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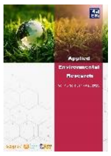

Review Article

Metal–Organic Frameworks: Opportunities and Challenges in Nutrient Recovery

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Abstract

Nutrient recovery from waste streams is a critical strategy for promoting sustainable agriculture and mitigating environmental degradation. Essential nutrients commonly present in organic waste and wastewater, such as nitrogen and phosphorus, can be reclaimed and reintegrated into agricultural systems. Metal–organic frameworks (MOFs), which are composed of metal clusters coordinated with organic ligands, have emerged as promising materials for adsorption and have the potential for nutrient recovery and pollutant removal because of their high porosity, large surface area, and tunable physicochemical properties. These attributes enable MOFs to serve in diverse applications, including heavy metal adsorption, organic pollutant degradation, and nutrient transformations. This review provides a comprehensive overview of MOF synthesis methods—including solvothermal, microwave-assisted, mechanochemical, electrochemical, and sonochemical techniques—and highlights their structural properties and adsorption mechanisms. The applications of MOFs are then discussed, with a particular emphasis on their potential for environmental contaminant removal and agricultural integration. To date, MOFs have demonstrated potential for reducing heavy metals through adsorption, enhancing organic degradation, and promoting nutrient mineralization. However, challenges in their application in agriculture remain. This review also examines the cytotoxicity, organ-specific toxicity, and phytotoxicity of MOFs to assess their environmental and health safety. Their integration into agricultural systems, including soilless agriculture, where liquid organic and inorganic fertilizers are used, is discussed from several perspectives. Overall, this paper reviews the potential of MOFs as multifunctional materials for environmental remediation and sustainable nutrient recovery in agriculture while highlighting the need for further research to ensure their safe and effective application.

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Introduction

Nutrient recovery is essential for sustainable agriculture and environmental protection, where valuable nutrients, such as nitrogen and phosphorus, are reclaimed from waste streams and then reintroduced into agricultural systems. This practice reduces the dependence on synthetic fertilizers and mitigates environmental pollution by reducing nutrient loss. Heavy metal adsorption from nutrient-rich waste streams has high potential for nutrient recovery from water/ wastewater because of its high efficiency and applicability in commercial and large-scale uses (Baharudin et al., 2025; Saliu and Oladoja, 2021). Adsorption also facilitates nutrient recovery through the capture of nutrients, such as ammonium and phosphate, from wastewater onto the surface of adsorbent materials, thereby enabling their subsequent desorption and reuse (Boudiombo et al., 2023). For example, natural adsorbents such as biochar and ceramsite can absorb certain nutrients, such as ammonium and phosphate, from wastewater for agricultural reuse; however, their ability and effectiveness are limited by their limited surface area, pore size distribution, and nonselective adsorption of competing contaminants, which reduce their capacity for targeted nutrient capture (Kumar et al., 2017). Thus, novel adsorbent materials with an enhanced surface area, optimized pore size distribution, and improved selectivity to functionally adsorb/ desorb nutrients (e.g., ammonium and phosphate) and adsorb heavy metals (e.g., cadmium (Cd) and nickel (Ni) are needed for environmental and agricultural applications.

Metal organic frameworks (MOFs) are hybrid compounds that are constructed with coordinating metal clusters (e.g., zinc (Zn), iron (Fe), copper (Cu), or chromium (Cr) and organic ligands that serve as linkers to form porous crystalline structures with diverse applications. Overall, MOFs have several advantages. First, MOFs have a high porosity and large specific area; thus, they can be applied for several purposes, such as heavy metal adsorption, organic pollutant removal, and gas separation, as well as nutrient recovery and heavy metal removal (Keshta et al., 2017). Second, MOFs have a tuneable topology and morphology, which means that their characteristics and functions can change depending on the intended application. Currently, researchers have developed a diverse array of MOFs to enhance their applications across various fields, including gas storage and separation, catalysis, sensing, drug delivery, environmental remediation, and energy storage. In addition, MOFs can be synthesized by several methods, such as solvothermal/hydrothermal, microwave, mechanochemical, electrical, and sonochemical synthesis (Zhang et al., 2022). Each MOF synthesis method offers distinct advantages and disadvantages, highlighting the versatility of the material.

Currently, MOFs are potentially suitable for various applications, such as wastewater treatment and agriculture, with the potential for nutrient recovery and heavy metal removal for environmental and agricultural applications. They exhibit good potential for adsorption and organic degradation and show outstanding characteristics that facilitate contaminant removal prior to efficient nutrient recovery. For environmental applications, MOFs can be used to remove heavy metals and persistent organic contaminants that are nonbiodegradable or hardly biodegradable (Pi et al., 2018). For heavy metal removal, MOFs can remove heavy metals by adsorption, allowing the nutrients in the waste stream to be used for nutrient recovery. Each type of MOF has different characteristics. The functions and characteristics of each type of MOF can affect the removal efficiency of a single pollutant, where the heavy metal removal efficiency depends on the MOF component and ligand characteristics (Gumus and Soylak, 2021).

The removal of organic compounds by MOFs occurs through the two main mechanisms of adsorption and oxidation. While the use of MOFs has potential for environmental and agricultural applications, their development is still ongoing, and challenges, such as their stability, scalability and cost-effectiveness of production and application, have yet to be fully addressed. Their widespread adoption is hindered by high production costs resulting from a lack of process optimization because of their novelty, potential toxicity due to a lack of individual and ecotoxicological research, and undiscovered/unknown byproducts from the MOF treatment processes. Additionally, few comprehensive studies and reviews have focused on the integration of MOFs for nutrient recovery in these specific contexts.

For their application in agriculture, the toxicity of MOFS still needs to be considered, especially in relation to human and animal use. Each type of MOF has different side effects, with their toxicity being dependent on their functions and characteristics. Polarity is among the important properties that affect biotransport and biotransformations. For example, polar MOF particles can pass through the blood–brain barrier, whereas lipophilic particles can penetrate cellular and organelle membranes and accumulate, for example, in the lysosomes of liver cells (Baati et al., 2013). Moreover, MOFs can affect cells via oxidative stress. Some types of MOFs can damage cell membranes, intracellular organelles, and deoxyribonucleic acid (DNA) (Wiśniewska et al., 2023). However, compared with other adsorbent materials, some MOFs are less toxic, and some accumulate in organs. This is only a short time before they are eliminated by the excretory system (Baati et al., 2013). Thus, the toxicity of MOFs needs to be considered for each application, but critical information is currently lacking.

Accordingly, this review focuses on MOF applications in environmental systems and waste streams to support nutrient recovery and contaminant removal for agricultural reuse. This review also summarizes MOF synthesis routes, key properties, and environmental functions and discusses potential health and ecological risks to clarify opportunities, limitations, and research gaps, including perspectives and challenges associated with the direct use of MOFs for nutrient recovery in soilless cultivation.

Synthesis of the MOFs

1) Solvothermal and hydrothermal synthesis

Solvothermal or hydrothermal synthesis is the most commonly used method for synthesizing MOFs because it is simple and does not require high-level or advanced technology (Zhang et al., 2022). This method uses a high temperature (higher than the solvent's boiling point) under high pressure (Huo et al., 2023) in a closed space (e.g., in an autoclave) to control the pressure (Figure 1A). The reaction solvent determines whether it is a solvothermal or hydrothermal synthesis, where hydrothermal synthesis uses an aqueous solution and the solvothermal method uses a nonaqueous solution. The advantages of solvothermal or hydrothermal synthesis include high reactivity and excellent crystallinity (Feng and Li, 2017). The disadvantage of this method is its lengthy reaction time, which can range from several hours to days (Joseph et al., 2021; Ma et al., 2020).

For example, the MOF MIL-88A was synthesized via solvothermal synthesis using 0.5 g of $FeCl_3$·H2O and 5 g of fumaric acid in 50 mL of deionized water and heating in a conventional oven at 85°C for 24 hours (Lin et al., 2015). The use of a Teflon-lined autoclave can significantly reduce the synthesis time and improve the quality of the obtained MOFs. In another study, MIL-100 was synthesized using iron chips as the metal source and trimesic acid as the organic linker with nitric acid (HNO_3), hydrofluoric acid (HF), and reagent-grade ethanol in deionized water at 150°C for 12 hours (Joseph et al., 2021). Additionally, MIL-88A was prepared using 2 mmol of FeCl3·6H2O and 2 mmol of 80 mL of fumaric acid in a 200-mL Teflon-lined autoclave at 70°C for 12 hours (Wu et al., 2018).

