react

with molecular oxygen to form superoxide ions ( $\text{O}_2^{\cdot-}$ ), which can further react with hydrogen ions to produce hydrogen peroxide ( $\text{H}_2\text{O}_2$ ). Superoxide and  $\text{H}_2\text{O}_2$  radicals then combine to create more  $\text{OH}^{\cdot}$  (potent oxidizing agents that break down organic pollutants into harmless products).<sup>99</sup> These ROS, along with photogenerated holes, attack the organic pollutants, forming oxidized intermediates that undergo fragmentation toward partial or complete mineralization ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ , and inorganic ions). The process of heterogeneous photocatalysis involving ZnO as the catalyst operates as follows (eqn (2)–(12)).<sup>70,100</sup>



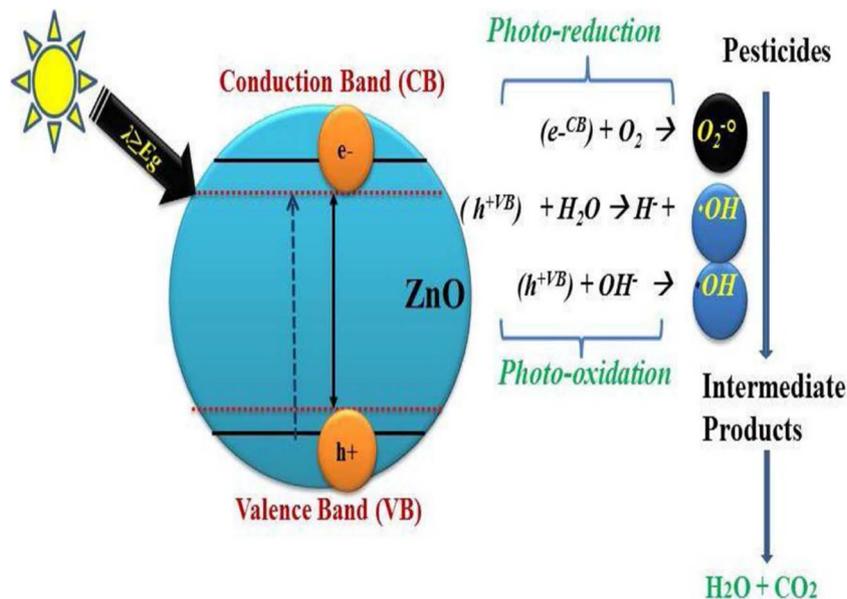
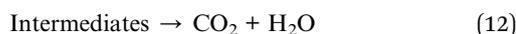
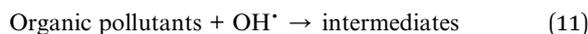


Fig. 7 Photocatalytic degradation mechanism at the surface of ZnO. This figure has been reprinted with permission from ref. 97, Elsevier, copyright 2020.



In case of pesticides remediation using ZnO, the pesticides undergo photolysis, a process in which UV-visible light breaks down their large molecules into smaller and simpler ones. During this process, photons are absorbed by pesticide molecules or surrounding species (such as water or sensitizers), leading to bond cleavage. For example, when water absorbs high-energy photons, it can undergo photolysis:  $\text{H}_2\text{O} + h\nu \rightarrow \text{OH}^\bullet + \text{H}^\bullet$ . These highly reactive  $\text{OH}^\bullet$  and  $\text{H}^\bullet$  radicals can then attack pesticide molecules, leading to their degradation.<sup>101</sup> The fundamental idea behind photocatalysts is their ability to generate electron-hole pairs, which is how  $\text{OH}^\bullet$  are created.<sup>102</sup>

Research has increasingly favored ZnO over other photocatalysts for pesticide degradation, particularly when compared to titanium dioxide ( $\text{TiO}_2$ ), which has been the most extensively studied photocatalyst for contaminant removal. Despite its popularity,  $\text{TiO}_2$  has notable drawbacks, such as low quantum efficiency, rapid charge recombination, and a wide band gap of approximately 3.2 eV, which limits its activation to ultraviolet light. These limitations have prompted a shift in focus toward ZnO as a more effective alternative. With comparable photocatalytic activity and improved UV absorption, ZnO also allows easier modification for visible-light activity.<sup>103</sup> ZnO further distinguishes itself with superior biological, optical, catalytic,

photochemical, and antibacterial properties compared to  $\text{TiO}_2$ , and has shown enhanced photocatalytic efficiency in dye-contaminated aqueous systems.<sup>104</sup> Its higher electron mobility (two orders of magnitude greater than  $\text{TiO}_2$ ),<sup>105</sup> together with versatile synthesis routes enabling diverse morphologies,<sup>106</sup> enhances its applicability. The unique properties of ZnO, including its band structure, wide band gap, highly positive valence band, and the presence of abundant defects, contribute to its effectiveness in degrading persistent pesticides. Additionally, its strong ROS generation and high charge mobility, coupled with its low cost and non-toxic nature, position ZnO as a superior photocatalyst compared to many alternatives, as listed in Table 5. Unlike traditional treatment methods, ZnO photocatalysts stand out because they do not produce secondary pollutants, require no external chemicals and operate without high energy inputs. Their capacity to harness natural sunlight renders the process low-carbon and particularly suitable for decentralized or rural wastewater systems, where energy resources may be limited.

## 7. Methods to enhance photocatalytic properties of ZnO and its nanomaterials

The photocatalytic performance of ZnO nanoparticles is determined by their synthesis technique. The hydrothermal and sol-gel techniques produce extremely crystalline, uniform ZnO with great efficiency but require longer processing durations. Chemical precipitation is less expensive and more environmentally friendly than solvothermal synthesis, which generates high-purity ZnO but requires careful control and a lot of energy. Green synthesis provides an environmentally friendly alternative with middling efficiency (Table 6). Other approaches,



Table 5 Comparative analysis of ZnO with other photocatalysts: pros and cons for pesticides degradation

Photocatalyst	Advantages of ZnO	Disadvantages of ZnO	Ref.
ZnO vs. TiO <sub>2</sub>	<ul style="list-style-type: none"> <li>• Higher quantum efficiency</li> <li>• More oxygen vacancies (stronger ROS)</li> <li>• Stronger oxidative holes (higher valence band)</li> <li>• Better adsorption of polar pesticides</li> <li>• Faster electron mobility</li> </ul>	<ul style="list-style-type: none"> <li>• TiO<sub>2</sub> is more stable under acidic/basic conditions</li> <li>• ZnO can undergo photocorrosion</li> </ul>	107
ZnO vs. Fe <sub>2</sub> O <sub>3</sub>	<ul style="list-style-type: none"> <li>• Fe<sub>2</sub>O<sub>3</sub> has very poor charge mobility</li> <li>• ZnO has faster electron transfer</li> <li>• Fe<sub>2</sub>O<sub>3</sub> absorbs visible light but produces very weak ROS</li> </ul>	<ul style="list-style-type: none"> <li>• Fe<sub>2</sub>O<sub>3</sub> is magnetically recoverable</li> </ul>	108
ZnO vs. spinel ferrites (ZnFe <sub>2</sub> O <sub>4</sub> , CoFe <sub>2</sub> O <sub>4</sub> )	<ul style="list-style-type: none"> <li>• Ferrites have extremely high recombination</li> <li>• ZnO produces stronger <sup>•</sup>OH</li> <li>• Ferrites often require composites to work well</li> </ul>	<ul style="list-style-type: none"> <li>• Ferrites are magnetically recoverable</li> </ul>	109
ZnO vs. g-C <sub>3</sub> N <sub>4</sub>	<ul style="list-style-type: none"> <li>• g-C<sub>3</sub>N<sub>4</sub> alone is weak under UV</li> <li>• ZnO produces stronger oxidative holes</li> <li>• ZnO adsorbs pesticide molecules more strongly (especially polar pesticides)</li> </ul>	<ul style="list-style-type: none"> <li>• g-C<sub>3</sub>N<sub>4</sub> works better under visible light alone</li> <li>• ZnO needs UV or doping to shift into the visible region</li> </ul>	110
ZnO vs. WO <sub>3</sub>	<ul style="list-style-type: none"> <li>• WO<sub>3</sub> has a very low conduction band (cannot generate <sup>•</sup>O<sub>2</sub><sup>-</sup> radicals)</li> <li>• ZnO can produce both <sup>•</sup>OH and <sup>•</sup>O<sub>2</sub><sup>-</sup> which leads to more complete pesticide mineralization</li> <li>• ZnO offers a higher degradation rate for chlorinated pesticides</li> </ul>	<ul style="list-style-type: none"> <li>• WO<sub>3</sub> is more stable in acidic conditions</li> </ul>	111
ZnO vs. Ag-based photocatalysts	<ul style="list-style-type: none"> <li>• ZnO is cheap, non-toxic</li> <li>• Ag is expensive and toxic, risk of Ag<sup>+</sup> leaching</li> <li>• Ag nanoparticles can deactivate due to oxidation</li> </ul>	<ul style="list-style-type: none"> <li>• Ag-based catalysts can show better visible-light activity</li> </ul>	112

including microwave-assisted, electrochemical, sonochemical, spray pyrolysis, and combustion, offer greater versatility by altering particle size, crystallinity, and overall photocatalytic activity.

However, synthesized ZnO still faces several intrinsic limitations that hinder its photocatalytic efficiency. One of the primary challenges is the rapid recombination of photogenerated electron-hole pairs, which significantly reduces the number of charge carriers reaching the catalyst surface. This recombination not only slows down the redox reactions but also leads to energy loss in the form of heat. Additionally, ZnO's wide band gap restricts its light absorption to the UV region, limiting its effectiveness under visible light irradiation.<sup>9</sup> Another drawback is the tendency of ZnO nanoparticles to agglomerate, which decreases the effective surface area available for light absorption and reactive species generation. These larger aggregates also reduce the photon flux within the reaction medium, further lowering the photocatalytic activity. Moreover,

charge carrier recombination within these aggregates contributes to a significant decline in overall performance.

