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# Organic framework based on photocatalytic pesticides degradation

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## ABSTRACT

The extensive use of pesticides in modern agriculture has resulted in their persistent presence in soil and aquatic environments, where they act as toxic organic pollutants and contaminants of emerging concern. A large fraction of these chemicals fails to reach their targets, leading to environmental accumulation, ecological imbalance, and serious human health effects such as endocrine disruption, oxidative stress, and increased cancer risk. Conventional remediation methods, including biodegradation, chemical oxidation, and adsorption, often suffer from limited efficiency, incomplete mineralization, or secondary pollution. Photocatalysis has therefore emerged as an effective approach for the degradation of pesticide residues into harmless by-products such as carbon dioxide and water under light irradiation. Among advanced photocatalytic materials, metal organic frameworks (MOFs) have gained considerable attention due to their crystalline porous structures, exceptionally high surface areas, tunable pore environments, and adjustable electronic properties. These characteristics facilitate efficient pesticide adsorption, enhanced light absorption, and improved separation of photogenerated charge carriers. This article presents an unstructured overview of pesticide toxicity, degradation pathways, and the role of photocatalysis in environmental remediation, with a particular focus on MOFs and MOF-based composites. Key factors influencing photocatalytic performance, including bandgap energy, surface functionality, adsorption capacity, degradation kinetics, removal efficiency, and recyclability, are explained. The findings highlight the potential of MOF-based photocatalysts as sustainable and efficient materials for pesticide degradation and water purification applications.

## KEY WORDS

Organic pollutants; Photocatalysis; Pesticide degradation; Metal organic framework; Remediation

## ARTICLE HISTORY

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## Introduction

Rapid industrialization and urbanization have increased the release of wastewater and chemical pollutants into ecosystems. These pollutants are chemically diverse and are collectively referred to as contaminants of emerging concern (CECs) due to their persistence, bioaccumulation potential, and adverse ecological and health impacts [1]. Among the most prevalent CECs are industrial chemicals, pharmaceuticals, personal care products, and pesticides, and many more as new compounds are introduced into the environment [2]. According to updated data from the Food and Agriculture Organization of the United Nations (FAO), global pesticide consumption reached approximately 4.11 million tonnes in 2017, reflecting the over dependency on these chemicals for agricultural activities [3]. Pesticides are primarily used to control pests, weeds, and plant diseases but their excessive application has led to significant environmental contamination [4]. Notably, more than 95% of applied pesticides fail to reach their targets, resulting in their dispersion into soil, water bodies, and the atmosphere [5,6].

The widespread presence of pesticide residues poses severe ecological risks and human health through endocrine disorder, oxidative stress, and long-term toxicity. Pesticides are commonly classified into herbicides, insecticides, acaricides, and bactericides based on their agricultural application [7-9], and they enter the environment through agricultural runoff, industrial discharge, urban sewage, and soil leaching processes [10]. From a sustainability perspective, the persistent nature of pesticide pollution, particularly in aquatic systems, necessitates the development of advanced and environmentally compatible remediation technologies.

Many treatments have been employed for pesticide removal, including biodegradation, electrochemical degradation, ultrasound-assisted degradation, oxidative degradation, photocatalysis, and adsorption [11-16]. Among these, adsorption-based approaches using high-surface-area porous materials such as metal–organic frameworks (MOFs), activated carbons (ACs), zeolites, and mesoporous materials have shown promise, as adsorption efficiency is strongly dependent on surface functionality and porosity [17-21]. However, adsorption alone often results in secondary pollution due to contaminant saturation and limited regeneration efficiency. Similarly, biological and chemical degradation methods may suffer from slow kinetics, incomplete mineralization, or sensitivity to environmental conditions.

Photocatalysis has emerged as an attractive alternative due to its ability to completely mineralize organic pollutants into environmentally benign products such as $CO_2$ and $H_2O$ under light irradiation [15]. The process starts when incident photon energy exceeds the bandgap of the photocatalyst, resulting in the excitation of electrons and the generation of reactive species capable of degrading pesticide molecules [6]. Strategies such as incorporating noble metal nanoparticles exploit surface plasmon resonance (SPR) effects to enhance visible-light absorption and charge carrier separation [7]. Despite these, conventional photocatalysts often exhibit limitations related to low visible-light activity, rapid electron–hole recombination, and limited selectivity.