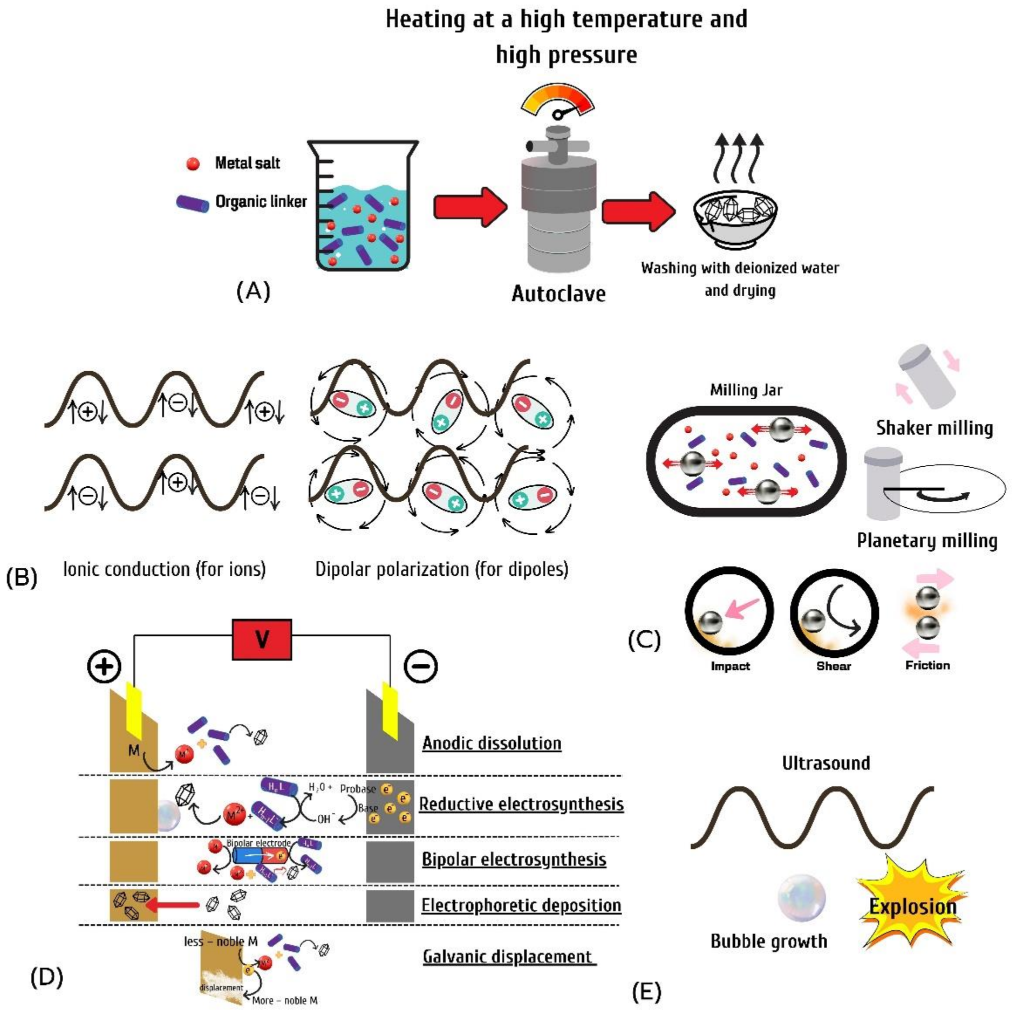

Figure 1 Illustration of the five synthesis methods used in the fabrication of MOFs: (A) solvothermal and hydrothermal synthesis, (B) microwave-assisted synthesis, (C) mechanochemical synthesis, (D) electrochemical synthesis, and (E) sonochemical synthesis.

Alternatively, solvothermal and hydrothermal methods have been used as sustainable and low-cost MOF synthesis techniques by valorizing various hazardous wastes, mitigating high precursor costs and disposal issues. For example, this strategy was successfully employed to transform phosphogypsum waste by converting its residual calcium component into Ca^{2+} salts, which were then assembled into functional Ca-MOFs (Yimer et al., 2024). Moreover, the solvothermal approach enabled the simultaneous use of two waste streams, Cr derived from tannery effluent and terephthalic acid (TPA) sourced from waste PET bottles (Delhali et al., 2023). These waste-derived MOFs exhibited structural properties, crystallinity, and porosity comparable to those of materials prepared using expensive commercial-grade precursors, suggesting the potential for a circular economy.

2) Microwave-assisted synthesis

Microwaves are nonionizing electromagnetic radiation with a frequency of approximately 300 MHz to 30 GHz (Głowniak et al., 2021). Microwave-assisted synthesis uses microwaves to vibrate molecules (Figure 1B), causing heat and reactions that lead to the formation of new substances (Javahershenas et al., 2024). It is more effective and uniform than using traditional heat in an oven (Zhang et al., 2021a). For the synthesis of MOFs, the application of microwave-assisted synthesis has been developed as an alternative to solvothermal or hydrothermal methods, which typically require a significant amount of time. Compared with the solvothermal method, which requires 12–24 hours to synthesize MIL-88A, the microwave-assisted method significantly reduces the synthesis time to only a few minutes (Lin et al., 2015; Mahmoud et al., 2020).

However, microwave-assisted synthesis has the disadvantage of producing smaller and more heterogeneous crystals. The suitability of a material for a microwave-heated synthesis reaction varies according to its dielectric constant (ε') and dielectric loss (ε''). The dielectric constant is a measure of a material's ability to store electrical energy in an electric field, whereas the dielectric loss is the energy dissipated as heat when the material is exposed to an alternating electric field. Water and dimethylformamide (DMF), which are widely used for the synthesis of MOFs, are suitable for use as microwave absorbents (Głowniak et al., 2021). For example, the microwave-assisted synthesis of MIL-88A using 10 mM fumaric acid and 10 mM $FeCl_3.6H_2O$ (10 mM) dissolved in deionized water could be achieved in 3 minutes.

3) Mechanochemical synthesis

The mechanochemical synthesis of MOFs relies primarily on a trial-and-error process. This requires the addition of reactants to a milling vessel filled with milling media. Shaker milling and planetary milling are the two most commonly used types of milling devices (Figure 1C). The type of milling device employed can significantly influence the reaction outcome. During shaking in the milling vessel, three types of reactions occur: impact, shear, and friction (Amrute et al., 2021). Mechanochemical synthesis methods can be separated into three types: neat grinding, liquid-assisted grinding, and ion- and liquid-assisted grinding. Of these, neat grinding is the simplest since it is solvent- or additive-free and thus prevents additive reactions. For liquid-assisted grinding, a liquid-phase catalyst can be introduced to enhance the mobility of the reactants. Ion-assisted grinding and liquid-assisted grinding additionally involve salt additives and liquid-phase catalysts to further promote the reaction (Tanaka, 2020). This method offers the primary advantages of having low technological complexity and low energy consumption, and the synthesis of MOFs by this method can be accomplished at room temperature (Chen et al., 2019). However, a disadvantage of this method is the production of low-purity products (Zhang et al., 2022). An example of mechanochemical synthesis is the synthesis of three-component MOFs composed of Zn-atz-ipa and Zn-datz-ipa mixed-ligand frameworks formed from azide-based and imidazole-based linkers, respec-tively (Gao et al., 2021). The procedure included mixing 10 mmol of zinc oxide with either 10 mmol of 3-amino-1,2,4-triazole to synthesize Zn-atz-ipa or with 10 mmol of 3,5 diamino-1,2,4-triazole to synthesize Zn-datz-ipa. Afterward, 5 mmol of isophthalic acid and a small amount of solvent were added, and the mixture was ground by planetary grinding at 800 rpm for 20 minutes (Gao et al., 2021).

4) Electrochemical synthesis

Electrochemical synthesis (Figure 1D) offers a promising route for the fabrication of MOFs. It has notable advantages, including the ability to control crystal morphology through direct manipulation of the applied voltage and reaction conditions. Furthermore, it can be conducted at ambient temperature and requires reduced reaction times. However, electrochemical methods also have several disadvantages. The electrolyte used in the process can clog the pores of the MOFs, leading to a low surface area (Patterson and Ignaszak, 2024). Electrochemical methods can be separated into five types: 1) anodic dissolution, 2) reductive electrosynthesis, 3) bipolar electrosynthesis, 4) electrophoretic deposition, and 5) galvanic displacement methods.

1) For anodic dissolution, metal clusters are used as the electrode (anode), and the solution contains the organic ligand and supporting electrolyte solution. Upon electrolysis, the organic ligand directly bonds with the metal ions that are dissolved from the electrode (Ghoorchian et al., 2020). Copper, aluminum (Al), and Zn are the metals that are commonly used as electrodes.

2) In reductive electrosynthesis, prebases, such as nitrate or perchlorate ions, are utilized to generate hydroxide ions. These hydroxide ions then deprotonate the organic ligands, facilitating the formation of MOF crystals (Ren and Wei, 2022).

3) For bipolar electrosynthesis, bipolar electrodes, such as carbon paper, are used, and synthesized MOFs are deposited on the bipolar electrode surface (Patterson and Ignaszak, 2024). Since organic solvents are often characterized by high flammability, low heat capacity, low thermal stability, and high corrosion potential, the use of green solvents is of interest (Asadi et al., 2022), such as in the synthesis of Zn-MOFs using plexiglass-based bipolar electrochemical cells (Asadi et al., 2022).

4) In electrophoretic deposition, MOFs are deposited on the electrode surface. This method can be applied for industrial applications (Zhu et al., 2015), such as in the fabrication of $Ni_3(HITP)_2$ (Nguyen et al., 2019).

5) In galvanic displacement, less noble metallic substrates are utilized, where the difference in the reduction potential allows more noble metals to replace less noble metals on the substrate (Al-Kutubi et al., 2015). For example, the synthesis of Cu-based MOFs using galvanic displacement with copper as the electrode in a silver diamine solution, where the more noble silver displaced the less noble copper. The displaced copper then reacted with the organic ligand to form Cu-based MOFs as the final product (Yun et al., 2022).