To overcome these limitations, various strategies have been developed to enhance the photocatalytic performance of ZnO. These include modifying its physical structure to increase surface area, doping with noble or non-noble metals to alter electronic properties, and forming heterojunctions with other semiconductors to promote charge separation. The deliberate introduction of structural defects has also been shown to improve light absorption and trap charge carriers.<sup>121</sup> Additionally, coupling ZnO with plasmonic and photothermal materials can extend its light absorption range into the visible spectrum and enhance photocatalytic efficiency through localized surface plasmon resonance.<sup>122</sup>

## 7.1. Doping to modify photocatalysts

### 7.1.1. Doping with metal.

Various transition metals such as silver (Ag), manganese (Mn), nickel (Ni), copper (Cu), and iron



Table 6 Influence of synthesis approach on the photocatalytic activity of ZnO nanomaterials

Method	Photo-catalyst	Band gap (eV)	Efficiency	Advantage/limitation	Ref.
Hydrothermal	ZnO NPs, nitrogen-doped ZnO	3.19	99.60	High crystallinity and purity, but requires extended processing times	113 and 114
Sol-gel	Nanosized ZnO	3.30	99.00	Simple and adaptable; produces uniform materials but may take longer to dry	115 and 116
Chemical precipitation	Nanosized ZnO	3.20	97.36	Low-cost, eco-friendly, and efficient; produces highly active ZnO photocatalysts	117
Solvothermal	Nanosized ZnO	2.99	92.00	The solvothermal method produces high-purity, uniform ZnO photocatalysts but demands high energy, long reaction times, and precise control	118 and 119
Green synthesis	Nanosized ZnO	3.20	87.00	Environmentally friendly, low-cost, and highly efficient; variability in quality may occur depending on the plant source	120

(Fe) have been utilized as dopants in ZnO; however, studies have shown that only optimal concentrations result can enhanced photocatalytic activity.<sup>123</sup> By reducing the band gap, doping with metal enables ZnO to absorb visible light, which makes up 40–45% of sunlight. Furthermore, doping modifies the photocatalyst's optical and electrical characteristics.<sup>124</sup> Consequently, ZnO doped with different metals is used in a variety of industries, such as paints, chemicals, tires, ceramics, pharmaceuticals, and agriculture. For example, scientists investigated the removal of chromium(vi) using a biosynthesized Ag-doped ZnO nanocomposite that contained activated carbon. After 60 hours of treatment, they discovered that the optimal adsorption took place at pH 2.5, with a concentration of 40 ppm of heavy metal ions.<sup>125</sup> When Fe<sup>3+</sup> ions are added to ZnO nanoparticles, more Zn<sup>2+</sup> is produced, which increases surface defects and improves degradation performance.<sup>126</sup> Ag-doped ZnO nanoparticles also show that noticeable surface defects improve degradation performance.<sup>127</sup> Additional finding also suggests that aluminum (Al) increases hydrophilicity and surface defects in ZnO while cathodically shifting the quasi-Fermi level. By creating smaller particles, Al doping also increases specific surface area, which promotes the breakdown of organic pollutants.<sup>128</sup> According to a study, hydroxyl ion absorption on nanoparticle surfaces is increased when high concentrations of magnesium (Mg) dopant are added to ZnO. As a result, carriers are efficiently trapped by abundant Mg<sup>2+</sup> ions, which lowers recombination and speeds up degradation.<sup>129</sup> At room

temperature, Cu-doping with ZnO increases the effectiveness of both photocatalytic and antioxidant activities. These nanoparticles are also versatile for wastewater treatment applications due to their pH-dependent photocatalytic properties.<sup>130</sup> It has been demonstrated that doping ZnO photocatalyst with rare earth metals, such as lanthanum (La), increases its efficiency. A study using La-doped ZnO photocatalysts to degrade 2-chlorophenol (2-CP) found that the degradation efficiency was higher when the catalyst dose was 10 mg and the irradiation period was 2 hours at an ideal pH of 2.<sup>131</sup> Table 7 contains the list of some metal dopants that are used with ZnO for photocatalytic applications.

**7.1.2. Doping with non-metal.** Non-metal dopants such as carbon (C), nitrogen (N), fluorine (F), iodine (I), and sulphur (S) improve ZnO composite photocatalytic efficiency under visible light. They modify the bandgap by replacing oxygen vacancies, increasing surface oxygen vacancy defects. Their minute size enables diffusion through lattice interstices, binding to atoms *via* oxidation to aid the process.<sup>136</sup> In contrast to metal ion dopants, non-metal ions have a lower likelihood of forming recombination centres. Therefore, they are more effective in enhancing photocatalytic activities. In the same context,<sup>137</sup> explored the impact of N-doping on ZnO nanoparticles for degrading methylene blue dye, and observed superior efficacy compared to pure ZnO under both UV and visible light. The author explains how N-doping lowered excitation energy, creating new energy states near ZnO's VB, thereby increasing

Table 7 Impact of metal dopants on improving the photodegradation capabilities of ZnO

Doping metal	Efficiency of ZnO (%)	Efficiency of doped-ZnO (%)	Contaminant degraded	Ref.
Ag	90.00	98.00	Carbaryl	132
La	75.85	83.92	2-Chlorophenol	131
Cu	58.50	96.97	Diazinon	133
Pd	38.00	82.00	Acetamiprid	134
Pd + graphene oxide	38.00	98.00		
WO <sub>3</sub>	27.00	78.00	2,4-Dichlorophenoxyacetic acid	135



electron-hole pair production under visible light. This narrower band gap facilitated more straightforward electron transfer and intensified oxygen vacancies, facilitating rapid carrier separation and enhancing photocatalytic activity over three cycles. In a separate study,<sup>138</sup> synthesized N-doped ZnO composites using a sol-gel combustion method, demonstrating excellent performance in degrading Eosin Yellow under visible light. XPS analysis confirmed the formation of N-Zn bonds, while improved photo response in the visible region resulted from N-induced lattice defects. Catalytic activity was increased by the composite's high surface area and porosity, which allowed for improved dye-catalyst contact. Likewise,<sup>139</sup> investigated the photocatalytic degradation of *p*-aminobenzoic acid using C-doped ZnO nanorods as a catalyst. A cost-effective precipitation method was used to produce nanorods. When exposed to sunlight, 97% of the *p*-aminobenzoic acid was degraded under ideal circumstances (0.5 g per L catalyst dosage). The nanorods maintained their high photodegradation efficiency and showed signs of reusability.

In another analysis,<sup>140</sup> investigated I-modified ZnO's antibacterial qualities in the presence of light. With its cage-like structure and abundance of oxygen defects, the composite efficiently separated photoexcited charge carriers to produce more free radicals. Furthermore, iodine and the cage structure decreased electron-hole pair recombination, and photocatalytic performance was greatly enhanced by a smaller grain size. Additionally, by using differently shaped S-doped and F-doped ZnO,<sup>141</sup> the photocatalytic degradation of methylene blue was compared. Under visible-light photocatalysis, these dopants changed the electron mobility rate and band gap structure. After six hours of exposure to visible light, S-doped ZnO showed better photoactivity (total removal) than F-doped ZnO. This was because S-doped ZnO had a smaller band gap and was more efficient at absorbing solar energy, which inhibited electron-hole recombination and increased photosensitive activity.

## 7.2. ZnO composites

Pairing ZnO with semiconductors can significantly boost its photocatalytic activity. This approach creates nanocomposites that improve light absorption, reduce recombination of charge carriers, and enhance charge separation. Combining ZnO with semiconductors that have different band gaps has shown great potential for improving photocatalysis.<sup>121</sup> Ref. 142 studied that longer-lived charge carriers in these composites lead to more effective photo-degradation. While<sup>143</sup> showed that adding CdS to ZnO changes its growth pattern, resulting in flower-like structures. The defects in the ZnO-CdS composite trap charge carriers, which reduce recombination and significantly enhance its ability to degrade rhodamine B (RhB).

Corresponding ref. 144 compared the degradation rate of chlorpyrifos, using  $\text{MoO}_3/\text{Al}_2\text{O}_3$  and  $\text{ZnO}\cdot\text{MoO}_3/\text{Al}_2\text{O}_3$ . The degradation kinetics showed that  $\text{ZnO}\cdot\text{MoO}_3/\text{Al}_2\text{O}_3$  (95%) degraded chlorpyrifos 8 times faster than  $\text{MoO}_3/\text{Al}_2\text{O}_3$  (86%). In addition, intermediate products of chlorpyrifos were not identified by GC/MS analysis, which could be more toxic than chlorpyrifos itself, indicating a thorough mineralization of the

pesticide,<sup>145</sup> demonstrated that Fe-ZnO nanocomposite achieved 93.5% degradation of chlorpyrifos in 60 minutes under UV light. The enhanced performance is attributed to its reduced optical band gap and magnetic properties, making it effective for visible light photocatalysis. According to ref. 146, the  $\beta\text{-CD-CuO/ZnO}$  nanocomposite exhibits improved photocatalytic efficiency, degrading methylene blue by up to 89.15% and malachite green by 79.90% in 180 minutes when exposed to radiation. Its capacity to encapsulate pollutants in its hydrophobic interior and enhanced electron-hole recombination are the reasons for its superior performance.