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Alternatively, metal organic frameworks have gained increasing attention due to their crystalline porous framework, high surface areas, tunable pore sizes, and adjustable electronic properties. MOFs enable efficient pollutant adsorption while simultaneously facilitating photocatalytic degradation, particularly when engineered as composites with active components [22]. Although significant literature are published on MOF-based pollutant removal, challenges remain regarding water stability, recyclability, and scalable application under realistic environmental conditions.

The objective of this review is to critically analyze the role of pristine MOFs and MOF-based composites in the adsorption and photocatalytic degradation of pesticides, with emphasis on structure-property relationships, degradation mechanisms, and performance-influencing parameters. This review also identifies current limitations in MOF-based remediation systems and highlights future research directions, including material stability enhancement, visible-light activation, composite design, and real-world application.

## Pesticides

Pesticides are a broad class of natural or synthetic chemical substances designed to kill, suppress, or repel insects, weeds, rodents, fungi, and other organisms that affect the agricultural productivity [23]. In regulatory terms, the Code of Federal Regulations (CFR) further classifies pesticides as substances or combinations of chemicals used as plant growth regulators, defoliants, or desiccants [24]. Over the years, the global dependency on pesticides has increased, with worldwide usage estimated to exceed 5.2 billion pounds annually, reflecting their widespread application in modern agriculture [25]. Based on chemical composition and mode of action, pesticides are commonly categorized into major groups such as organochlorines, carbamates, organophosphates, pyrethroids, and neonicotinoids, which together form most commercially available formulations [26]. Despite their effectiveness in pest control, the extensive use of these compounds has raised serious environmental and ecological concerns. Many pesticides exhibit non-selective toxicity, leading to unintended impacts on non-target plant and animal species, disruption of ecological balance, and long-term environmental preservation, therefore overshadowing their agricultural benefits [27].

## Use of Agrochemicals

The use of agrochemicals has been higher in developed regions, particularly across European countries, where intensive input use has been closely associated with increased agricultural yields and rising per capita food production. A comprehensive cross-country analysis of pesticide consumption between 1990 and 2009 demonstrated a strong positive correlation between pesticide use per hectare and crop output per hectare, with an estimated 1.8% increase in pesticide application accompanying every 1% rise in crop productivity [28]. As national economies increase, insecticide usage tends to stabilize; however, overall pesticide consumption does not reduce, as reductions in insecticide use are frequently balanced by increased application of herbicides and fungicides [29]. Also, the quality and regulation of agrochemicals in developing regions remain a major concern. Approximately 30% of pesticides marketed in developing countries, particularly in parts of Africa, fail to meet internationally recognized quality standards, modelling significant risks to environmental integrity and human health [30].

Beyond crop protection, pesticides play a broader role in maintaining agricultural and ecological systems by controlling unwanted plant species, insects, and pest populations in forests and wildlife habitats. Their use also limits rodent and insect vectors responsible for transmitting infectious diseases [31]. Consequently, many countries have implemented strict regulatory frameworks governing the manufacture, distribution, and application of agrochemicals, often requiring official authorization for their use [32]. Despite their well-documented adverse effects, the regulated use of agrochemicals continues to offer benefits. Crop protection chemicals reduce disease transmission through contaminated food sources [33], enhance agricultural productivity [34], and mitigate projected yield losses that could otherwise reach up to 40% of global crop production in the absence of effective pest management strategies [35].

## Human Health Hazards

Different individuals were investigated in the study, including farmers, aerial sprayers, children of pesticide applicators, and employees at pesticide factories. Only a few studies examine pesticide exposure in gardens and homes. Pesticides as a broad contact category, as well as subcategories of pesticide, as well as specific pesticides, are all included in the study's exposures.