5) Sonochemical synthesis

Sonochemical synthesis (Figure 1E) employs ultrasound at frequencies exceeding 20 kHz. For MOF synthesis, these frequencies can reach 1 MHz. Ultrasound induces fluctuations in the liquid medium, leading to the formation and implosive collapse of bubbles. This phenomenon generates localized regions of high temperature and pressure, facilitating the synthesis process. The advantages of sonochemical synthesis include a short reaction duration, simple operation, and low energy requirements. The size of the MOF crystals that are created by this method is very small, so it is suitable for the synthesis of MOF nanoparticles. However, this method has the disadvantage of a low production yield of MOFs (Vaitsis et al., 2020).

Examples of the use of sonochemical synthesis include the use of MOF-545 and MOF-525 for nitrogen gas absorption (Yu et al., 2021). For the synthesis of MOF-545, 0.32 mmol of zirconyl chloride octahydrate, 0.01 mmol of benzoic acid, and 8 mL of DMF were used. For MOF-525, 0.32 mmol of zirconyl chloride octahydrate was mixed with 5.82 mmol of trifluoroacetic acid and 10 mL of DMF. To optimize the sonochemical synthesis conditions, ultrasonic irradiation was applied at varying power levels (30–60%), and the effects of ultrasound intensity on the crystallinity and yield of the resulting MOFs were systematically evaluated. That study revealed that different power conditions and durations can influence crystal characteristics. High-power conditions resulted in particles with a high surface area (Yu et al., 2021).

6) Large-scale synthesis of MOFs

The cost, environmental impact, and safety of the large-scale production of MOFs must be considered. MOF synthesis typically involves three main components: a metal source, an organic linker, and a solvent. Metal nitrates and chlorides can be replaced with safer alternatives such as metal acetates, carbonates, oxides, and sulfates. Low-toxicity metals commonly used for MOF synthesis include Al, calcium (Ca), Fe, magnesium (Mg), Zn, titanium (Ti), and zirconium (Zr). The overall cost of MOFs also depends strongly on the organic linker; suitable linkers should be low-cost, low-toxicity, and commercially available (Chakraborty et al., 2024).

N,N-Dimethylformamide (DMF) is widely used as a solvent for MOF synthesis. However, several studies have reported the potential health and environmental risks associated with DMF (Hong et al., 2024). In addition, a dominant environmental impact of MOF production arises from the use of organic solvents during the washing process. Therefore, research efforts have focused on replacing DMF with safer solvents (Dutta et al., 2024). For scalable production, continuous-flow synthesis can be applied at the commercial scale to reduce residence time and potentially minimize cost (Bagi et al., 2021; Rahman et al., 2025). In addition, several methods can be implemented in batch processes, including air-flow impact, spray drying, microwave-assisted synthesis, microdroplet synthesis, supercritical CO_2-assisted synthesis, and ultrasound synthesis (Bagi et al., 2021; Rahman et al., 2025).

As an example, MOF-303 was synthesized using four methods (solvothermal, reflux, vessel, and microwave). This report revealed that microwave-assisted synthesis was the fastest method; however, it was suggested to be more suitable for small-scale production. In contrast, vessel and reflux synthesis required approximately 4–8 h but could be applied to larger-scale synthesis (5–10 L reaction volumes) (Zheng et al., 2023). MOF-808 has also been synthesized using a continuous-flow process, which increased production yield and reduced solvent consumption. Moreover, the energy consumption of continuous-flow synthesis was lower than that of batch methods (Bagi et al., 2021).

Properties and environmental applications of MOFs

1) The unique properties of MOFs

Various heavy metals, such as Zn, Fe, Cu, and Cd, have been utilized as metal clusters in MOF synthesis (Zhang et al., 2022). Owing to the tuneable topology and morphology of MOFs, which are achieved by the selection of appropriate metal clusters and organic ligands, MOFs have been widely applied in diverse fields, including wastewater treatment, drug delivery, gas separation, and agriculture (Gumus and Soylak, 2021; Shrestha et al., 2021). High purity and a large specific surface area are key characteristics of MOFs. Their high purity enables their application as adsorbents, such as activated carbon. The advantages of MOFs over traditional adsorbent materials are their high chemical and thermal stability and high adsorption capacity (Zhao et al., 2021). The properties of MOFs can significantly influence their adsorption capacity, thereby affecting the efficiency of nutrient recovery and pollutant removal. As a result, MOFs exhibit various adsorption mechanisms, depending on the type of MOF and the nature of the adsorbate (Zhang et al., 2022). In addition, MOFs can be used as catalysts because of their chemical characteristics (Dapaah et al., 2022). However, certain properties of MOFs, such as their chemical composition, surface polarity, and particle size, can contribute to increased toxicity (Baati et al., 2013; Ettlinger et al., 2022), as discussed later in the following section.

2) Adsorption isotherms of the MOFs

Adsorption isotherms illustrate the correlation between the concentration of an adsorbate (e.g., a heavy metal) in solution and its absorption by MOFs at a fixed temperature. Langmuir and Freundlich isotherms (Eqs. 1 and 2) are widely used to describe equilibrium conditions in liquid–solid phase adsorption (Ugwu et al., 2020):

Langmuir isotherm:

$$\mathbf{q_e} = \mathbf{q_{max}}(\mathbf{K_L}[\mathbf{A}]/\mathbf{1} + \mathbf{K_L}[\mathbf{A}]) \quad \text{(Eq.1)}$$

Freundlich isotherm:

$$\mathbf{q_e} = \mathbf{q_{max}}\mathbf{K_F}[\mathbf{A}]^{\mathbf{1/n}} \quad \text{(Eq.2)}$$

where q_e is the adsorption capacity at equilibrium, q_{max} is the maximum adsorption capacity, K_L is the Langmuir constant, K_F is the Freundlich constant, and [A] is the absorbent concentration.

The Langmuir model is based upon adsorption occurring on a homogenous surface or monolayer. The MIL-88A MOF, modified with nanomagnetic iron oxide and 3-aminopropyltrimethoxysilane (APTMS), was used for the adsorption of heavy metals, including Cr, lead (Pb), and Cd. Under fixed temperature conditions, the adsorption behavior was well described by the Langmuir isotherm model (Mahmoud et al., 2020). Similarly, the absorption of Cu and Cr on MIL-101 was well described by the Langmuir model at fixed temperatures (Elaiwi and Sirkecioglu, 2020).

In contrast, Freundlich isotherms demonstrate that adsorption occurs on multiple layers and is not uniform. Several MOF adsorption reactions have been found to fit well with Freundlich isotherms. For example, Pb can be absorbed by Fe-MIL-88NH_2 (Fu et al., 2021). With respect to their kinetics, MOFs have been found to follow pseudofirst- and pseudo-second-order kinetic models, which are the most widely used models to describe the kinetics of adsorption.

3) Heavy metal removal via MOF adsorption

Heavy metal contamination in water sources poses serious environmental and public health threats because of the high toxicity of these metals to both humans and ecosystems. Moreover, as heavy metals are nonbiodegradable, they tend to persist and accumulate in the environment (Zhang et al., 2022). Various methods have been developed for their removal from water, including chemical precipitation, adsorption, ion flotation, ion exchange, coagulation and flocculation, electrochemical processes, chemical hydrogels, nanotechnology, membrane separation, electrodialysis, and photocatalysis (Shrestha et al., 2021). However, the potential implementation of MOFs is still at the research level only.

For adsorption by MOFs, heavy metals are retained on the surface of the adsorbent. This offers several advantages, including high efficiency, rapid kinetics, simple equipment requirements, the ability to remove multiple contaminants, and cost effectiveness (Zhang et al., 2022; Chai et al., 2021). Moreover, MOFs have several other advantages that make them highly effective as adsorbents, including a high porosity, large specific surface area, tunable functionality, high stability, accessible metal ion sites, and the presence of unsaturated coordination sites (Wu et al., 2018). Furthermore, MOFs can absorb light, which facilitates the photocatalytic reduction of heavy metal ions (Li et al., 2021). Consequently, they have been widely used for heavy metal adsorption in wastewater treatment (Amenaghawon et al., 2023). Overall, MOFs can absorb various types of heavy metals, such as Cu, Zn, Cd, arsenic (As), and Pb, but the amount of heavy metals adsorbed depends on the specific MOF employed, as different frameworks facilitate various adsorption mechanisms, including surface complexation, ion or ligand exchange, physisorption, hydrogen bonding, and electrostatic interactions (Zhang et al., 2022).

The studies that have applied MOFs for heavy metal removal are summarized in Table 1. With respect to As adsorption, MIL-88A exhibited a high capacity of up to 145 mg g^{-1}, which was attributed to the formation of As–O–Fe bonds within the Fe-based MOFs. Moreover, the pH influenced the adsorption capacity by affecting the zeta potential, which reflects the surface charge of the particles and their stability in solution (Huang et al., 2018). Combining MIL-88A with APTMS to form nFe_3O_4 @MIL-88A(Fe)/APTMS resulted in maximum adsorption capacities for Cd, Pb, and Cr of 693.0, 536.22 and 1,092.22 mg g^{-1}, respectively (Mahmoud et al., 2020).