Another nanocomposite,  $\text{ZnO/BaBi}_2\text{O}_6$ , demonstrated noticeably greater rates of methyl orange, RhB, and eosin degradation than pure ZnO, and it was able to degrade methyl orange by over 95% in 40 minutes. With a band gap energy of 2.89 eV and stability after five reuse cycles,  $\text{h}^+$  and radical  $\text{O}^{2-}$  were found to be important components in the degradation process.<sup>147</sup> A sustainable biogenic process was used to create the ZnO/multi-walled carbon nanotubes composite, which exhibits remarkable photocatalytic efficiency in eliminating hazardous pollutants and has the potential to be used for environmental remediation with high reusability.<sup>148</sup> In another study,<sup>149</sup> chemical precipitation was used, which creates free radicals at the conduction band (superoxide ion) and valence band (hydroxyl group) levels in  $\text{Ag/Fe}_2\text{O}_3/\text{ZnO}$  heterostructure, producing effective photocatalysis and superhydrophobic qualities. In another study, Cu-MOF/ZnO nanocomposite was found to exhibit high photocatalytic efficiency, degrading rose bengal by 97.4% in 45 minutes when exposed to natural sunlight. It is a promising material for environmental remediation because it retains stability and effective performance for up to five reuse cycles.<sup>150</sup>

## 7.3. Impacts of structural defect

The structure and form of ZnO, or morphology, have a significant impact on its photocatalytic capabilities. For example, although rods have a larger surface area, researchers have found that hexagonal or spherical ZnO nanoparticles often perform better than rod-shaped ones.<sup>151</sup> In other cases, researchers have also emphasized the enhancement of the performance of needle-shaped<sup>152</sup> or nanowire ZnO.<sup>153</sup> Moreover, studies have also been examining structural flaws in addition to the morphology of ZnO nanoparticles. In particular, oxygen defects have emerged as a major focus of current photocatalysis research.<sup>154</sup>

In this context,<sup>155</sup> investigated ZnO nanoparticles and how structural defects influence their photocatalytic efficiency in degrading RhB dye under UV light. Their findings revealed that the catalyst with the highest number of defects exhibited the greatest degradation performance. This improvement was attributed to an increased specific surface area resulting from the presence of more defects. Research suggests that zinc and oxygen vacancies can act as traps for charge carriers, which helps prevent the recombination of electron-hole pairs and thus enhances photocatalytic activity. For instance, ultrathin  $\text{ZnO/Al}_2\text{O}_3$  nanosheets with a high density of oxygen defects were shown to rapidly degrade tetracycline and RhB dye within



150 minutes, achieving degradation rates of 88.4% and 76.9%, respectively.<sup>156</sup> Similarly,<sup>157</sup> synthesized ZnO/NiO nanoparticles with oxygen vacancies using solvothermal and high-temperature reduction methods to enhance their photocatalytic performance. The best solar-driven photocatalytic performance was shown by OZN-10, which almost degraded methylene blue due to its small size and large surface area. Because of its distinct structure and surface flaws, its efficiency was roughly double that of pure ZnO.

Ar-ZnO, which had the highest concentration of oxygen vacancies, showed a reduced bandgap of 3.03 eV, according to an experiment conducted by ref. 158 in which flower-like ZnO photocatalysts with porous nanosheets were prepared under various calcination atmospheres. This enhancement resulted in a 94.5% degradation of methyl orange under UV light in 30 minutes, with a degradation rate constant 3.2 times higher than ZnO calcined in air. Moreover, defect engineering in ZnO ceramics improved electrical conductivity and reduced thermal conductivity, enhancing their thermoelectric performance by increasing oxygen vacancies.<sup>159</sup> Oxygen defects are known to boost photocatalytic efficiency and indicate that more defects lead to a larger surface area. However, some research suggests that oxygen and zinc defects can sometimes negatively affect ZnO's photocatalytic performance by serving as recombination centres, which reduces its effectiveness.<sup>98</sup>

## 8. Remediation of pesticides by ZnO photocatalysts

Over the years, there has been significant focus on utilizing ZnO and its nanoparticles as photocatalysts to break down pesticides. The majority of research on ZnO as a catalyst indicates that its photocatalytic efficacy in aqueous environments is heavily influenced by factors such as light source and intensity, reaction conditions, catalyst type, presence of oxidizing agents, solution pH, temperature, and pesticide concentration.<sup>160</sup> Ref. 161 investigated the impact of the synthesis medium (ethanol and water) on the efficiency of ZnO/carbon xerogel photocatalysts to degrade 4-chlorophenol and bisphenol A. Carbon xerogel was chosen due to its electrical conductivity, surface area, and porosity. The maximum degradation rates achieved were 88% for 4-chlorophenol and 78% for bisphenol A after 5 hours. The photocatalytic mechanism relies heavily on the generation of OH<sup>•</sup>, and the materials remained stable for up to three reuse cycles. The result shows that hybrid systems have shown greater efficiency in recent years when compared to pure systems. Another study<sup>162</sup> shows that the GO-ZnO nanocomposite is excellent for breaking down the organophosphate pesticide quinalphos in water when exposed to UV light. This approach performs better than graphene GO nanosheets and ZnO nanoflowers. The nanocomposite exhibits pseudo-first-order kinetics and reaches a 98% degradation rate in 45 minutes at pH 6. Researchers found that OH<sup>•</sup> were the main active species in the degradation process after identifying smaller, innocuous byproducts through LC-MS analysis. The produced nanocomposite offers a workable way to degrade

pesticides without requiring neutralization before being released into water bodies because it is stable and reusable for at least five cycles. Similarly,<sup>163</sup> found that fungicide residues (difenoconazole and thifluzamide) in soil samples can be efficiently removed by chitosan-ZnO nanoparticles, which remain for days in the absence of these nanoparticles. In contrast, no activity was seen with chitosan-ZnO nanoparticle; photocatalytic studies demonstrated a significant increase in activity over a predetermined period. This indicates promising environmental remediation solutions and emphasizes the critical role that chitosan-ZnO nanoparticles play in promoting pesticide degradation.

Ref. 164 discovered that the pesticide chlorpyrifos is efficiently degraded by Ni-doped ZnO-TiO<sub>2</sub> nanocomposites. These nanocomposites have a large surface area, distinct crystallinity, and good optical qualities. They convert chlorpyrifos into innocuous byproducts and function well in both visible and ultraviolet light. When exposed to UV light instead of darkness, the electrochemical analysis performed better. Degradation proceeds according to pseudo-first-order kinetics, with UV light causing higher rates (0.0221 min<sup>-1</sup>) than visible light (0.0088). In related work<sup>165</sup> using a hydrothermal process, synthesize a SWAC/ZrO<sub>2</sub>-ZnO nanocomposite that efficiently breaks down 100 ppm of chlorpyrifos under UV light in 50 minutes at pH 6. A crystal size of 39.41 nm was confirmed by characterization techniques, and LC-MS analysis revealed that chlorpyrifos was fragmenting into smaller pieces. DFT simulations indicated the formation of reactive hydrogen bonds, and the degradation proceeded according to pseudo-first-order kinetics. According to<sup>166</sup> study the NiO-ZnO nanocomposite's photocatalytic performance for breaking down the herbicide bentazon under UV light after 100 minutes of exposure. The study found that bentazon had a 70% degradation efficiency. This suggests that the nanocomposite may be useful in breaking down pesticides in water.<sup>167</sup> Investigated the photocatalytic degradation of the pesticide lambda-cyhalothrin (LCY) using cerium-doped ZnO nanocomposites in the presence of natural sunlight. The coprecipitation method was used to synthesize Ce-ZnO, and methods like PXRD, SEM, FTIR, and EDAX were used to characterize its properties. The nanocomposites demonstrated high photocatalytic efficiency, degrading approximately 92% of LCY under ideal conditions (100 ppm initial concentration, 20 mg catalyst dose, and a UV index of 10–11) after three hours of exposure to sunlight. The average crystallite size was 31.42 nm. A pseudo-first-order kinetic model described the degradation.

The efficiency of photocatalytic degradation, as outlined in Table 8, is influenced by several factors, including the type of catalyst, the structure of the pesticide, the source of irradiation, and the conditions of the reaction. Modified ZnO systems, which may be doped, defect engineered, or formed as composites, demonstrate enhanced activity due to better charge separation and an optimized band structure. When parameters such as catalyst dosage, pH, and exposure time are carefully controlled, these well-designed ZnO catalysts can achieve rapid pesticide removal, typically exceeding 80–95% efficiency under UV or visible light. Ultimately, the interplay between the light source and the design of the catalyst plays a crucial role in