### Mechanisms involved in pesticide toxicity and health effects

Pesticide-induced toxicity is largely controlled through the generation of reactive oxygen species (ROS) and the activation of inflammatory signalling pathways, which together promote oxidative stress within biological systems [36-38]. Oxidative stress occurs from an imbalance between pro-oxidant production and antioxidant defense mechanisms, leading to the excessive accumulation of ROS in cells and tissues [39]. This mechanism represents a central pathway through which many pesticides exert their toxic effects (Figure 1). Elevated ROS levels can damage cellular macromolecules, including lipids, proteins, and nucleic acids, resulting in DNA strand breaks, chromosomal aberrations, and mutations that may ultimately initiate carcinogenesis and other chronic diseases. Along with genomic damage, pesticide exposure has been shown to disturb mitochondrial structure and endoplasmic reticulum function, thereby damaging energy metabolism, protein folding, and intracellular signalling processes [40].

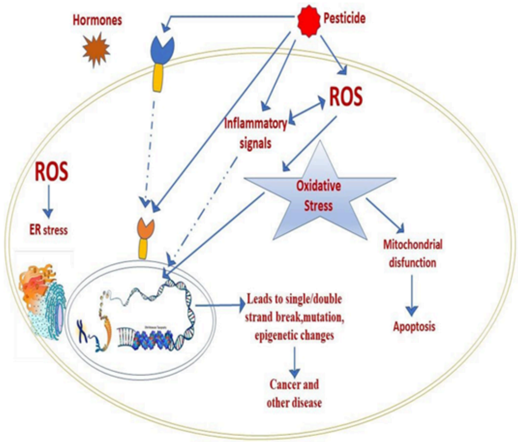


Figure 1: Mechanisms involved in pesticide toxicity and health effects.



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Epidemiological evidence indicates that only a small proportion of cancer cases are caused due to inherited genetic factors, whereas more than 70% are linked to environmental and lifestyle-related exposures, including chemical pollutants such as pesticides [41]. Among these, organochlorine pesticides (OCPs) are of major concern due to their physicochemical properties, including high lipophilicity, resistance to biotransformation, environmental persistence, and high endocrine-disrupting activity. These characteristics facilitate bioaccumulation and biomagnification of OCPs in humans and wildlife, with residues commonly detected in adipose tissue, serum, fatty organs, and breast milk [42]. Several OCPs, notably DDT, aldrin, and dieldrin, have been classified as xenoestrogens because of their ability to mimic or interfere with endogenous hormone signalling, thereby promoting estrogenic or antiandrogenic effects associated with hormone-dependent cancers such as breast cancer [43]. Along with this, DDE and DDT, the primary metabolites of DDT, are among the most frequently detected organochlorine residues in human tissues [44].

Independent studies have repeatedly confirmed the association between OCP exposure and environmentally induced breast cancer, reinforcing concerns regarding long-term low-dose exposure [45,46]. Age has been identified as a significant factor of pesticide bioaccumulation, as prolonged environmental exposure increases the exposure of persistent compounds with time. In addition to OCPs, widely used pesticides such as chlorpyrifos and carbofuran have been shown to induce oxidative stress and DNA damage, resulting in measurable genotoxic effects in exposed populations [47].

Blood is particularly vulnerable to pesticide exposure, as it serves as a primary transport medium for ingested and absorbed chemicals. Haematological parameters are therefore considered sensitive and reliable biomarkers for assessing physiological disturbances. Haematological tests offer practical advantages, including non-destructive sampling and the ability to detect early functional damage at the organismal level. Although haematological responses may not always be specific to individual chemicals, they provide valuable reports of systemic toxicity and oxidative imbalance. Reinforcing these observations, environmental and lifestyle factors remain dominant contributors to cancer incidence [48], with organochlorine pesticides continuing to pose a substantial risk due to their persistence, endocrine-disrupting potential, and documented associations with breast cancer development [49,50].

## Degradation of Pesticides

The pesticide degradation in the environment is controlled by a complex interplay of chemical properties of the active compounds and specific environmental conditions, leading to substantial changes in degradation rates across different soil-pesticide systems [51]. Key physicochemical parameters, including soil organic-carbon content, texture, moisture, and microbial activity, influence pesticide persistence. In many cases, higher organic carbon content enhances sorption and microbial availability, thereby positively affecting degradation processes. Soil pH also plays a critical role, as degradation kinetics often correlate with the dominant transformation pathway of a given pesticide, such as hydrolysis, oxidation, or photolysis [52].