However, nFe_3O_4@MIL-88A(Fe)/APTMS exhibited high adsorption capacities for Cd and Pb at high pH, whereas Cr showed a higher adsorption capacity at low pH (Mahmoud et al., 2020). Layered double hydroxides (LDHs) derived from MIL-88A were used to remove Pb from water (Huo and Yu, 2022), taking advantage of the lamellar structure of LDHs with their stacked, sheet-like layers. This gives LDHs their large specific surface area, which makes them highly suitable for adsorption processes. The maximum adsorption capacity of LDHs derived from MIL-88A was 512.8 mg g^{-1} at a pH of 3, and the adsorption mechanism was Pb–O–Fe complexation and Pb compound precipitation (Huo and Yu, 2022). In comparison, MIL-101(Cr) and MIL-101(Cr) had higher adsorption capacities for Cu, Cd, and Pb than MIL-100(Fe), with the highest adsorption capacity being 19,043 mg g^{-1} for Pb (Joseph et al., 2021). MOFs are tunable materials that can be tailored for various applications. In many studies, compared with conventional adsorbents such as activated carbon and zeolite, MOFs have shown higher adsorption capacities. However, MOFs remain relatively expensive for large-scale applications. In addition, regeneration and desorption performance depends on the material structure. For example, MOF-808-pNB was used as a selective adsorbent for Pb removal and exhibited high desorption efficiency. The regeneration cost was reported to be lower than that of commercial adsorbents (Essalmi et al., 2024).

4) Adsorption and degradation of organic pollutants using MOFs

Organic pollutants in the environment can cause serious issues, including anoxic conditions and ecological and health risks, because of the persistence of many organic compounds. Elevated levels of organic matter (OM) in water sources can significantly reduce dissolved oxygen concentrations, further degrading water quality. Therefore, organic pollution represents a critical environmental concern. Various approaches have been developed to reduce organic pollutants, including biological, chemical, and physical methods (Dapaah et al., 2022; Phonhem et al., 2025). The main advantage of using MOFs for organic pollutant removal lies in their tunable functionality. Organic pollutants can be removed by MOFs through two primary mechanisms: adsorption and degradation (Figure 2).

In terms of adsorption, MOFs have a high porosity and a large specific surface area and can absorb OM (Figure 2). Examples of different types of organic pollutants that MOFs have been used to adsorb, such as dyes, antibiotics, and pesticides, are summarized in Table 2. The mechanisms of adsorption include hydrophobic interactions, π–π stacking, hydrogen bonding, acid–base interactions, and electrostatic interactions (Tchinsa et al., 2021). For example, the absorption of organic pollutants from wastewater by graphene oxide (GO)/MOFs was evaluated (Wei et al., 2021). The study used tetracycline hydrochloride (TC) and Orange II with 50 mg of GO/MOFs per 100 mL of the contaminants, where the highest obtained adsorption efficiency was 96.1% for 10 mg L^{-1} TC and 98.8% for 25 L^{-1} Orange II (Wei et al., 2021).

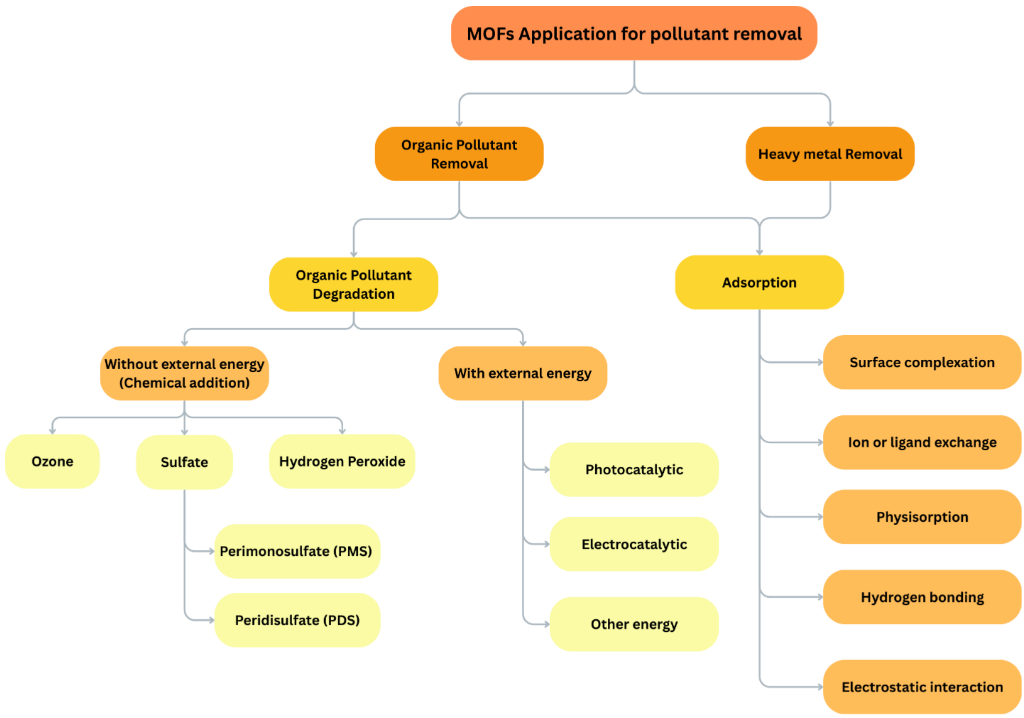

Figure 2 Applications of MOFs for the removal of organic and heavy metal pollutants through degradation and adsorption mechanisms.

Table 1 Summary of selected MOFs used for heavy metal removal, including metal clusters, organic ligands, target contaminants, adsorption capacities or removal efficiencies, and experimental conditions

MOFs	Metal cluster	Organic ligand	Contaminant	Capacity /efficiency	Tested conditions	References
MIL-88A	Fe	Fumaric acid	As (V)	145 mg g^{-1}	250 mL of arsenic solution, 0.1 g of adsorbent, 25 ± 1°C at pH 5	Wu et al.(2018)
MIL-88A	Fe	Fumaric acid	Cr (VI)	1124.39 mg g^{-1}	pH 2, 0.3 mol L^{-1} (30 min)	Mahmoud et al. (2020)
MIL-88A	Fe	Fumaric acid	Pb (II)	646.3 mg g^{-1}	pH 6, 0.3 mol L^{-1} (20 min)	Mahmoud et al. (2020)
MIL-88A	Fe	Fumaric acid	Cd (II)	755.89 mg g^{-1}	pH 6, 0.3 mol L^{-1} (20 min)	Mahmoud et al. (2020)
MIL-100(Fe)	Fe	Trimesic acid (BTC, 95%)	Cu (II)	59%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-100(Fe)	Joseph et al. (2021)
MIL-100(Fe)	Fe	BTC (95%)	Pb (II)	33%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-100(Fe)	Joseph et al. (2021)
MIL-100(Fe)	Fe	BTC (95%)	Cd (II)	57%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-100(Fe)	Joseph et al. (2021)
MIL-101(Cr)	Cr (III)	TPA (98%)	Cu (II)	68%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-101(Cr)	Joseph et al. (2021)
MIL-101(Cr)	Cr (III)	TPA (98%)	Lead (II)	33%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-101(Cr)	Joseph et al. (2021)
MIL-101(Cr)	Cr (III)	TPA (98%)	Cd (II)	49%	C_0 = 10 mg L^{-1}; adsorbent 100 mg L^{-1}; 20 ◦C, 40 mg MIL-101(Cr)	Joseph et al. (2021)
ED-MIL-101	Cr (III)	Aminoterephthalic acid (ATPA)	Cu (II)	70%, 69.9 mg g^{-1}	C_0 = 100 mg L^{-1}, pH 6	Elaiwi and Sirkecioglu (2020)
ED-MIL-101	Cr (III)	ATPA	Cd (II)	60%, 63.15 mg g^{-1}	C_0 = 100 mg L^{-1}, pH 6	Elaiwi and Sirkecioglu (2020)
Fe-MIL-88NH_2	Fe	2-amino-terephthalic (BDC-NH_2)	Pb (II)	195 mg g^{-1}	C_0 = 80 mg L^{-1}	Fu et al. (2021)
MIL-88A	Fe	Fumaric acid	COD	~92.64%	Coolant oil concentation 5%, pH 9, air flow rate 2 L m^{-1}, MIL-88A 1.0 g, 177 min	Suwannasung et al. (2023)
MIL-121@calcium alginate beads	Al	H4BTC	Cu (II)	204.5 mg g^{-1}	20 mg of wet bead adsorbent, 20 mL of metal ion contaminated water (500 mg L^{-1}), 25 ◦C, stirring (300 rpm)	Ma et al. (2020)
MIL-121@calcium alginate beads	Al	H4BTC	Cd (II)	88.7 mg g^{-1}	20 mg of wet bead adsorbent, 20 mL of metal ion contaminated water (500 mg L^{-1}), 25 ◦C, stirring (300 rpm).	Ma et al. (2020)
A-MIL-121	Al	H4BTC	Cu (II)	> 95%	High salinity ([Na^+]/[Cu^{2+}] = 20,000) water at normal temperature	Ji et al. (2021)
MIL-53(Fe)	Fe	H2BDC	Pb (II)	714.28 mg g^{-1}	pH 6; 0.3 mol L^{-1} (20 min)	Ghanbarian et al. (2020)
MIL-53(Fe)	Fe	H2BDC	Cd (II)	178.57 mg g^{-1}	pH 6; 0.3 mol L^{-1} (20 min)	Ghanbarian et al. (2020)