Table 8 Degradation of different pesticides using ZnO nano-photocatalyst

Photocatalyst	Pesticide	Efficiency (%)	Light source	Reaction condition	Ref.
ZnO/ $\alpha$ -Fe <sub>2</sub> O <sub>3</sub>	Carbamate	89	Solar light	Pesticide dose = 5 g L <sup>-1</sup> , catalyst dose = 1 g L <sup>-1</sup> , time = 3 h, pH = 8.5	18
La-doped ZnO	2-Chlorophenol	83.92	Visible light	Pesticide dose = 10 ppm, catalyst dose = 10 mg, time = 2 h	131
Ag-doped ZnO	Carbaryl	98	UV light	Pesticide dose = 5 ppm, photocatalyst = 5 mg L <sup>-1</sup> , time = 60 min	132
ZnO NPs	<i>p</i> -Nitrophenol	92	UV light	Pesticide dose = 20 mg L <sup>-1</sup> , catalyst dose = 1.5 g L <sup>-1</sup> , time = 180 min	118
ZnO	Lambda-cyhalothrin	87	Solar light	Pesticide dose = 20 mL of 100 ppm, ZnO = 50 ppm, temperature = 31 °C, time = 30 min (dark), 60 min (light)	168
Fe-ZnO	Chlorpyrifos	67	Solar light	Pesticide dose = 5 mg L <sup>-1</sup> , pH = 8, time = 140 min	169
Cu-ZnO heterostructure	Chlorpyrifos	95	Solar light	Pesticide dose = 200 mg L <sup>-1</sup> , catalyst dose = 3 g L <sup>-1</sup> , pH = 6.0, time = 240 min	170
Ce-ZnO nanocomposites	Lambda-cyhalothrin	92	Solar light	Pesticide dose = 100 ppm, catalyst dose = 20 mg, time = 3 h	167
Pbi-ZnO-g-C <sub>3</sub> N <sub>4</sub>	Atrazine	85.3	Visible light	Catalyst dose = 216.40 g L <sup>-1</sup> , time = 260 min	171
ZnO/rGO	Metalaxyl	90.25	UV light	Pesticide dose = 10 mg L <sup>-1</sup> , catalyst dose = 0.75 g L <sup>-1</sup> , pH = 7, time = 120 min, UV intensity = 220 MW cm <sup>-2</sup>	172
ZnO/rGO	Metalaxyl (real agricultural runoff)	51.17	UV light	Pesticide dose = 10 mg L <sup>-1</sup> , catalyst dose = 0.75 g L <sup>-1</sup> , pH = 7, time = 120 min, UV intensity = 220 MW cm <sup>-2</sup>	
rGO/Fe <sub>3</sub> O <sub>4</sub> /ZnO	Metalaxyl	92.11	Visible light	Time = 120 min, order of reaction = 1 <sup>st</sup> order kinetic model	173
ZnO·WO <sub>3</sub> composite	Paraquat dichloride	88.3	UV light	Pesticide dose = 35 mg L <sup>-1</sup> , catalyst dose = 0.04 g, pH = 9, temperature = 40 °C, cycles of reaction = 3	174
ZnO	Methamidophos	86.66	UV light	Pesticide dose = 50 mg L <sup>-1</sup> , catalyst dose = 3 g L <sup>-1</sup> with ultra-pure water	175
ZnO	Methamidophos	57.95	UV light	Pesticide dose = 50 mg L <sup>-1</sup> , catalyst dose = 3 g L <sup>-1</sup> with river water	
Fe <sub>2</sub> O <sub>3</sub> -ZnO	Profenofos	100	Dark	Pesticide dose = 1825 mg L <sup>-1</sup> , time = 60 min	176
CuO-ZnO nanocomposite	Profenofos	100	UV light	Pesticide dose = 1215 mg L <sup>-1</sup> , time = 80 min	177
ZnO/Cu/GO	Quinalphos	99	Visible light	Pesticide dose = 40 ppm, catalyst dose = 3 mg L <sup>-1</sup> , time = 20 min, pH = neutral	178
PANI/ZnO-CoMoO <sub>4</sub>	Imidacloprid	97	Visible light	Pesticide dose = 4.5 ppm, catalyst dose = 163.5 mg, time = 180 min, pH = 4	179
ZnO/rGO	Dimethoate	99	UV light	Pesticide dose = 5 mg L <sup>-1</sup> , catalyst dose = 50 mg, light intensity = 2.45 mW cm <sup>-2</sup> , time = 180 min	180
ZnO/CoFe <sub>2</sub> O <sub>4</sub>	Imidacloprid	98.1	Visible light	Pesticide dose = 5 ppm, catalyst dose = 0.05 g, pH = 10	181

determining the degradation performance across various pesticide classes.

## 9. Conclusion

This document reveals the distinctive electrical and structural properties of ZnO-based photocatalysts, which include a direct band gap, favorable band-edge positions, and defect-induced donor states. These characteristics contribute to their exceptional ability to degrade various pesticide contaminants. Although other photocatalytic materials offer certain benefits,

ZnO surpasses them in oxidative strength, charge mobility, efficiency of electron-hole separation, and surface reactivity, especially when exposed to UV light. Additionally, recent advancements in ZnO engineering such as metal and non-metal doping, defect manipulation, heterojunction formation, plasmonic coupling, and photothermal integration have substantially enhanced its light-harvesting efficiency, charge transfer dynamics, and ROS generation. These enhancements effectively mitigate ZnO's inherent challenges, including photocorrosion and limited sensitivity to visible light, thereby improving its applicability in real-world wastewater treatment scenarios.



This document specifically pinpoints the potential environmental benefits of ZnO based nanomaterials in agriculture, particularly through photocatalytic processes that can eliminate pesticide-laden runoff, thereby minimizing groundwater contamination and protecting irrigation sources and aquatic ecosystems. This not only supports safe food production but also alleviates ecological pressures on soil microorganisms, aquatic flora, and beneficial insect populations. As the global community strives for low-impact and energy-efficient water treatment solutions, ZnO-based photocatalytic systems emerge as a promising avenue for developing sustainable, climate-resilient, and environmentally responsible remediation technologies.

Despite these promising results, current research on ZnO nanomaterials for wastewater treatment, particularly in pesticide degradation, reveals several critical areas or limitations for further exploration to improve their effectiveness and practical application. One key challenge is to enhance the long-term stability and reusability of ZnO photocatalysts, which are crucial for achieving sustainable and cost-effective solutions. While ZnO has shown potential in laboratory settings, there is a significant gap in studies that combine ZnO photocatalysis with other wastewater treatment techniques, such as biological treatments or membrane filtration, creating hybrid systems that integrate these methods could optimize pollutant removal and broaden the application of ZnO in real-world scenarios. Additionally, research into combining ZnO with 2D materials like black phosphorus and carbon nitride could enhance photocatalytic efficiency by improving light absorption and promoting effective charge separation, addressing some of ZnO's inherent limitations.

Future research should concentrate on integrating these strategies by advancing the design of ZnO nanostructures through controlled defects, facet engineering, and lattice strain, which can improve charge separation and broaden activity into the visible light spectrum. Additionally, combining ZnO with plasmonic metals, carbon materials, or narrow band-gap semiconductors can enhance solar absorption and increase degradation efficiency.

The photocorrosion of ZnO in acidic environments necessitates ongoing efforts to enhance its stability, with effective strategies including surface passivation, core-shell structures, and protective coatings. Additionally, green synthesis methods utilizing plant extracts or biopolymers promote environmentally friendly and scalable production processes. The use of immobilized ZnO in forms such as membranes, coatings, and 3D-printed structures is expected to become increasingly prevalent, enabling catalyst recovery and sustained operation in practical applications. Furthermore, integrating ZnO with photothermal materials, adsorption components, solar concentrators, or LED-powered systems presents promising opportunities for the remediation of agricultural runoff in real-world settings.

## Conflicts of interest

Authors declare no conflict of interest.

## Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

## Acknowledgements

Dr Haji Muhammad expresses his gratitude to TUBITAK for granting him a visiting scientist fellowship under the "2221-Visiting Scientists Fellowship Programme 2023/6." Additionally, Dr Asma Siddiqui extends her thanks to TWAS/TUBITAK for awarding her a fellowship through the 2216B Programme 2024/01.

## References

- 1 M. Tudi, *et al.*, Agriculture development, pesticide application and its impact on the environment, *Int. J. Environ. Res. Publ. Health*, 2021, **18**(3), 1112.
- 2 P. Kumar, *et al.*, Impact of pesticides application on aquatic ecosystem and biodiversity: a review, *Biol. Bull.*, 2023, **50**(6), 1362–1375.
- 3 S. Bose, *et al.*, Microbial degradation of recalcitrant pesticides: a review, *Environ. Chem. Lett.*, 2021, **19**(4), 3209–3228.
- 4 L. Rani, *et al.*, An extensive review on the consequences of chemical pesticides on human health and environment, *J. Cleaner Prod.*, 2021, **283**, 124657.
- 5 J. dos Santos Mendonça, *et al.*, Mutagenicity, hepatotoxicity, and neurotoxicity of glyphosate and fipronil commercial formulations in Amazon turtles neonates (*Podocnemis expansa*), *Sci. Total Environ.*, 2023, **898**, 165529.
- 6 J. H. O'Driscoll, *et al.*, A risk ranking of pesticides in Irish drinking water considering chronic health effects, *Sci. Total Environ.*, 2022, **829**, 154532.
- 7 W. Boedeker, *et al.*, The global distribution of acute unintentional pesticide poisoning: estimations based on a systematic review, *BMC Public Health*, 2020, **20**(1), 1–19.
- 8 D. Rawtani, *et al.*, Nanotechnology-based recent approaches for sensing and remediation of pesticides, *J. Environ. Manage.*, 2018, **206**, 749–762.
- 9 F. Abdullah, N. A. Bakar and M. A. Bakar, Current advancements on the fabrication, modification, and industrial application of zinc oxide as photocatalyst in the removal of organic and inorganic contaminants in aquatic systems, *J. Hazard Mater.*, 2022, **424**, 127416.
- 10 O. Ounas, B. Lekhlif and J. Jamal-eddine, The facile immobilization of ZnO into a polymer surface for photodegradation of organic contaminants, *Mater. Today: Proc.*, 2020, **30**, 816–822.
- 11 K. Pszczolińska, H. Barchańska and D. Lalek, Comprehensive multiresidue chromatographic methods for monitoring pesticides in agricultural areas and corresponding plant protection zones, *Environ. Pollut.*, 2024, **344**, 123422.