Pesticide degradation occurs through both abiotic and biotic transformation mechanisms. Abiotic processes include chemical reactions such as hydrolysis, oxidation–reduction reactions, and photochemical transformations driven by solar radiation, whereas biotic degradation is primarily mediated by microorganisms capable of metabolizing pesticide molecules [53]. These processes collectively convert parent compounds into less toxic or environmentally compatible products, although intermediate metabolites may sometimes exhibit residual or enhanced toxicity. Globally, between 1 and 2.5 million tonnes of active pesticide ingredients are applied annually, predominantly in agricultural systems, with herbicides accounting for approximately 40% of total usage, followed by insecticides and fungicides [54]. Since their introduction in the 1940s, a wide range of pesticides with diverse chemical structures and modes of action have been extensively applied in both agricultural and urban environments, making pesticide application a significant source of diffuse chemical inputs into ecosystems [55].

The specific degradation pathways of pesticides are largely dictated by their molecular structure and the environmental conditions to which they are exposed. Redox gradients in soils, sediments, and aquifers determine the feasibility of oxidative or reductive transformations, while photochemical reactions are restricted to surface environments where sunlight penetration is sufficient, such as the upper layers of water bodies, plant surfaces, and thin soil horizons [56]. Atmospheric phototransformation may also contribute to pesticide degradation under certain conditions. Current regulatory assessments rely on laboratory-based test data, including aqueous hydrolysis, photolysis in air and water, biodegradability in soils and water–sediment systems under aerobic and anaerobic conditions, and lysimeter studies that simulate soil fate [57].

Despite their value, these experimental approaches provide limited insight into in situ degradation dynamics and often fail to capture the influence of interacting environmental factors, such as the presence of specific reactants or co-contaminants [58]. Moreover, uncommon environmental settings, including highly sulfidic systems such as estuaries or prairie potholes, are rarely considered, and degradation behaviour at low residual concentrations where biodegradation may cease is insufficiently addressed [59]. Consequently, although intrinsic reactivity can often be inferred from molecular structure, accurate quantitative predictions of environmental pesticide degradation remain challenging.

## Pesticide degradation by photocatalysis

TiO2 nanoparticles and UV light are used to photocatalytically degrade the pesticides [60]. Minerals, salts, and environment friendly substances like H2O and CO2 are the end products of photocatalysis. The photocatalysts are chemically and physiologically inert, sustainable, non-toxic, renewable, and usable under situations [61]. Photocatalyst activation takes place in the presence of sunlight as well as artificial light (Figure 2) [62].

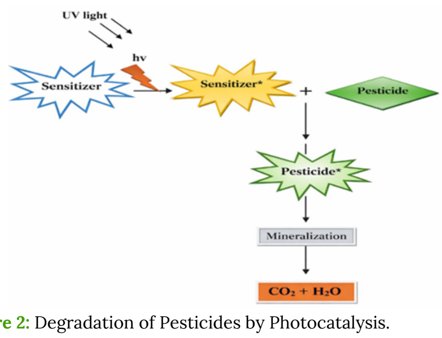


**Figure 2:** Degradation of Pesticides by Photocatalysis.



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## Biodegradation of pesticides

Biodegradation is a process by which a pesticide is transformed into eco-friendly substance that is environmentally compatible with the site to which it was applied [63]. The most common type of degradation is carried out in the soil by microorganisms, especially fungi and bacteria that use pesticides as food source [64]. Fungi degrade pesticides by minor structural changes to non-toxic substances and are released to soil, where it is susceptible to further biodegradation by bacteria [65].

## MOF for photocatalysis

Metal-organic frameworks (MOFs) are organic-inorganic hybrid materials with crystalline pores that are made up of positively charged metal ions encircled by organic "linker" molecules [64]. The metal ions form nodes that bind the arms of the linkers together to form a repeating, cage-like structure. Due to this hollow structure, MOFs have a large internal surface area [65]. A network with organic ligands that may include voids form the metal-organic framework [66]. Although crystalline molecules make up most MOFs presented in the literature, amorphous MOFs and other disordered stages also exist. Due to the great porosity of MOFs, which traps the contaminants, they significantly contribute to the photocatalytic process [67]. The MOFs' capacity to capture and direct light energy is a key factor in the selection of MOFs for photocatalytic applications. Some MOFs with Fe, Cr, Zr, and Ti metal ions have high water stability and can capture and direct solar energy [68]. They are thought to be promising candidates for photocatalytic degradations of organic contaminants because they typically have bandgap that helps visible light stimulation [69].