Table 2 Summary of selected MOFs used for organic compound removal, including metal clusters, organic ligands, target contaminants, adsorption capacities or removal efficiencies, and experimental conditions

MOFs	Metal cluster	Organic ligand	Contaminant	Capacity/ efficiency	Tested conditions	References
GO/MOFs	Fe, Zr	DMF	TC	96.10%	100 mL of 10 mg L^{-1}TC solution, 4 hour	Wei et al. (2021)
GO/MOFs	Fe, Zr	DMF	Orange II	98.80%	25 mg L^{-1} orange II solution, 4 hour	Wei et al. (2021)
MIL-101	Cr (III)	PTA	p-Nitroaniline	378.9 mg g^{-1}, 90.20%	Cr: Fe (50: 50), pH 5, 40°C , 180 min	Dapaah et al. (2022)
ZIF-67	Co	Methanol	Methylene blue	80%	2 h continuous operation at 50 mL min^{-1}	Wang et al. (2024a)
Cu–Fe-MOF	Fe, Cu	PTA	Phenol	100%	pH 5–9, 100 mL of phenol solutions at 50 mg L^{-1}	Wang et al. (2024b)
Fe-MOF	Fe	Terephthalic acid	TC	87.12%	TC at 25 ppm, catalyst 40 mg, pH 5.5	Rana et al. (2024)
CoFe-MOF	Co, Fe	BDC	TC	92.90%	TC at 20 mg L^{-1}, H_2O_2 6 mM	Chen et al. (2024a)
MIL-125(Ti)	Ti	BDC	Rhodamine B (RB) dye	96.75%	MX@MIL-125(Ti) = 0.25 g L^{-1}, ultrasonic power 150 W, and 60 min. (RhB)	Yang et al. (2024a)
MIL-125(Ti)	Ti	BDC	Micro-PE	88.60%	MPs (0.5 g L^{-1}) within 6 h in the presence of PDS (catalyst 2.0 g L^{-1})	Yang et al. (2024a)
ZIF-67	Co	Methylimidazole	Methylene blue	99.90%	MB 10 mg/L (20 mL), material (8 mg), adsorption time (30 min), and photocatalytic (0−60 min)	Yang et al. (2024b)
MIL-100(Fe)	Fe	Trimesic acid (BTC, 95%)	TC	80.40%	[catalysts] = 200 mg L^{-1}, [H_2O_2] = 100 mM, 60 min	Shi et al. (2024)
MIL-68	Fe	BDC	RB dye	99%	15 min, RhB 10 mg L^{-1}, PMS 0.4 mM, catalyst 0.2 g L^{-1}, initial pH 5.6	Chen et al. (2024b)
MIL-88A	Fe	Fumaric acid	RB dye	~ 100%	Persulfate 300 mg L^{-1}, MIL-88A 1500 mg L^{-1}, 40°C	Lin et al. (2015)

The degradation of OM by MOFs can be classified into two types: processes that occur without external energy input and those that require external energy (Figure 2). In the absence of external energy activation, MOFs can degrade OM by generating hydroxyl radicals. To generate hydroxyl radicals, hydrogen peroxide (H_2O_2), perimonosulfate (PMS), peridisulfate (PDS), or ozone is added as an auxiliary oxidant. Hydroxyl radicals have a strong oxidation capacity and thus can degrade organic compounds. PMS is suitable for Cobased MOFs, whereas PDS is suitable for Fe-based MOFs. Several studies have used MOFs for OM degradation (Table 2). For example, Cu–Fe-MOFs were used to remove organic pollutants, such as phenol, bisphenol A, 2,4-dichlorophenol, methyl blue, rhodamine B (RB), TC, and sulfamethoxazole, in the presence of PMS for the oxidation process. The maximum obtained degradation efficiency was nearly 100%. Moreover, Cu–Fe-MOFs are reusable materials. Cu–Fe-MOFs can be recovered by centrifugation and reused, although the removal efficiency gradually decreases to approximately 75% after four cycles (Wang et al., 2024b). Likewise, PMS was used as the catalyst together with ZIF-67 fabricated on wood to remove methylene blue, resulting in a maximum removal efficiency of approximately 90%, with a water flux rate of 5,119 L m^{-2} h^{-1} (Wang et al., 2024a). Alternatively, graphitic carbon nitride (g-C_3N_4) and MIL-100(Fe) were used to degrade TC in the presence of H_2O_2 to activate the reaction, resulting in a degradation efficiency of approximately 80%.

The reusability of g-C_3N_4@MIL-100(Fe) was evaluated using cycle tests, and the removal efficiency decreased to approximately 80% after five cycles [70]. Fenton-like reactions at elevated temperatures (≥55°C) reduced NH_3 emissions by mineralizing nitrogenous organic matter and increasing the NO_3^-–N content. In addition, Cu- and Fe-based powders are highly capable of NH_4^+ reduction (Xie et al., 2026). In the nanometallic powder–amended group, the NO_3^-–N concentration was greater than that in the control group. Moreover, Fenton-like indicators (e.g., H_2O_2, •OH, and • O_2^-) were negatively correlated with NH_3 emissions. Compared with conventional sorbents, Fe-based and regenerable (e.g., magnetic or composite) MOFs are likely more suitable for agricultural systems because of their lower toxicity and improved recovery/reuse potential; however, cost remains a major constraint (Xie et al., 2026).

Several types of energy inputs can be used to activate the reaction instead of chemicals, such as photo, electrical, mechanical, hydrogen, and microwave energy (Figure 2) (Wang et al., 2024c). A modified air-Fenton process was used with MIL-88A to remove organic compounds from the coolant oil. The optimum conditions for treating 5% coolant oil were 1 g MIL-88A, an aeration flow rate of 2 L min^{-1} and a pH of 9 for 177 min, which resulted in a removal efficiency of 92.64% (Suwannasung et al., 2023). Photoenergy was used with g-C_3N_4/Fe-MOF to degrade TC, resulting in the highest removal efficiency of 87.12% at 25 ppm TC (Rana et al., 2024). Likewise, a CoFe-MOF/TiO_2 composite, which was fabricated with a poly(vinylidene fluoride)-based membrane, was used to remove TC through a photoFenton-like oxidation process. The highest removal efficiency was 92.9% (Chen et al., 2024a). Ultrasound irradiation was used with MXene @MIL-125(Ti) to remove dyes and microplastics, with the highest removal efficiency of more than 90% for rhodamine B (RhB) within 60 minutes and 75% for micropolyethylene within 4 hours (Yang et al., 2024a).

5) MOF-based nitrogen and phosphorus capture and recovery

MOFs can be used as nutrient slow-release materials to reduce nutrient deficiency caused by leaching. Mg-based MOFs have been applied in cultivation, and one study demonstrated that the use of MOFs enhanced Mg and P uptake in plants (Morales-Cámara et al., 2025). Similarly, Fe-based MOFs synthesized from ferric chloride, dipotassium hydrogen phosphate, diammonium hydrogen phosphate, urea, and oxalic acid have been used as slow-release fertilizers to reduce the leaching rates of phosphorus (P), nitrogen (N), potassium (K), and Fe (Asemave and Lubem, 2024; Wu et al., 2022).

For nutrient recovery from wastewater, aluminum fumarate (AlFu) MOFs have been applied with a forward osmosis (FO) membrane to increase the recovery of nutrients such as NO_3—N and phosphorus. After wastewater treatment using AlFu and FO, the concentration (accumulation) rate for real wastewater was higher than that for synthetic wastewater, and nutrients were recovered by precipitation as struvite ($MgNH_4PO_4 \cdot 6H_2O$), thereby leading to the recovery of NH_4^+ and PO_4^{3-} (Lakra et al., 2021).

Regenerable magnetic Fe_3O_4 and lanthanum (La)-based MOFs have also been used to adsorb P from wastewater. These materials exhibited high P adsorption efficiency and high P selectivity, and regeneration was achieved via electrostatic interactions and precipitation (He et al., 2023). La-based MOFs are considered excellent selective P adsorbents, with high adsorption performance under complex conditions. In contrast, many adsorbents have low P selectivity because of their hydrophobic nature (Lakra et al., 2021). According to the Hofmeister series (ion ranking by hydration strength), $H_2PO_4^-$ is preferred over less hydrated anions. In addition, some studies have reported that amine functional groups can enhance P-selective adsorption. For example, NH_2^--MIL-101(Al/Fe) showed high P selectivity and sorption capacity. NH_2-MIL-101(Fe) exhibited a higher P sorption capacity than NH_2-MIL-101(Al) because of its higher surface area, whereas compared with NH_2-MIL-MIL-101 (Fe), NH_2-MIL-101(Al) showed faster kinetics, likely because of its higher zeta potential (Liu et al., 2019).