- 12 R. de Oliveira, W. da Silva Martini and A. C. Sant'Ana, Combined effect involving semiconductors and plasmonic nanoparticles in photocatalytic degradation of pesticides, *Environ. Nanotechnol. Monit. Manag.*, 2022, **17**, 100657.
- 13 F. P. Carvalho, Pesticides, environment, and food safety, *Food Energy Secur.*, 2017, **6**(2), 48–60.
- 14 C. Chang, *et al.*, Current pesticide profiles in blood serum of adults in Jiangsu Province of China and a comparison with other countries, *Environ. Int.*, 2017, **102**, 213–222.
- 15 M. Tudi, *et al.*, Exposure routes and health risks associated with pesticide application, *Toxics*, 2022, **10**(6), 335.
- 16 M. Singhal, *et al.*, Microalgae based sustainable bioremediation of water contaminated by pesticides, *Biointerface Res. Appl. Chem.*, 2021, **12**, 149–169.
- 17 G. K. Sidhu, *et al.*, Toxicity, monitoring and biodegradation of organophosphate pesticides: a review, *Crit. Rev. Environ. Sci. Technol.*, 2019, **49**(13), 1135–1187.
- 18 A. Dehghan, *et al.*, Green synthesis of ZnO/ $\alpha$ -Fe<sub>2</sub>O<sub>3</sub> nanophotocatalyst for efficient removal of carbamate pesticides in wastewater: optimization, mineralization, and financial analysis, *Korean J. Chem. Eng.*, 2024, **41**(1), 249–269.
- 19 M. Ahmad, *et al.*, Photocatalytic Degradation of Deltamethrin in Drinking Water Under Visible Light by Using ZnO and TiO<sub>2</sub>, *International Journal of Innovations in Science and Technology*, 2025, **7**, 57–67.
- 20 D. Kathuria, *et al.*, A Review on Methods for the Elimination of Imidacloprid: 2018–2022, *ChemistrySelect*, 2023, **8**(34), e202302293.
- 21 S.-M. Lam, *et al.*, Sunlight responsive WO<sub>3</sub>/ZnO nanorods for photocatalytic degradation and mineralization of chlorinated phenoxyacetic acid herbicides in water, *J. Colloid Interface Sci.*, 2015, **450**, 34–44.
- 22 J. Fenoll, *et al.*, Semiconductor-sensitized photodegradation of s-triazine and chloroacetanilide herbicides in leaching water using TiO<sub>2</sub> and ZnO as catalyst under natural sunlight, *J. Photochem. Photobiol., A*, 2012, **238**, 81–87.
- 23 S. Tariq, G. Chotana and A. Rashid, Photocatalytic degradation of paraquat dichloride in the presence of ZnO. WO<sub>3</sub> composite, *Int. J. Environ. Sci. Technol.*, 2022, **19**(4), 2583–2598.
- 24 Q. Liu, *et al.*, Phototransformation of phosphite induced by zinc oxide nanoparticles (ZnO NPs) in aquatic environments, *Water Res.*, 2023, **245**, 120571.
- 25 W. J. McCormick, *et al.*, Enhanced monitoring of photocatalytic reactive oxygen species: using electrochemistry for rapid sensing of hydroxyl radicals formed during the degradation of coumarin, *J. Phys. Chem. A*, 2023, **127**(23), 5039–5047.
- 26 S. Ali, *et al.*, Environmental and health effects of pesticide residues, *Sustainable Agriculture Reviews 48: Pesticide Occurrence, Analysis and Remediation*, 2021, vol. 2 analysis, pp. 311–336.
- 27 A. Bagheri, N. Emami and C. A. Damalas, Monitoring point source pollution by pesticide use: an analysis of farmers' environmental behavior in waste disposal, *Environment, Development and Sustainability: A Multidisciplinary Approach to the Theory and Practice of Sustainable Development*, 2023, ch. 7, vol. 25, pp. 6711–6726.
- 28 X. Zhu, *et al.*, Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: a review of evidence and processes, *Plant Soil*, 2020, **453**(1), 45–86.
- 29 R. Wang, *et al.*, Cleaner agricultural production in drinking-water source areas for the control of non-point source pollution in China, *J. Environ. Manage.*, 2021, **285**, 112096.
- 30 J. Yang, *et al.*, Characteristics of non-point source pollution under different land use types, *Sustainability*, 2020, **12**(5), 2012.
- 31 R. D. A. Acayaba, *et al.*, Occurrence of pesticides in waters from the largest sugar cane plantation region in the world, *Environ. Sci. Pollut. Res.*, 2021, **28**, 9824–9835.
- 32 E. S. Severo, *et al.*, Ecological risk of pesticide contamination in a Brazilian river located near a rural area: a study of biomarkers using zebrafish embryos, *Ecotoxicol. Environ. Saf.*, 2020, **190**, 110071.
- 33 N. L. Scholz, *et al.*, A perspective on modern pesticides, pelagic fish declines, and unknown ecological resilience in highly managed ecosystems, *Bioscience*, 2012, **62**(4), 428–434.
- 34 K. Pohorecka, *et al.*, The exposure of honey bees to pesticide residues in the hive environment with regard to winter colony losses, *J. Apicult. Sci.*, 2017, **61**(1), 105–125.
- 35 K. R. Hakeem, M. S. Akhtar and S. N. A. Abdullah, *Plant, Soil and Microbes*, Springer, 2016.
- 36 P. Rajak, *et al.*, Agricultural pesticides—Friends or foes to biosphere?, *J. Hazard. Mater. Adv.*, 2023, **10**, 100264.
- 37 M. S. Sankhla, *et al.*, Water contamination through pesticide & their toxic effect on human health, *Int. J. Res. Appl. Sci. Eng. Technol.*, 2018, **6**(1), 967–970.
- 38 M. Ataei and M. Abdollahi, A systematic review of mechanistic studies on the relationship between pesticide exposure and cancer induction, *Toxicol. Appl. Pharmacol.*, 2022, 116280.
- 39 K. G. Bernal-González, *et al.*, Organophosphate-Pesticide-Mediated Immune Response Modulation in Invertebrates and Vertebrates, *Int. J. Mol. Sci.*, 2023, **24**(6), 5360.
- 40 A. Fucic, *et al.*, Reproductive health risks associated with occupational and environmental exposure to pesticides, *Int. J. Environ. Res. Publ. Health*, 2021, **18**(12), 6576.
- 41 W. Lai, Pesticide use and health outcomes: evidence from agricultural water pollution in China, *J. Environ. Econ. Manag.*, 2017, **86**, 93–120.
- 42 A. G. Akerdi and S. H. Bahrami, Application of heterogeneous nano-semiconductors for photocatalytic advanced oxidation of organic compounds: a review, *J. Environ. Chem. Eng.*, 2019, **7**(5), 103283.
- 43 A. Boudebouz, *et al.*, Pesticide residues levels in raw cow's milk and health risk assessment across the globe: a systematic review, *Environ. Adv.*, 2022, **9**, 100266.
- 44 S. Lorn, *et al.*, Pyrethroid susceptibility in *Stomoxys calcitrans* and *Stomoxys indicus* (Diptera: Muscidae) collected from cattle farms in southern Thailand, *Insects*, 2022, **13**(8), 711.



