




Metal organic frameworks: Innovation in fertilization and crop defense

Oluwatoyosi Oyebiyi^a, Felice Modugno^a, Konstantinos C. Christoforidis^b,
Panagiota Stathopoulou^c, George Tsiamis^c, Spyridon Ntougias^b, Antonio Scopa^a,
Marios Drosos^{a,*} 

^a Department of Agricultural, Forest, Food, and Environmental Sciences, University of Basilicata, Viale dell'Ateneo Lucano 10, 85100, Potenza, Italy

^b Department of Environmental Engineering, Democritus University of Thrace, 12 Vas. Sofias, 67132, Xanthi, Greece

^c Department of Sustainable Agriculture, University of Patras, 2 G. Seferi St., 30131, Agrinio, Greece

ARTICLE INFO

Keywords:

Sustainability
Pesticide
Fertilizer
Food security
Agronomic practices
Nutrient-use efficiency

ABSTRACT

As food demand increases, low nutrient-use inefficiency and significant environmental losses associated with the widespread use of conventional fertilizers and pesticides highlight the need for technological upscale. Metal-Organic Frameworks (MOFs) are organometallic porous materials well-known for their high surface areas, various architectures, and the ability to be chemically modified. These characteristics have attracted attention regarding their use in agriculture, environmental remediation and food safety, particularly as controlled-release fertilizers for improved crop productivity; however, a clear gap between promising laboratory results and field agricultural use still exists. This review provides an integrated assessment of MOFs as multifunctional delivery platforms for nutrients and phytosanitary management, their performance, limitations, and practical applicability in agriculture. Recent literature on MOF synthesis, structural properties, and functional mechanisms is critically evaluated, with emphasis on their applications as controlled-release fertilizers and agrochemical carriers. MOF-based systems exhibit high capacity for nutrient loading and controlled-release properties, leading to improved nutrient use efficiency and reduced leaching losses compared to conventional fertilizers. MOFs can be utilized to deliver pesticides and antimicrobials in a controlled and gradual manner, while minimizing environmental effects through low-cost compositions with high crop protection efficacy. Additionally, some MOFs demonstrate intrinsic antimicrobial activity, capable of protecting plants and postharvest losses. Despite this, the challenges of material stability in soil, long-term environmental fate, potential toxicity, and economic cost remain bottlenecks to large-scale adoption. This review combines insights from fertilization and crop protection perspectives to illustrate the potential of MOFs as multifunctional agricultural inputs and outlines knowledge gaps in field performance, safety assessment, and upscaling. Interdisciplinary research that addresses these challenges is key to advancing MOF-based technologies beyond the laboratory and into practical large scale agricultural systems. Adoption of MOFs in sustainable nutrient management strategies can potentially lead to progress toward resource use efficiency, environmental impact reduction, and next-generation agricultural inputs.

1. Introduction

In the last two decades, extended efforts have been made to address food security challenges. This has resulted in an increased interest in innovations that can sustain food production considering a rapidly growing global population. The goal is not only to improve crop yields but also to reduce the environmental pressure amplified by chemical fertilizers and pesticides [1]. Although conventional farming techniques have resulted in high yields, their continuous extended application has

been linked to certain environmental concerns. These include the leaching of nutrients into groundwater, the accumulation of synthetic pesticides in the soil and aquatic ecosystems, and the reduction in soil microbial biodiversity [2]. According to FAO [3], most of the N applied to soil is not assimilated by the plants and it is lost into the environment as nitrates or nitrogen oxides, which highly contribute to eutrophication and greenhouse gas emissions. These make clear the necessity for developing new technologies that can enhance nutrient-use efficiency and prevent the excess release of agrochemicals into the environment.

* Corresponding author. Viale dell'Ateneo Lucano 10, 85100, Potenza, Italy.
E-mail address: marios.drosos@unibas.it (M. Drosos).

<https://doi.org/10.1016/j.jafr.2026.102976>

Received 8 April 2026; Received in revised form 30 April 2026; Accepted 1 May 2026

Available online 2 May 2026

2666-1543/© 2026 Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Metal-Organic Frameworks (MOFs) have attracted attention due to their high structural versatility and their potential to release both nutrients and plant protection compounds in a controlled manner. However, there is a critical gap between laboratory-scale innovations and their field performance under real agricultural conditions, with factors such as soil heterogeneity, climate variability, and multi-season dynamics influencing performance. MOFs are crystalline compounds of high porosity formed by linking metal ions or clusters with organic ligands such as polycarboxylates, azoles, or phosphonates [4]. The current concept of MOFs mainly relied on the pioneering works by Yaghi et al. [5,6], which demonstrated that crystalline porous frameworks could be deliberately designed with exceptionally large surface areas and tunable chemical characteristics. Since their introduction, MOFs have found applications in numerous sectors, including gas storage, catalysis, CO₂ capture, sensing, drug delivery, removal of pollutants and food packaging [7–10].