Therefore, MOFs represent a promising platform for P and N capture and reuse in agriculture.

Among the major nutrients, phosphorus could be more readily recovered using MOFs because phosphate species can strongly bind to metal nodes and can also be recovered via precipitation pathways (e.g., metal phosphate or struvite formation). In contrast, nitrogen recovery could be more complex because nitrogen occurs in multiple forms (e.g., NH_4^+, NO_2^-, NO_3^-, and organic nitrogen) and is controlled by conditions that govern mineralization and nitrification. Consequently, MOF-based strategies for nitrogen recovery are more sensitive to operational conditions and remain important areas for further investigation.

Toxicological effects of MOFs on living cells and safety considerations

Given that MOFs consist of metal clusters and organic ligands and can be applied in various fields, including gas storage, water treatment, catalysis, energy conversion, and biomedicine, there is a potential risk of exposure to humans and animals (Figure 3). Consequently, understanding the toxicity of MOFs is essential for mitigating any potential health risk associated with their applications. Owing to their small particle size, MOFs can penetrate physiological barriers. Their toxicity is influenced by several factors, including particle size, aggregation state, morphology, chemical composition, biostability, and surface chemistry (Ettlinger et al., 2022). In addition, postsynthetic functionalization can influence the toxicity of MOFs. For example, MOFs of the same type can still exhibit different half maximal inhibitory concentration values depending on the nature of the postsynthetic modifications. Moreover, the type of metal cluster also affects the toxicity of the MOF. Those synthesized from Zr or Zn are more hazardous than those synthesized from Fe (Tamames-Tabar et al., 2014). The following sections discuss the toxicity effects of MOFs in different organs.

1) Cytotoxicity and embryotoxicity

The adverse effects of MOFs on intracellular organisms occur through their interaction with cellular components or through disruption of their physiological functions (Figure 3). Their metal component can act as a catalyst, leading to the formation of reactive oxygen species (ROS) that can damage intracellular components and both cell and organelle membranes. The primary mechanisms of membrane damage include increased permeability and disruption of ionic exchange processes. The main pathways through which MOFs can enter cells are endocytosis, diffusion, and adsorption (Wiśniewska et al., 2023). After entering cells, MOFs can damage the nucleus and mitochondria via the production of ROS.

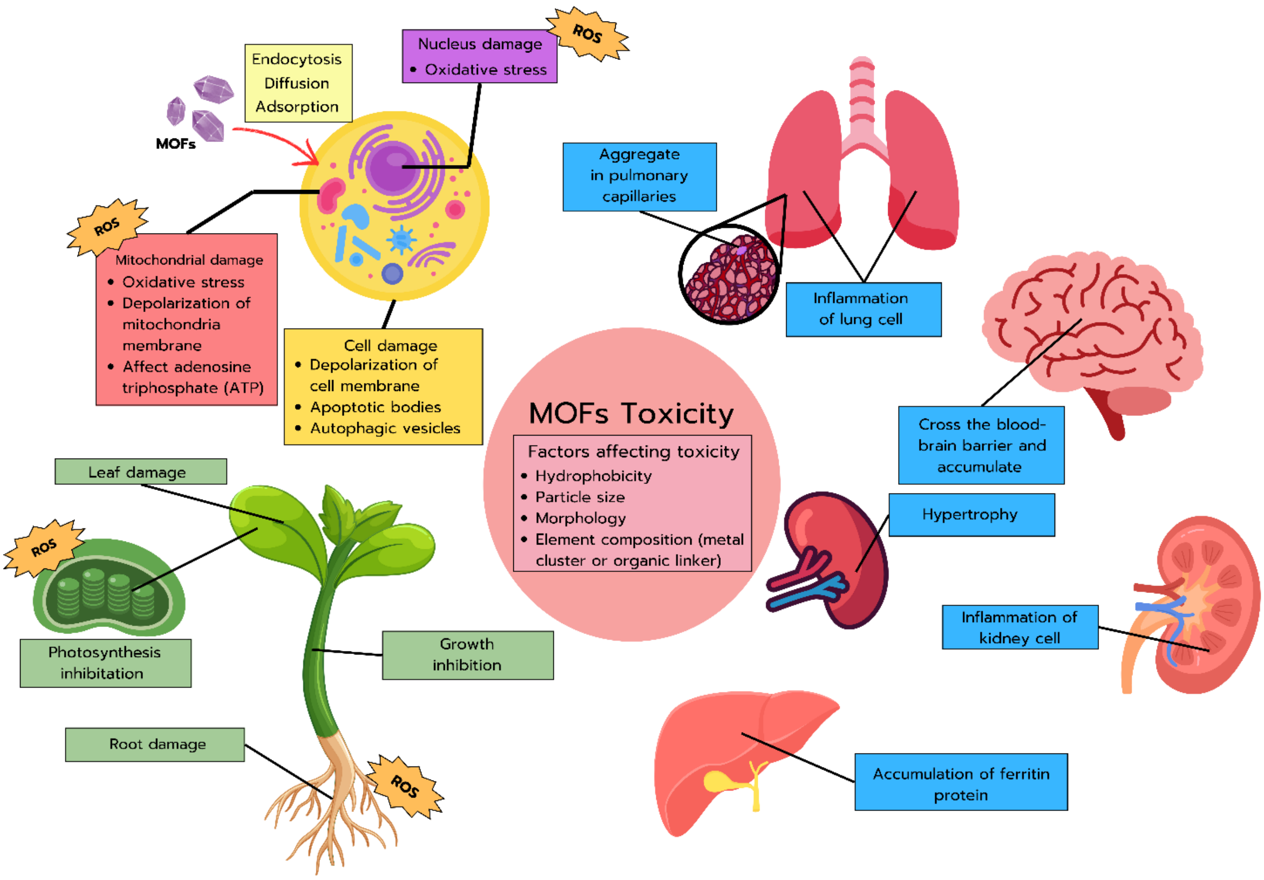

Figure 3 Overview of the toxicity of MOFs to living organisms, including cytotoxicity and embryotoxicity, lung toxicity, organ-specific toxicity, and phytotoxicity.

Because MOFs can catalyze Fenton-like reactions, the generation of ROS may also influence microbial communities. A previous study demonstrated that Fenton-like reactions can shift the microbial community composition at the phylum level by increasing the tolerance of taxa to oxidative stress. In particular, Pseudomonadota and Bacteroidota were strongly positively correlated with hydrogen peroxide and hydroxyl radicals, suggesting tolerance to Fenton-like oxidation stress (Xie et al., 2026). A study of the effects of four different MOF types (UiO-66 (Zr), HKUST-1 (Cu), MIL-53 (Fe), and MIL-125 (Ti)) on coronaviruses revealed that HKUST-1 exhibited toxicity toward cell lines (Huh7 TMPRSS2, VeroE6, and Vero-81), whereas the other MOFs showed no evidence of cell line inactivation (Plastiras et al., 2024). The MOF HKUST-1 was found to have cytotoxic activity against human embryonic kidney cells (HEK293), including the depolarization of the mitochondrial membrane, the formation of apoptotic bodies, autophagic vesicles, and oxidative stress that damaged DNA strands. However, this effect was significant only under very high concentrations of HKUST-1 (Chen et al., 2021). In addition, HKUST-1, a Cu-based MOF, induced mortality in freshwater fish and their embryos in a dose-dependent manner (Abramenko et al., 2021). At a HKUST-1 concentration of approximately 3 mg/L, the percentage mortality reached nearly 100%. This MOF also affects the hatching rate and morphology of zebrafish embryos (Abramenko et al., 2021).

2) Lung toxicity

Following inhalation, MOFs have the potential to accumulate in the lungs (Figure 3). Evaluation of three Fe-based MOFs (MIL-88B_4CH3, MIL-88A, and MIL-100) revealed the presence of aggregates in pulmonary capillaries, which was due to their small particle size. However, these compounds are not toxic to lung cells (Baati, 2013). Moreover, there are cellular mechanisms through which to degrade or remove MOFs. Thus, after 7 days, the iron concentration had returned to normal (Baati, 2013). Various studies have evaluated MOFs as potential drug delivery systems for the treatment of lung disease. The biodegradable MOF MIL-100 was found to accumulate in the lungs 30 minutes after injection and disappeared 24 hours after injection (Simon-Yarza et al., 2017). However, MIL-160(Al) and ZIF-8(Zn) were found to be cytotoxic to human lung epithelial cells, with the degree of cytotoxicity depending on the hydrophobicity, element composition, morphology, and size of the MOFs (Wagner et al., 2019). As a result, compared with MIL-160 (Al), ZIF-8 (Zn) exhibited a greater degree of toxicity, primarily because of the presence of Zn clusters, which are more toxic than aluminum (Al). Moreover, the smaller particle size of ZIF-8 compared with that of MIL-160 may further contribute to its increased toxicity (Wagner et al., 2019). A crosslinked cyclodextrin MOF (CDF) was examined as a potential lung cancer drug delivery system (He et al., 2021). The results showed that CDF has the potential to be used as a drug delivery material with no indicators of tissue damage or adverse effects after treatment (He et al., 2021).