- 45 R. Giugliano, *et al.*, Monitoring of Non-Maximum-Residue-Level Pesticides in Animal Feed: A Study from 2019 to 2023, *Toxics*, 2024, **12**(9), 680.
- 46 S. Bogialli, *et al.*, Development of a multiresidue method for analyzing herbicide and fungicide residues in bovine milk based on solid-phase extraction and liquid chromatography–tandem mass spectrometry, *J. Chromatogr. A*, 2006, **1102**(1–2), 1–10.
- 47 M. Miclean, E. A. Levei and O. Cadar, Organochlorine Pesticides in Dairy Cows' Diet and the Carryover into Milk in NW Romania, *Sustainability*, 2024, **16**(1), 434.
- 48 L. Zhao, *et al.*, The Associations between Organophosphate Pesticides (OPs) and Respiratory Disease, Diabetes Mellitus, and Cardiovascular Disease: A Review and Meta-Analysis of Observational Studies, *Toxics*, 2023, **11**(9), 741.
- 49 J. Kaushal, M. Khatri and S. K. Arya, A treatise on Organophosphate pesticide pollution: current strategies and advancements in their environmental degradation and elimination, *Ecotoxicol. Environ. Saf.*, 2021, **207**, 111483.
- 50 J. Perry, *et al.*, Organophosphate exposure and the chronic effects on farmers: a narrative review, *Rural Remote Health*, 2020, **20**(1), 206–222.
- 51 R. Jayaraj, P. Megha and P. Sreedev, Organochlorine pesticides, their toxic effects on living organisms and their fate in the environment, *Interdiscip. Toxicol.*, 2016, **9**(3–4), 90.
- 52 M. A. Mohammadkhani, *et al.*, Insights into Organochlorine Pesticides Exposure in the Development of Cardiovascular Diseases: A Systematic Review, *Arch. Iran. Med.*, 2023, **26**(10), 592.
- 53 G.-H. Lee and K.-C. Choi, Adverse effects of pesticides on the functions of immune system, *Comp. Biochem. Physiol., Part C: Toxicol. Pharmacol.*, 2020, **235**, 108789.
- 54 S. Moreira, *et al.*, Carbamate pesticides: shedding light on their impact on the male reproductive system, *Int. J. Mol. Sci.*, 2022, **23**(15), 8206.
- 55 A. Chrustek, *et al.*, Current research on the safety of pyrethroids used as insecticides, *Medicina*, 2018, **54**(4), 61.
- 56 I. Holyńska-Iwan and K. Szewczyk-Golec, Pyrethroids: how they affect human and animal health?, *Medicina*, 2020, **56**(11), 582.
- 57 A.-M. Saillenfait, D. Ndiaye and J.-P. Sabaté, Pyrethroids: exposure and health effects—an update, *Int. J. Hyg Environ. Health*, 2015, **218**(3), 281–292.
- 58 X. Chen, *et al.*, Simultaneous removal of triadimefon and dinotefuran by a new biochar-based magnesium oxide composite in water: performances and mechanism, *Sep. Purif. Technol.*, 2024, **336**, 126213.
- 59 Z.-H. Diao, *et al.*, Removal of herbicide atrazine by a novel biochar based iron composite coupling with peroxymonosulfate process from soil: synergistic effect and mechanism, *Chem. Eng. J.*, 2021, **409**, 127684.
- 60 N. M. Islam, *et al.*, Development of a novel catalytic membrane reactor for heterogeneous catalysis in supercritical CO<sub>2</sub>, *Int. J. Mol. Sci.*, 2010, **11**(1), 164–172.
- 61 D. Sud and P. Kaur, Heterogeneous photocatalytic degradation of selected organophosphate pesticides: a review, *Crit. Rev. Environ. Sci. Technol.*, 2012, **42**(22), 2365–2407.
- 62 S. Ahmed, *et al.*, Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater, *J. Hazard Mater.*, 2021, **416**, 125912.
- 63 S. Gangola, *et al.*, Biotechnological tools to elucidate the mechanism of pesticide degradation in the environment, *Chemosphere*, 2022, **296**, 133916.
- 64 J. Colina-Márquez, F. Machuca-Martínez and W. Salas, Enhancement of the potential biodegradability and the mineralization of a pesticides mixture after being treated by a coupled process of TiO<sub>2</sub>-based solar photocatalysis with constructed wetlands, *Ing. Compet.*, 2013, **15**(2), 181–190.
- 65 G. R. M. Echavia, F. Matzusawa and N. Negishi, Photocatalytic degradation of organophosphate and phosphonoglycine pesticides using TiO<sub>2</sub> immobilized on silica gel, *Chemosphere*, 2009, **76**(5), 595–600.
- 66 Z. Zihan, *et al.*, Photocatalytic degradation of an organophosphorus pesticide using a ZnO/rGO composite, *RSC Adv.*, 2020, **10**, 11929–11938.
- 67 J. M. Poyatos, *et al.*, Advanced oxidation processes for wastewater treatment: state of the art, *Water, Air, Soil Pollut.*, 2010, **205**, 187–204.
- 68 A. Oliveira, *et al.*, Solar photo-chemistry for environmental remediation-advanced oxidation processes for industrial wastewater treatment, *Molecular Photochemistry-Variou Aspects*, InTech, Rijeka, 2012, pp. 195–223.
- 69 M. Saad, *et al.*, Ultrasonically enhanced photocatalytic degradation of methylene blue by nano-CoFe<sub>2</sub>O<sub>4</sub>-immobilized *Saccharomyces cerevisiae* yeast composite as a photo-Fenton catalyst: a central composite design study, *Int. J. Biol. Macromol.*, 2025, 147068.
- 70 A. Shamim, *et al.*, Removal of pesticide pollutants from aqueous waste utilizing nanomaterials via photocatalytic process: a review, *Int. J. Environ. Sci. Technol.*, 2024, **21**(4), 4653–4684.
- 71 J. Wang and R. Zhuan, Degradation of antibiotics by advanced oxidation processes: an overview, *Sci. Total Environ.*, 2020, **701**, 135023.
- 72 A. Hossain, *et al.*, Kinetics of degradation of eosin Y by one of the advanced oxidation processes (AOPs)—Fenton's process, *Am. J. Anal. Chem.*, 2016, **7**(12), 863–879.
- 73 U. Hübner, *et al.*, Advanced oxidation processes for water and wastewater treatment—guidance for systematic future research, *Heliyon*, 2024, **10**(9), e30402.
- 74 G. Lu, *et al.*, Recent advances in metal-organic frameworks-based materials for photocatalytic selective oxidation, *Coord. Chem. Rev.*, 2022, **450**, 214240.
- 75 T. Katagi, Direct photolysis mechanism of pesticides in water, *J. Pestic. Sci.*, 2018, **43**(2), 57–72.
- 76 S. S. Patil, *et al.*, Photocatalytic degradation of organic dyes and binary mixture of dyes by Fe and Cu doped ZnO



- nanoparticles under artificial light and sunlight, *Inorg. Chem. Commun.*, 2025, **172**, 113751.
- 77 J. Schneider, *et al.*, *Photocatalysis: Fundamentals and Perspectives*, Royal Society of Chemistry, 2016.
- 78 M. R. D. Khaki, *et al.*, Application of doped photocatalysts for organic pollutant degradation—a review, *J. Environ. Manag.*, 2017, **198**, 78–94.
- 79 G. Ren, *et al.*, Recent advances of photocatalytic application in water treatment: a review, *Nanomaterials*, 2021, **11**(7), 1804.
- 80 M. Devi, S. Praharaj and D. Rout, Industrial problems and solution towards visible light photocatalysis, in *Nanostructured Materials for Visible Light Photocatalysis*, Elsevier, 2022, pp. 535–567.
- 81 M. Mrowetz, *et al.*, Oxidative power of nitrogen-doped TiO<sub>2</sub> photocatalysts under visible illumination, *J. Phys. Chem. B*, 2004, **108**(45), 17269–17273.
- 82 Z. Moradi, S. Z. Jahromi and M. Ghaedi, Design of active photocatalysts and visible light photocatalysis, in *Interface Science and Technology*, Elsevier, 2021, pp. 557–623.
- 83 A. Samal, *et al.*, Photocatalytic degradation and kinetic investigations of ZnO–SnO<sub>2</sub> heterostructures for treatment of methyl violet using non-conventional approach, *Inorg. Chem. Commun.*, 2024, **159**, 111809.
- 84 V. Kitsiou, *et al.*, Heterogeneous and homogeneous photocatalytic degradation of the insecticide imidacloprid in aqueous solutions, *Appl. Catal., B*, 2009, **86**(1–2), 27–35.
- 85 S. I. Wani and A. S. Ganie, Ag<sub>2</sub>O incorporated ZnO–TiO<sub>2</sub> nanocomposite: ionic conductivity and photocatalytic degradation of an organic dye, *Inorg. Chem. Commun.*, 2021, **128**, 108567.
- 86 M. Hadei, *et al.*, A comprehensive systematic review of photocatalytic degradation of pesticides using nano TiO<sub>2</sub>, *Environ. Sci. Pollut. Res.*, 2021, **28**, 13055–13071.
- 87 K. Balkus, Metal oxide nanotube, nanorod, and quantum dot photocatalysis, *New and Future Developments in Catalysis*, 2013, pp. 213–244.
- 88 D. K. Sharma, *et al.*, A review on ZnO: fundamental properties and applications, *Mater. Today: Proc.*, 2022, **49**, 3028–3035.
- 89 S. Munir, S. M. Shah and H. Hussain, Effect of carrier concentration on the optical band gap of TiO<sub>2</sub> nanoparticles, *Mater. Des.*, 2016, **100**(92), 64–72.
- 90 T. Zhang, *et al.*, Tuning the bandgap of MnO<sub>2</sub> homojunction by building active high-index facet to achieve rapid electron transfer for enhanced photocatalytic sterilization, *J. Mater. Sci. Technol.*, 2024, **168**, 265–275.
- 91 K. A. Mohammed, *et al.*, Capping agent effect on optical properties of Fe<sub>2</sub>O<sub>3</sub> nanoparticles, *Mater. Today: Proc.*, 2022, **56**, 2010–2015.
- 92 S. Pazouki and N. Memarian, Effects of Hydrothermal temperature on the physical properties and anomalous band gap behavior of ultrafine SnO<sub>2</sub> nanoparticles, *Optik*, 2021, **246**, 167843.
- 93 A. Dilshad, *et al.*, Araucaria cunninghamii Linn leaves silver nanoparticles for simultaneous naked-eye detection of iron II and III, *Moroc. J. Chem.*, 2025, **13**(3), 1290.
- 94 H. Kisch, Semiconductor photocatalysis—mechanistic and synthetic aspects, *Angew. Chem., Int. Ed.*, 2013, **52**(3), 812–847.
- 95 N. Premalatha and P. Rex, A comprehensive review on photocatalytic degradation of organophosphorus pesticide using ZnO coupled photocatalysts, *Desalination Water Treat.*, 2024, **320**, 100753.
- 96 W. Li, Photocatalysis of oxide semiconductors, *J. Aust. Ceram. Soc.*, 2013, 41–46.
- 97 S. H. Khan and B. Pathak, Zinc oxide based photocatalytic degradation of persistent pesticides: a comprehensive review, *Environ. Nanotechnol., Monit. Manage.*, 2020, **13**, 100290.
- 98 V. Gurylev and T. P. Perng, Defect engineering of ZnO: review on oxygen and zinc vacancies, *J. Eur. Ceram. Soc.*, 2021, **41**(10), 4977–4996.
- 99 P. Veerakumar, *et al.*, Palladium and silver nanoparticles embedded on zinc oxide nanostars for photocatalytic degradation of pesticides and herbicides, *Chem. Eng. J.*, 2021, **410**, 128434.
- 100 A. Saifaldeen and E. E. Al-Abodi, Exciting new nanocomposite by using the solar energy to remove BG dye pollutants from waste water, in *AIP Conference Proceedings*, AIP Publishing, 2021.
- 101 A. A. Shaikh, *et al.*, Synthesis and characterization of Ag doped ZnO nanomaterial as an effective photocatalyst for photocatalytic degradation of Eriochrome Black T dye and antimicrobial agent, *Inorg. Chem. Commun.*, 2023, **151**, 110570.
- 102 N. Miguel, *et al.*, Photocatalytic degradation of pesticides in natural water: effect of hydrogen peroxide, *Int. J. Photoenergy*, 2012, **2012**(1), 371714.
- 103 S. Liang, *et al.*, A novel ZnO nanoparticle blended polyvinylidene fluoride membrane for anti-irreversible fouling, *J. Membr. Sci.*, 2012, **394**, 184–192.
- 104 M. Kouhail, *et al.*, A Comparative study between TiO<sub>2</sub> and ZnO photocatalysis: photocatalytic degradation of textile dye, in *IOP Conference Series: Materials Science and Engineering*, IOP Publishing, 2020.
- 105 D. Štrbac, *et al.*, Photocatalytic degradation of Naproxen and methylene blue: comparison between ZnO, TiO<sub>2</sub> and their mixture, *Process Saf. Environ. Prot.*, 2018, **113**, 174–183.
- 106 S. Shahzad, S. Javed and M. Usman, A review on synthesis and optoelectronic applications of nanostructured ZnO, *Front. Mater.*, 2021, **8**, 613825.
- 107 H. AlMohamadi, *et al.*, Photocatalytic activity of metal- and non-metal-anchored ZnO and TiO<sub>2</sub> nanocatalysts for advanced photocatalysis: comparative study, *Catalysts*, 2024, **14**(7), 420.
- 108 M. Shekofteh-Gohari, *et al.*, Magnetically separable nanocomposites based on ZnO and their applications in photocatalytic processes: a review, *Crit. Rev. Environ. Sci. Technol.*, 2018, **48**(10–12), 806–857.