The interest in their use in agriculture is relatively recent but rapidly growing. The underlying idea could be likened to the one that guided the use of MOFs in the pharmaceutical field: exploiting their porosity, the ability to adsorb and release molecules in a controlled manner and the possibility of chemically modifying both metal knots and organic binders to regulate the properties of the material. Several studies show that some MOF based on Fe, Zn, Zr or Mg exhibit sufficient stability and biocompatibility to serve as promising carriers for nutrients such as N, P and micronutrients [11,12]. They have also been explored for the encapsulation of pesticides and fungicides to reduce volatility, prevent premature degradation, and minimize dispersion in soil [13–15].

One of the main advantages of MOFs, compared to other controlled release systems such as biodegradable polymers or nanoclays, lies in their “designability”. Choice of metal nodes, organic binders, and synthesis conditions is routinely used to tune MOF water stability, pH-based behavior, degradability and molecular affinity [16,17]. The high internal surface, which in some cases exceeds 6000 m² g⁻¹, also allows significant quantities of active molecules to be stored, increasing the load available for agronomic applications [18,19]. Recent studies suggest that MOFs can significantly reduce nitrate leaching and improve the efficiency of nutrient use by plants [20], although most of these applications are still at the laboratory level or in the pilot phase [14,21,22].

Despite the promising prospects from the use of MOFs in agriculture, several critical issues have been raised that require careful evaluation. These include the stability of materials under field conditions, and other challenges relating to their biodegradability, the potential release of metal ions, toxicity to non-target organisms and long-term environmental accumulation. In addition, the lack of specific regulations for the use of porous nanomaterials in agriculture poses challenges for both industrial development and commercial use authorization [23]. Economic analyses show that the synthesis costs of MOFs, still considerably higher than those of conventional fertilizers, remain a major barrier to their widespread adoption. However, advances in large-scale production techniques and the development of green synthesis approaches are progressively reducing these limitations [24,25]. This review provides an integrated evaluation of MOFs as multifunctional agricultural systems, combining fertilization and crop protection while explicitly assessing the limitations of current laboratory-based evidence for field-scale implementation. Recent literature on MOF synthesis, structural properties, and functional mechanisms, were critically evaluated, with emphasis on their application as controlled-release fertilizers and carriers for agrochemicals.

The objective of this paper is to provide a critical and integrative review of the use of MOFs in agriculture, with emphasis on their chemical foundations, synthesis pathways, operating mechanisms, potential benefits and related risks. Based on recent scientific findings, agronomic performance, environmental sustainability, and safety from the application of MOFs are critically evaluated. Moreover, future opportunities and the main technological and economic constraints from full-scale implementation of MOFs are discussed.

2. History of Metal-Organic Frameworks

The development of MOF is relatively recent, but the underlying concepts date to the 19th century coordination chemistry. By the late 1800s, Alfred Werner had defined the fundamental principles governing the coordination of metal ions with organic or inorganic ligands, laying the foundation for understanding how multidimensional structures could be formed from metal units and multidentate molecules [26,27]. However, for most of the twentieth century, these complexes were studied primarily as discrete coordination complexes rather than as extended, crystalline networks with permanent porosity [6,28]. A significant precursor to modern MOFs was the development of “coordination polymers,” in which metal nodes and organic ligands form chains or extended networks [29]. During the 1980s and early 1990s, a number of porous structures based on coordination bonds began to emerge, but their stability and ability to maintain porosity after solvent removal were still limited [30,31].

The real revolution came between the end of the nineties and early 2000s with the advent of reticular chemistry. Yaghi et al. [6] demonstrated that it was possible to obtain extended and highly porous crystalline lattices through a strategy of reticular synthesis based on the rational choice of metal nodes and rigidly defined organic ligands. Also, the 1999 report of MOF-5, a structure based on zinc and terephthalic acid nodes, provided a prominent example of materials characterized by a high surface area and permanent porosity even after solvent evacuation [32]. These two works laid the foundations for a new family of materials capable of far surpassing, in terms of porosity and modularity, traditional zeolites and activated carbons.

From the 2000s onwards, interest in MOFs grew rapidly, accompanied by an extraordinary expansion of the number of structures synthesized. The review by Kitagawa et al. [33] helped to formalize the distinction between MOF and the earlier “porous coordination polymers,” underlining the role of permanent porosity as a discriminating criterion. At the same time, the field began to diversify into sub-families of materials with specific characteristics: the MIL (Materials Institute Lavoisier) developed by the Gérard Férey's group, offered robustness and flexibility suitable for demanding operating conditions [34]; the UiO-MOFs (University of Oslo), pioneered by the Karl Petter Lillerud group delivered remarkable thermal and hydrolytic stability due to zirconium clusters [35]; and the ZIFs (Zeolitic Imidazolate Frameworks), structural analogues of zeolites but based on imidazole binders [6,36].