3) Toxicity of MOFs to internal organs

Some types of MOFs can accumulate in the brain because of their polarity and small particle size (Figure 3). Particles with greater hydrophobicity and smaller sizes can cross the blood–brain barrier, which explains why MIL-88B_4CH3, which is smaller and more hydrophobic than MIL-88A and MIL-100, can accumulate in the brain [9]. However, no toxicity was associated with MIL-88B_4CH3. Normal creatine phosphokinase levels, which is used as a biochemical marker, confirmed the nontoxic nature of MIL-88B_4CH3. Moreover, the amount of MOFs decreased to normal concentrations after 7 days (Baati, 2013). However, slight hypertrophy of the spleen cells was noted after injection of MIL-88B_4CH3, MIL-88A, or MIL-100. Nevertheless, the plasma interleukin levels remained within the normal range, indicating the absence of inflammation (Baati, 2013). Moreover, although some MOFs accumulated in the spleen, their levels decreased after 7 days but disappeared after 30 days (Baati, 2013).

The liver is a vital organ responsible for the elimination of foreign substances from the body. Systemic injection of MIL-88B_4CH3, but not MIL-88A or MIL-100, induced some initial cell abnormalities linked to the lipophilic components of the MOF, but the liver returned to normal after 7 days, and inflammation did not occur (Baati, 2013). However, MIL-88A accumulates on ferritin (an iron storage protein), which might inhibit the degradation of the MOFs (Baati, 2013). In vitro, MIL-100 was found to have low cytotoxicity against normal liver and hepatocellular carcinoma cells and good biocompatibility; thus, it has the potential to be used in medical applications (Chen et al. 2019). Oral exposure to MOF-74, a Cobased MOF, in mice caused no significant body weight loss, although slight inflammation was observed in the liver and kidneys. Thus, the researchers concluded that MOF-74 is less toxic (Lan et al., 2022).

4) Phytotoxicity

In addition to humans and animals, plants can also be affected by MOFs (Figure 3). For example, in terms of decreased root length, fresh weight, and dry weight, MOF-74 (Co) inhibited photosynthesis in pea seedlings. In addition, the net photosynthesis rate decreased, whereas the intracellular carbon dioxide concentration increased, likely because of the presence of MOF-74 (Co) nanoparticles (Hu et al., 2024). The Co ions released from MOF-74(Co) can cause oxidative damage to the leaves and photosynthetic processes, indicating that the metal clusters in MOFs can cause toxicity (Hu et al., 2024). Indeed, different metal clusters can cause different types of damage. Copper ions can induce increased ROS levels, leading to protein and DNA damage, as well as alterations in cellular function. Similarly, Zn ions have been shown to increase ROS levels. Moreover, MOFs can cause growth inhibition and disrupt normal photosynthesis processes (Angulo-Bejarano et al., 2021). Evaluation of the phytotoxicity of HKUST-1, a Cu-based MOF, against seven types of Cu-tolerant plants revealed that HKUST-1 promoted the growth of most plant species at low concentrations (less than 100 mg L^{-1}) but induced oxidative stress at high concentrations (Loera-Serna et al., 2024). MIL-101(Cr) exposure in soybeans caused leaf damage at high concentrations (500 and 1000 mg L^{-1}) and metabolic changes at relatively low concentrations, including an increase in the levels of sucrose, which is a primary energy source for plants (Liu et al., 2024). The porous coordination network PCN - 224, a Zr-based MOF, increased the germination rate in A. thaliana but inhibited overall plant growth because of oxidative stress (Safdar et al., 2025). With respect to Zn-based MOFs, ZIF-8 and ZIF-67 are toxic and inhibit plant growth via the inhibition of chlorophyll synthesis and adenosine triphosphate (ATP) synthesis in mitochondria (Zhang et al., 2021b). However, studies on the phytotoxicity of MOFs to plants in complex environments, such as agricultural soil, wetlands, and hydroponic systems, remain limited.

Opportunities and challenges associated with the use of MOFs for nutrient recovery in soilless agriculture

Nutrient recovery from waste streams for use in agricultural production, particularly for high-value crops, is essential for achieving sustainable agriculture (Figure 5). First, the OM must be partially decomposed and transformed into inorganic forms, while inorganic nutrients should be enriched. Moreover, organic carbon levels must be minimized to avoid excessive biological and chemical oxygen demand during degradation, which can lead to anoxic conditions and root rot (Wongkiew et al., 2021). In addition to nutrient recovery, contaminants commonly present in waste streams, such as heavy metals and organic pollutants, must be reduced to safe levels to mitigate health risks. Animal manure-derived organic waste and wastewater often contain heavy metals, which can accumulate in plants and thus enter the food chain and pose serious health risks. In soil-based agriculture, heavy metals can be adsorbed by soil particles, reducing their bioavailability and mitigating their impact. In contrast, soilless cultivation systems lack this buffering capacity, increasing the risk of heavy metal accumulation in crops when organic fertilizers are applied.

Theoretically, MOFs offer promising potential for addressing this challenge, as they can selectively adsorb various heavy metals depending on their chemical and physical properties (Ugwu et al., 2020). Their tunable structures allow the selection of specific MOFs tailored to the types of heavy metal contaminants present in wastewater or organic fertilizers. Therefore, integrating MOFs into nutrient recovery strategies presents a valuable opportunity to increase the safety, efficiency, and sustainability of resource reuse in agriculture. Leaching stability (e.g., metal/ligand release under relevant pH and ionic strength) should be assessed to support environmental safety and regulatory acceptance.

1) Organic degradation by MOFs for nutrient enhancement

Organic waste typically contains high OM loads and high carbon-to-nitrogen (C/N) ratios, which can negatively affect plant growth—particularly in soilless cultivation systems. High organic loading may lead to oxygen depletion in the water and around the root zone, resulting in low dissolved oxygen levels. These conditions adversely impact both root development and the microbial communities responsible for nutrient transformation (e.g., nitrogen) into plant-available forms (Wongkiew et al., 2021; Zhi et al., 2021). Therefore, the degradation of carbon-based OM in fertilizers, compost, or organic wastewater could be essential prior to its application in soilless agricultural systems.

Although MOFs have been widely studied for their ability to degrade persistent organic pollutants (Pi et al., 2018), they show strong potential for application in soilless agricultural nutrient recovery through OM degradation. By facilitating the breakdown of complex organic compounds, MOFs can increase the bioavailability of nutrients while mitigating the risk of oxygen depletion. In addition to chemical additives, external energy sources can be used to activate MOFs and drive degradation reactions while minimizing chemical residues. One such approach is the modified air-Fenton process, which involves aeration without the need for additional chemical reagents. In this system, oxygen interacts with the MOFs to generate ROS, particularly oxygen radicals, which can then initiate the Fenton-like degradation of OM for high-nutrient liquid fertilizer synthesis (Suwannasung et al., 2023).

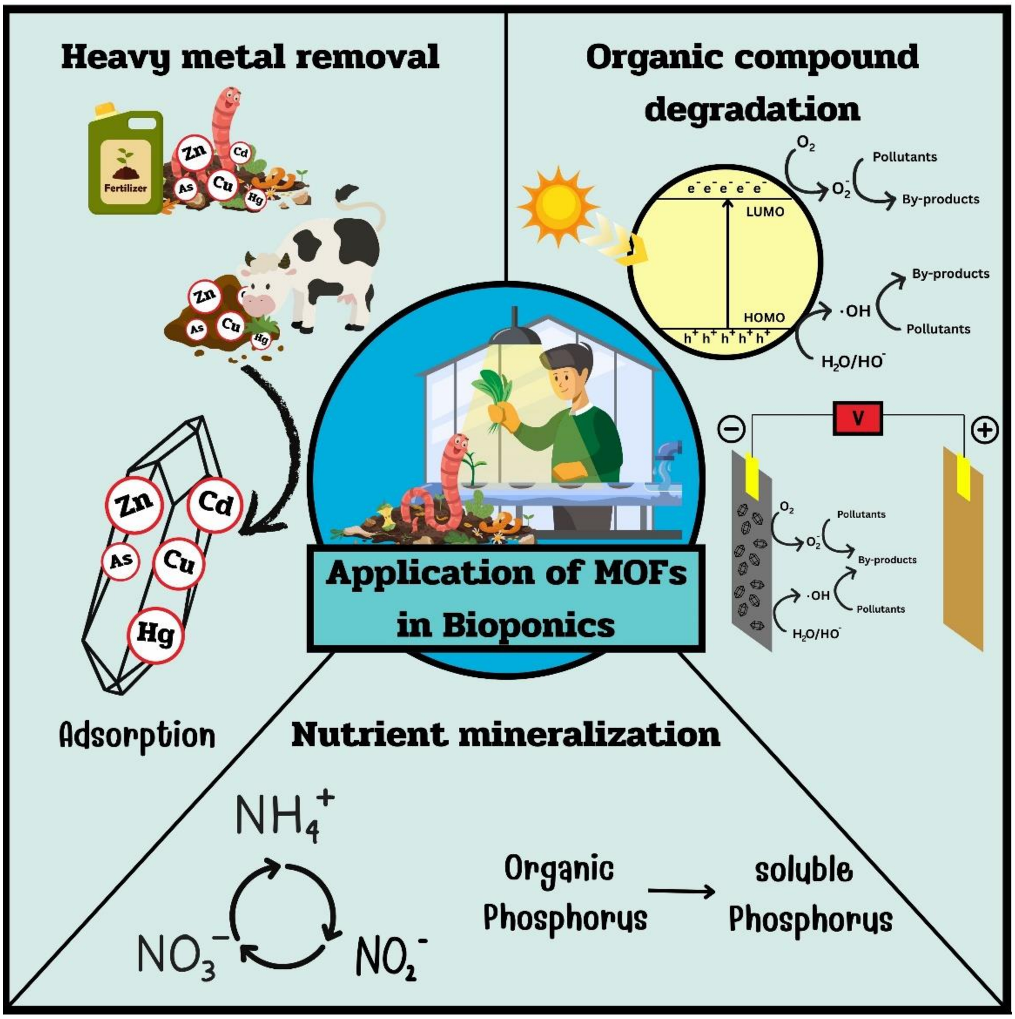

Figure 4 Opportunities and challenges associated with the use of MOFs for nutrient recovery in soilless agriculture, including heavy metal removal, organic compound degradation, nutrient mineralization, and their applications.