- 109 M. Bhattu, R. Acevedo and A. Shnain, A comprehensive review on the synthesis routes, properties and potential applications of ZnFe<sub>2</sub>O<sub>4</sub> ferrites, in *E3S Web of Conferences*, EDP Sciences, 2024.
- 110 N. T. T. Truc, *et al.*, The advanced photocatalytic degradation of atrazine by direct Z-scheme Cu doped ZnO/g-C<sub>3</sub>N<sub>4</sub>, *Appl. Surf. Sci.*, 2019, **489**, 875–882.
- 111 Y. N. Kanafin, *et al.*, A review on WO<sub>3</sub> photocatalysis used for wastewater treatment and pesticide degradation, *Heliyon*, 2025, **11**, e40788.
- 112 H. J. Jung, *et al.*, Enhanced photocatalytic degradation of lindane using metal–semiconductor Zn@ ZnO and ZnO/Ag nanostructures, *J. Environ. Sci.*, 2018, **74**, 107–115.
- 113 T. Sansenya, *et al.*, Hydrothermal synthesis of ZnO photocatalyst for detoxification of anionic azo dyes and antibiotic, *J. Phys. Chem. Solids*, 2022, **160**, 110353.
- 114 E. Prabakaran and K. Pillay, Synthesis of N-doped ZnO nanoparticles with cabbage morphology as a catalyst for the efficient photocatalytic degradation of methylene blue under UV and visible light, *RSC Adv.*, 2019, **9**(13), 7509–7535.
- 115 R. Saravanan, *et al.*, Comparative study on photocatalytic activity of ZnO prepared by different methods, *J. Mol. Liq.*, 2013, **181**, 133–141.
- 116 N. T. Nguyen and V. A. Nguyen, Synthesis, characterization, and photocatalytic activity of ZnO nanomaterials prepared by a green, nonchemical route, *J. Nanomater.*, 2020, **2020**(1), 1768371.
- 117 Y. Kedruk, *et al.*, Facile low-cost synthesis of highly photocatalytically active zinc oxide powders, *Front. Mater.*, 2022, **9**, 869493.
- 118 Y. Wang, *et al.*, Solvothermal synthesis of ZnO nanoparticles for photocatalytic degradation of methyl orange and p-nitrophenol, *Water*, 2021, **13**(22), 3224.
- 119 L. Ndlwana, *et al.*, Sustainable hydrothermal and solvothermal synthesis of advanced carbon materials in multidimensional applications: a review, *Materials*, 2021, **14**(17), 5094.
- 120 S. A. Mousa, *et al.*, Enhanced photocatalytic activity of green synthesized zinc oxide nanoparticles using low-cost plant extracts, *Sci. Rep.*, 2024, **14**(1), 16713.
- 121 S. Abou Zeid and Y. Leprince-Wang, Advancements in ZnO-Based Photocatalysts for Water Treatment: A Comprehensive Review, *Crystals*, 2024, **14**(7), 611.
- 122 A. Hezam, *et al.*, Smart plasmonic Ag/Ag<sub>2</sub>O/ZnO nanocomposite with promising photothermal and photodynamic antibacterial activity under 600 nm visible light illumination, *J. Photochem. Photobiol., A*, 2023, **435**, 114322.
- 123 M. R. Shakil, *et al.*, Single-doped and multidoped transition-metal (Mn, Fe, Co, and Ni) ZnO and their electrocatalytic activities for oxygen reduction reaction, *Inorg. Chem.*, 2018, **57**(16), 9977–9987.
- 124 K. Rekha, *et al.*, Structural, optical, photocatalytic and antibacterial activity of zinc oxide and manganese doped zinc oxide nanoparticles, *Phys. B*, 2010, **405**(15), 3180–3185.
- 125 A. Taha, E. Da'na and H. A. Hassanin, Modified activated carbon loaded with bio-synthesized Ag/ZnO nanocomposite and its application for the removal of Cr (VI) ions from aqueous solution, *Surf. Interfaces*, 2021, **23**, 100928.
- 126 M. L. Levy, *et al.*, Key recommendations for primary care from the 2022 Global Initiative for Asthma (GINA) update, *npj Prim. Care Respir. Med.*, 2023, **33**(1), 7.
- 127 S. Iqbal, *et al.*, Design Ag-doped ZnO heterostructure photocatalyst with sulfurized graphitic C<sub>3</sub>N<sub>4</sub> showing enhanced photocatalytic activity, *Mater. Sci. Eng., B*, 2021, **272**, 115320.
- 128 F. Ajala, *et al.*, The influence of Al doping on the photocatalytic activity of nanostructured ZnO: the role of adsorbed water, *Appl. Surf. Sci.*, 2018, **445**, 376–382.
- 129 R. E. Adam, *et al.*, Synthesis of Mg-doped ZnO NPs via a chemical low-temperature method and investigation of the efficient photocatalytic activity for the degradation of dyes under solar light, *Solid State Sci.*, 2020, **99**, 106053.
- 130 R. Sonkar, *et al.*, Cu doped ZnO nanoparticles: correlations between tuneable optoelectronic, antioxidant and photocatalytic activities, *J. Phys. Chem. Solids*, 2024, **185**, 111715.
- 131 S. Rani, *et al.*, Highly Efficient Photocatalytic Properties of La-Doped ZnO over Pristine ZnO for Degradation of 2-Chlorophenol from Aquatic Agriculture Waste, *Chem. Afr.*, 2023, **6**(4), 1981–1990.
- 132 A. Satheesh, *et al.*, UV Assisted Enhanced Photodegradation of Carbaryl Pesticide with Ag Doped ZnO NPs, *J. Sci. Res.*, 2024, **16**(2), 561–573.
- 133 M. Shirzad-Siboni, *et al.*, Enhancement of photocatalytic activity of Cu-doped ZnO nanorods for the degradation of an insecticide: kinetics and reaction pathways, *J. Environ. Manag.*, 2017, **186**, 1–11.
- 134 C. Sayury Miyashiro and S. Hamoudi, Palladium and graphene oxide doped ZnO for aqueous acetamiprid degradation under visible light, *Catalysts*, 2022, **12**(7), 709.
- 135 Y. Zandsalimi, *et al.*, Photocatalytic removal of 2, 4-dichlorophenoxyacetic acid from aqueous solution using tungsten oxide doped zinc oxide nanoparticles immobilised on glass beads, *Environ. Technol.*, 2022, **43**(5), 631–645.
- 136 C. Di Valentin and G. Pacchioni, Trends in non-metal doping of anatase TiO<sub>2</sub>: B, C, N and F, *Catal. Today*, 2013, **206**, 12–18.
- 137 C. Tang, *et al.*, Enhancement of degradation for nitrogen doped zinc oxide to degrade methylene blue, *Phys. B*, 2020, **583**, 412029.
- 138 S. Ramachandran and A. Sivasamy, Synthesis and characterization of nanocrystalline N-doped semiconductor metal oxide and its visible photocatalytic activity in the degradation of an organic dye, *J. Environ. Chem. Eng.*, 2018, **6**(3), 3770–3779.
- 139 P. Perillo and M. Atia, C-doped ZnO nanorods for photocatalytic degradation of p-aminobenzoic acid under sunlight, *Nano-Struct. Nano-Objects*, 2017, **10**, 125–130.