## Limitations and Future Scopes

Despite the substantial progress explained in this review, several limitations remain that inhibit the practical deployment of MOF-based photocatalytic systems for pesticide degradation. A primary limitation arises from the intrinsic stability of many MOFs under aqueous and irradiation conditions. Although several studies report high degradation efficiencies under laboratory settings, prolonged exposure to water, variable pH, natural organic matter, and ionic species often leads to framework degradation, metal leaching, or crystallinity loss, which compromises long-term performance [70]. Moreover, a large proportion of reported studies uses model pesticides at relatively high concentrations and under controlled light sources, which may not reflect environmentally relevant conditions where pesticide residues exist at trace levels and compete with co-contaminants for active sites [71].

Another limitation is the incomplete understanding of degradation pathways and intermediate products during photocatalytic treatment. While mineralization to $CO_2$ and $H_2O$ is frequently observed, many investigations depend primarily on removal efficiency or parent compound disappearance, with limited identification and toxicity assessment of intermediate by-products [72].

In addition, kinetic data are often reported without standardized conditions, making cross-comparison between different MOF systems difficult. The lack of unified protocols for evaluating photocatalytic performance, recyclability, and stability limits translation from bench-scale studies to real-world applications. Most MOFs exhibit limited visible-light activity due to wide bandgaps, requiring UV irradiation or complex modifications such as metal doping, ligand functionalization, or composite formation. While these approaches enhance performance, they may increase synthesis complexity, cost, and environmental footprint, which are rarely addressed in current literature [73].

Future research should therefore prioritize the rational design of water-stable and sunlight-active MOFs capable of operating under realistic environmental conditions. Greater emphasis is needed on long-term stability tests, life-cycle assessment, and regeneration studies to evaluate practical probability. Advanced analytical techniques should be systematically employed to reduce degradation pathways, identify intermediate species, and assess their ecotoxicological risks. Integrating MOFs with complementary treatment processes, such as biodegradation or membrane filtration, may offer collaborative benefits and enhance overall remediation efficiency [74].

## Conclusion

The increasing use of pesticide residues in environment, together with their ecological and health complications, mediates the development of efficient and environmentally sustainable remediation technologies. Conventional treatment strategies frequently exhibit limitations, including incomplete mineralization, and reduced effectiveness under harsh environmental conditions. Under this, photocatalytic degradation has emerged as an alternative, and the research on MOFs has created a clear need for a critical assessment. The review systematically synthesizes and evaluates published studies to evaluate the potential of MOFs and MOF-based composites for pesticide degradation. Through comprehensive analysis of the existing literature, this review mentions the structural and electronic characteristics of MOFs such as exceptionally high surface areas, tunable pore architectures, and adjustable band structures that enable their effective dual functionality as both adsorptive and photocatalytic materials. Also, the review critically identifies persistent results in current research, majorly the predominance of laboratory-scale studies using simplified model systems, limited elucidation of degradation pathways, insufficient assessment of transformation product toxicity, and inadequate investigation of catalyst durability under prolonged operational conditions. The data from this review explains that future research must progress toward environmentally and operationally relevant cases. Importance should be given to the development of hydrolytically stable, solar-active MOF systems, the establishment of standardized performance evaluation protocols, and comprehensive mechanistic and ecotoxicological analyses. Additionally, research in scalable synthesis methodologies and the integration of MOF-based photocatalysis with complementary remediation technologies will be critical for facilitating practical implementation. Also, the review provides a rigorous justification for continued research in this field and offers a coherent framework to guide the rational advancement of MOF-based photocatalytic strategies for sustainable pesticide remediation.

## Disclosure Statement

The author does not have conflict of interest in this research.

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