2) Nutrient mineralization by MOFs for bioavailable nutrients

Nutrient mineralization is a critical step in making nutrients available for plant uptake. Although organic fertilizers and nutrient-rich wastes or wastewaters contain essential nutrients, these nutrients are often present in organic forms that are not directly available to plants. In soil-based systems, microorganisms play a vital role in mineralization and the transformation of organic nutrients into plant-available forms. However, chemical reactions can facilitate the mineralization of organic compounds for microbial transformations in later steps.

Nitrogen, an essential nutrient for plant growth, often exists in organic forms within waste streams. Through oxidation processes, such as the Fenton reaction, organic nitrogen can be converted into ammonium, a form readily usable by plants (Silva et al., 2013). Fe-based MOFs can catalyze Fenton-like reactions when activated by external oxidants, such as H_2O_2, PMS, or ozone. However, reliance on external catalysts can limit mineralization efficiency and increase system complexity. To address this, photoFenton processes—driven by light rather than added chemicals—have been proposed as a more sustainable alternative. Here, the MOFs can serve as photocatalysts, initiating the generation of the ROS necessary for degrading OM and facilitating nitrogen transformation without the need for additional reagents (Ma et al., 2020). Furthermore, previous studies have shown that organic nitrogen can be mineralized into nitrate via the Fenton process (Carlos et al., 2010), with ammonium acting as an intermediate in the nitrification pathway. By enhancing these mineralization processes, MOFs hold significant potential to increase the availability of nitrogen in organic fertilizers and nutrient-rich waste streams. As a result, MOFs can be effectively integrated into agricultural systems to support sustainable nutrient recovery and reuse.

3) Safety considerations: Bioaccumulation

Bioaccumulation is a critical factor to consider when assessing the environmental and health impacts of the use of MOFs in agricultural applications. Owing to their small particle size, certain MOFs can penetrate cellular membranes and even pass through organ tissues and organelles, increasing the risk of accumulation within organisms (Baati et al., 2013). The bioaccumulation behavior of MOFs is largely influenced by their polarity. Hydrophilic MOFs have been shown to cross physiological barriers, such as the blood–brain barrier, leading to accumulation in the brain. In contrast, lipophilic MOFs tend to accumulate within intracellular compartments, such as lysosomes (Baati et al., 2013). These interactions highlight the importance of physicochemical properties in determining the fate and distribution of MOFs in biological systems. Despite these risks, most organisms possess excretory systems capable of eliminating foreign particles. Thus, MOFs with low toxicity are more likely to be excreted efficiently without causing adverse effects. Therefore, both the potential for bioaccumulation and the toxicity profile of MOFs must be carefully evaluated before their application in agricultural settings. Among the various types of MOFs, Fe-based MOFs are considered more suitable for agricultural use because of their relatively low toxicity and favorable biocompatibility, making them promising options for safer integration into soilless agricultural systems.

Nutrient recovery by MOFs in bioponics: A perspective

Bioponic systems combine organic fertilizers—such as chicken manure, vermicompost, or organic compost—with hydroponic (soilless) cultivation. These systems aim to recover nutrients from organic waste and wastewater and convert them into plant biomass, contributing to sustainable agriculture. While synthetic fertilizers are currently formulated specifically for hydroponic use, they are typically derived from chemical compounds rather than natural sources. In contrast, organic fertilizers, although suitable for soil-based systems, often contain undecomposed OM, limiting their immediate availability for plant uptake under hydroponic conditions. To make organic fertilizers compatible with hydroponic systems, additional processing steps are often needed. For instance, microbial inoculation can facilitate the decomposition and mineralization of nutrients into forms readily absorbed by plants (Park and Williams, 2024; Wongkiew et al., 2022). However, bioponic systems face several limitations. High organic loading levels from organic fertilizers can reduce dissolved oxygen levels in water, impairing microbial decomposition efficiency and root function (Zhi et al., 2021). Furthermore, animal-manure-based fertilizers may contain heavy metals because of environmental contamination (Lv et al., 2016), which raises concerns regarding food safety and plant health.

The integration of MOFs into bioponic systems presents a novel opportunity to enhance nutrient recovery and reduce contaminants. In particular, Fe-based MOFs can catalyze Fenton and photoFenton reactions to degrade complex organic compounds and convert organic nitrogen into the plant-available forms of ammonium and nitrate (Cao et al., 2022). This process not only supports nutrient mineralization but also may reduce nitrogen losses associated with nitrous oxide emissions—a significant contributor to greenhouse gas emissions in agriculture. Additionally, owing to their high porosity, MOFs can adsorb ammonium ions, potentially inhibiting nitrogen loss and improving nitrogen use efficiency.

Despite these benefits, challenges remain. Fenton reactions facilitated by MOFs may inhibit phosphorus availability because of the precipitation of phosphate with ferrous ions (Kumar, 2011), thereby limiting the critical nutrient required for plant growth. Moreover, MOFs can generate ROS, which pose toxicity risks to microbial communities and plant cell walls. These ROS can damage the cell membranes, DNA, and intracellular components of beneficial microbes (Plastiras et al., 2024), potentially disrupting essential biological processes, such as nutrient cycling and OM degradation. Furthermore, MOF-induced changes in water chemistry—including shifts in nutrient concentrations, pH, and dissolved oxygen—may alter the structure and function of microbial communities within the bioponic system. For example, increased inorganic nitrogen levels may favor nitrogen-utilizing microbes, whereas reduced organic carbon substrates could suppress heterotrophic bacteria. Such changes could affect system stability, nutrient cycling, and overall ecosystem health.

Therefore, while MOFs hold promise for improving nutrient recovery and reducing contaminants in bioponic systems, their impact on microbial ecology and plant health must be carefully evaluated. Future research should focus on understanding these interactions to optimize the safe and effective application of MOFs in sustainable soilless agriculture. Moreover, MOF should be designed for agricultural compatibility, long-term environmental impacts should be assessed, and strategies to mitigate potential toxicity should be developed. With proper design and management, MOFs could play a critical role in advancing sustainable nutrient recovery and contaminant control in next-generation soilless agricultural systems. Although MOFs have been studied at the laboratory scale in soil cultivation for pesticide, nutrient, and plant-hormone delivery, quantitative evidence for their performance in soilless agriculture (e.g., hydroponics/bioponics) and nutrient mineralization remains limited. Future studies should report key metrics (e.g., nutrient recovery/removal efficiency, release kinetics, plant uptake, and microbial impacts) under realistic cultivation conditions to support feasibility and scale-up.

Conclusions

Currently, MOFs can be synthesized by several methods, including solvothermal, microwave-assisted, mechanochemical, electrochemical, and sonochemical techniques. In terms of large-scale production, compared with traditional batch processes, continuous-flow synthesis methods can be applied to reduce cost and energy demand, and they are considered more suitable for real-world implementation. MOFs have shown great potential for diverse applications, particularly in environmental remediation, including the removal of organic pollutants and heavy metals. In addition, MOFs can be considered nutrient slow-release fertilizers, and previous studies have reported nutrient recovery from urea and wastewater using MOF-based approaches. In soilless agricultural systems, MOFs offer promising opportunities to enhance sustainable practices. Their high surface area, tunable porosity, and catalytic properties enable them to degrade persistent organic compounds, remove heavy metals from organic fertilizers, and facilitate nutrient recovery by transforming organic nitrogen into plant-available forms. However, certain MOF-induced reactions, such as phosphate precipitation, may limit the availability of essential nutrients such as phosphorus, thereby affecting plant growth. These characteristics make MOFs valuable for advancing nutrient recycling in soilless agricultural systems, including bioponics. However, the application of MOFs in agriculture presents several challenges. Despite some limited evidence, the potential toxicity to humans, animals, and beneficial microorganisms must be carefully evaluated. For instance, MOFs can generate ROS, which can damage cellular membranes and DNA, thereby affecting microbial communities essential for nutrient cycling. However, further work is needed to improve cost-effectiveness and confirm long-term safety in agricultural systems.

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Data availability statement

Information and data used in the study will be disclosed upon request.

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Sumeth Wongkiew: Conceptualization, Data curation, Writing – Review & editing, Supervision, Project acquisition

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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