- 140 Y. Jin, *et al.*, Synthesis of caged iodine-modified ZnO nanomaterials and study on their visible light photocatalytic antibacterial properties, *Appl. Catal., B*, 2019, **256**, 117873.
- 141 R. J. Ramalingam, *et al.*, Synthesis, characterization and optical properties of sulfur and fluorine doped ZnO nanostructures for visible light utilized catalysis, *Optik*, 2017, **148**, 325–331.
- 142 C.-C. Lin and Y.-J. Chiang, Preparation of coupled ZnO/SnO<sub>2</sub> photocatalysts using a rotating packed bed, *Chem. Eng. J.*, 2012, **181**, 196–205.
- 143 I. Zgura, *et al.*, Wet chemical synthesis of ZnO-CdS composites and their photocatalytic activity, *Mater. Res. Bull.*, 2018, **99**, 174–181.
- 144 F. Attaria, *et al.*, Photocatalytic Removal of the Endocrine Disruptor Chlorpyrifos using a ZnO. MoO<sub>3</sub> Composite Supported on Al<sub>2</sub>O<sub>3</sub>, *ChemistrySelect*, 2024, **9**(23), e202400627.
- 145 S. H. Khan, B. Pathak and M. Fulekar, Synthesis, characterization and photocatalytic degradation of chlorpyrifos by novel Fe: ZnO nanocomposite material, *Nanotechnol. Environ. Eng.*, 2018, **3**, 1–14.
- 146 R. Yadav, *et al.*, Photocatalytic degradation of textile dyes using  $\beta$ -CD-CuO/ZnO nanocomposite, *J. Phys. Chem. Solids*, 2022, **165**, 110691.
- 147 P. A. Roozbahani, H. Behnejad and M. Hamzehloo, Synthesis, analysis, and application of zinc oxide and bismuth-based nanocomposites (ZnO/BaBi<sub>2</sub>O<sub>6</sub>) as a photocatalyst for organic dyes degradation, *Inorg. Chem. Commun.*, 2024, **168**, 112821.
- 148 N. Mishra, *et al.*, Enhanced photocatalytic degradation of hazardous dyes under visible light with biogenically synthesized ZnO-decked multi-walled carbon nanotubes (ZnO/MWCNT) nanocomposite: catalyst fabrication, performance and mechanistic insight, *Nano-Struct. Nano-Objects*, 2024, **39**, 101200.
- 149 M. I. Rahmah, R. S. Sabry and W. J. Aziz, Preparation of superhydrophobic Ag/Fe<sub>2</sub>O<sub>3</sub>/ZnO surfaces with photocatalytic activity, *Surf. Eng.*, 2021, **37**(10), 1320–1327.
- 150 S. Roy, J. Darabdhara and M. Ahmaruzzaman, ZnO-based Cu metal-organic framework (MOF) nanocomposite for boosting and tuning the photocatalytic degradation performance, *Environ. Sci. Pollut. Res.*, 2023, **30**(42), 95673–95691.
- 151 I. Daou, O. Zegaoui and A. Elghazouani, Physicochemical and photocatalytic properties of the ZnO particles synthesized by two different methods using three different precursors, *C. R. Chim.*, 2017, **20**(1), 47–54.
- 152 F. M. Collares, *et al.*, Exploring needle-like zinc oxide nanostructures for improving dental resin sealers: design and evaluation of antibacterial, physical and chemical properties, *Polymers*, 2020, **12**(4), 789.
- 153 M. Kwoka, *et al.*, Novel insight on the local surface properties of ZnO nanowires, *Nanotechnology*, 2020, **31**(46), 465705.
- 154 I. Ayoub, *et al.*, Advances in ZnO: manipulation of defects for enhancing their technological potentials, *Nanotechnol. Rev.*, 2022, **11**(1), 575–619.
- 155 P. Nandi and D. Das, Photocatalytic degradation of rhodamine-B dye by stable ZnO nanostructures with different calcination temperature induced defects, *Appl. Surf. Sci.*, 2019, **465**, 546–556.
- 156 Q. Nie, *et al.*, High piezo-catalytic activity of ZnO/Al<sub>2</sub>O<sub>3</sub> nanosheets utilizing ultrasonic energy for wastewater treatment, *J. Cleaner Prod.*, 2020, **242**, 118532.
- 157 J. Zhang and J. Li, The oxygen vacancy defect of ZnO/NiO nanomaterials improves photocatalytic performance and ammonia sensing performance, *Nanomaterials*, 2022, **12**(3), 433.
- 158 T. Bi, *et al.*, Preparation of flower-like ZnO photocatalyst with oxygen vacancy to enhance the photocatalytic degradation of methyl orange, *Appl. Surf. Sci.*, 2023, **614**, 156240.
- 159 A. T. T. Pham, *et al.*, Oxygen vacancy-activated thermoelectric properties of ZnO ceramics, *Ceram. Int.*, 2024, **50**(2), 3511–3518.
- 160 B. Rajeev, S. Yesodharan and E. Yesodharan, Sunlight activated ZnO mediated photocatalytic degradation of acetophenone in water, *IOSR J. Appl. Chem.*, 2016, 55–70.
- 161 N. P. de Moraes, *et al.*, Effect of synthesis medium on structural and photocatalytic properties of ZnO/carbon xerogel composites for solar and visible light degradation of 4-chlorophenol and bisphenol A, *Colloids Surf., A*, 2020, **584**, 124034.
- 162 R. Garg, *et al.*, Eliminating pesticide quinalphos from surface waters using synthesized GO-ZnO nanoflowers: characterization, degradation pathways and kinetic study, *Chemosphere*, 2022, **286**, 131837.
- 163 W. M. Daqa, *et al.*, Potential Applications of Chitosan-Coated Zinc Oxide Nanoparticles for Degrading Pesticide Residues in Environmental Soils, *Crystals*, 2023, **13**(3), 391.
- 164 H. Esfandian, M. R. Cherati and M. Khatirian, Electrochemical behavior and photocatalytic performance of chlorpyrifos pesticide decontamination using Ni-doped ZnO-TiO<sub>2</sub> nanocomposite, *Inorg. Chem. Commun.*, 2023, 111750.
- 165 S. L. Ezung, *et al.*, Photocatalytic degradation of the organophosphorus insecticide chlorpyrifos in aqueous suspensions using a novel activated carbon ZrO<sub>2</sub>-ZnO nanocomposite under UV light, *Korean J. Chem. Eng.*, 2023, **40**(6), 1360–1372.
- 166 S. Yasmeen, *et al.*, Photocatalytic Degradation of Organic Pollutants—Nile Blue, Methylene Blue, and Bentazon Herbicide—Using NiO-ZnO Nanocomposite, *Nanomaterials*, 2024, **14**(5), 470.
- 167 M. D. Sani, V. K. Abbaraju and N. Venugopal, Synthesis of Cerium-Doped Zinc Oxide Nanocomposites and Their Application for Photocatalytic Degradation of Lambda-Cyhalothrin in Agricultural Runoff Under Natural Solar Irradiation, *Int. J. Nanosci.*, 2024, 2350089.
- 168 S. Mahadi Danjuma, V. D. N. Kumar Abbaraju and N. V. S. Venugopal, Photocatalytic Degradation of



- Lambda-Cyhalothrin (Pyrethroid) in Wastewater using Zinc Oxide Nanoparticle, *Rasayan J. Chem.*, 2023, **16**(3), 1396–1402.
- 169 N. S. Shah, *et al.*, Enhanced solar light photocatalytic performance of Fe-ZnO in the presence of H<sub>2</sub>O<sub>2</sub>, S<sub>2</sub>O<sub>8</sub><sup>2-</sup>, and HSO<sub>5</sub><sup>-</sup> for degradation of chlorpyrifos from agricultural wastes: toxicities investigation, *Chemosphere*, 2022, **287**, 132331.
- 170 D. Pathania, *et al.*, Bio-synthesized Cu-ZnO hetero-nanostructure for catalytic degradation of organophosphate chlorpyrifos under solar illumination, *Chemosphere*, 2021, **277**, 130315.
- 171 X. An, *et al.*, Core-shell P-laden biochar/ZnO/g-C<sub>3</sub>N<sub>4</sub> composite for enhanced photocatalytic degradation of atrazine and improved P slow-release performance, *J. Colloid Interface Sci.*, 2022, **608**, 2539–2548.
- 172 S. Dehghan, *et al.*, Preparation and photocatalytic performance of reduced graphene oxide/ZnO nanocatalyst for degradation of metalaxyl from aqueous solution: effect of operational parameters, mineralisation and toxicity bioassay, *Int. J. Environ. Anal. Chem.*, 2022, **102**(18), 7112–7134.
- 173 S. Dehghan, *et al.*, Visible-light-driven photocatalytic degradation of metalaxyl by reduced graphene oxide/Fe<sub>3</sub>O<sub>4</sub>/ZnO ternary nanohybrid: influential factors, mechanism and toxicity bioassay, *J. Photochem. Photobiol., A*, 2019, **375**, 280–292.
- 174 S. Tariq, G. Chotana and A. Rashid, Photocatalytic degradation of paraquat dichloride in the presence of ZnO. WO 3 composite, *Int. J. Environ. Sci. Technol.*, 2021, 1–16.
- 175 H. R. Yucra-Condori, *et al.*, Photocatalytic degradation of methamidophos in water using zinc oxide as a photocatalyst, *Energy Nexus*, 2024, **15**, 100317.
- 176 S. Ullah, *et al.*, Efficient removal of the organophosphate pesticide, profenofos using polymer-stabilized microporous Fe<sub>2</sub>O<sub>3</sub>-ZnO nanocomposite: kinetic and thermodynamic analysis, *Appl. Surf. Sci.*, 2024, **662**, 160027.
- 177 S. Ullah, *et al.*, Efficient photocatalytic degradation of profenofos by CuO-ZnO nanocomposite, *J. Photochem. Photobiol., A*, 2024, 115787.
- 178 S. S. Stalin and E. K. V. Jino, Fabrication of Cu doped ZnO nanocrystals hybridised with graphene oxide nanosheets as an efficient solar light driven photocatalyst for the degradation of Quinalphos pesticide in aqueous medium, *J. Water Environ. Nanotechnol.*, 2023, **8**(2), 94–107.
- 179 H. Adabavazeh, *et al.*, Synthesis of polyaniline decorated with ZnO and CoMoO<sub>4</sub> nanoparticles for enhanced photocatalytic degradation of imidacloprid pesticide under visible light, *Polyhedron*, 2021, **198**, 115058.
- 180 Z. Zhu, *et al.*, Photocatalytic degradation of an organophosphorus pesticide using a ZnO/rGO composite, *RSC Adv.*, 2020, **10**(20), 11929–11938.
- 181 M. Naghizadeh, M. A. Taher and A.-M. Tamaddon, Facile synthesis and characterization of magnetic nanocomposite ZnO/CoFe<sub>2</sub>O<sub>4</sub> hetero-structure for rapid photocatalytic degradation of imidacloprid, *Heliyon*, 2019, **5**(11), e02870.