In the early 2000s, the applications of MOFs focused mainly on the storage of hydrogen and methane, CO₂ capture and catalysis, areas in which MOFs showed competitive performance compared to traditional porous materials [37]. The ability to chemically modify both metal nodes and organic ligands made MOFs extremely versatile materials, giving rise to thousands of different structures. In the past decade, a growing interest in their biological and environmental uses has been shown. For instance, Fe- or Zr-based MOFs have been investigated as slow-release fertilizers capable of providing nutrients in a controlled manner under soil conditions (e.g. Fe-MOF nutrient carriers). More recently, agricultural applications, including nutrient delivery and agrochemical encapsulation, are emerging as a promising frontier. Today MOFs represent one of the most studied materials in the world, with applications ranging from energy to medicine, from water purification to environmental catalysts, up to innovative systems for fertilization and crop protection. Although their industrial development is still limited by high costs and regulatory issues, their history suggests that they could play a significant role in the technologies of the future, including the agricultural sector.

3. What are Metal-Organic Frameworks: definition and chemical principles

Metal-Organic Frameworks are porous crystalline materials made of

metal nodes and organic ligands that form three-dimensional structures with nano-sized cavities and tubes [38,39]. Their hybrid nature between inorganic and organic materials, differentiate them from simple inorganic zeolitic networks and porous organic polymers and make them a unique class of synthesized materials with improved adsorption properties [9,40]. Chemically, MOF is formed by metal units, often single metal ions or polynuclear clusters, which act as coordination nodes, and polytoothed organic ligands, such as carboxylates, imidazoles, pyridines, or phosphonates, which act as connectors [41]. The geometry and rigidity of both the metal node and the ligand determine the final topology of the lattice, according to the principles of reticular chemistry [40].

One of the most distinguishing characteristics of MOFs is their permanent porosity, exhibited by the ability to maintain stable internal cavities even after the removal of the solvents used during crystallization. This phenomenon, rare in earlier coordination polymers, results from the rigidity of the metal-ligand bonds and the deliberate geometric arrangement of the framework. The surface area of some MOFs is exceptionally high, e.g. MOF-177 and NU-110 have specific surface areas that exceed 4500-6000 m² g⁻¹, much greater than the specific surface area of common porous materials [28]. Due to their uniform and chemically adjustable pores, MOFs can be engineered in terms of dimensions and functionality to be suitable for the targeted compounds. The nature of metal nodes plays a key role in determining thermal and chemical stability, as well as any catalytic or redox behavior. MOFs can include metals or clusters of metals, such as Zn, Cu, Zr, Fe, Mg, Cr or Al. For example, the Zr-based UiO-MOFs is characterized by high hydrolytic and thermal resistance, while Fe-based MOFs have shown good biocompatibility suitable for environmental and biological applications [35].

Organic ligands, on the other hand, define not only lattice geometry, but also surface chemistry and functionalization. Ligands such as terephthalate (BDC), trimesate (BTC) and imidazole derivatives allow networks to be built with very different topologies [42]. The possibility of introducing functional groups directly on ligands (such as -NH₂, -OH, -COOH) allows them to impart specific reactivity, modulated polarity or affinity towards certain host molecules. This capacity for chemical programming is one of the reasons for the success of MOFs in areas such as catalysis, gas storage or the controlled release of drugs and agrochemicals [38].

Another fundamental concept is directional coordination and structural flexibility shown by some MOFs. These frameworks can undergo reversible changes in their architecture when exposed to external stimuli such as variations in pressure, shifts in temperature, or the presence of specific guest molecules. This behavior, known as “gating” or “breathing”, is characteristic of some materials of the MIL series and other flexible MOFs [43,44]. This property can be advantageous for controlled release applications, because it allows the material to open and close by modulating the diffusion of the host molecules.

However, the stability of MOFs depends to a large extent on the type of metal and ligand used. Some MOFs, such as those based on Zn and simple carboxylates (e.g. MOF-5), show poor moisture resistance and tend to degrade in the presence of water [37]. Others, such as UiO-66 or MIL-101, exhibit remarkable robustness and can withstand much more extreme conditions, including wide pH ranges, elevated temperatures, and exposure to water or other polar solvents [28,34,35]. As interest in their environmental and biological applications has grown, significant research has focused on understanding how these materials break down under hydrolytic or thermal stress. Table 1 summarizes the most investigated MOFs reported for agricultural and environmental research, presenting their metal composition, ligands, surface area, pore characters and associated physicochemical characteristics.

4. Use of MOF in agriculture

The application of Metal-Organic Frameworks in agriculture

represents one of the most recent and promising strands of porous materials research. Although MOFs were initially designed for applications in the energy, environmental and pharmaceutical fields, their modular structure, large surface area and the ability to control the kinetics of adsorption and release of molecules have made them candidates of great interest for the development of intelligent fertilizers and advanced phytosanitary formulations.

The growing need for more efficient and sustainable agricultural systems has helped to direct part of the research towards materials capable of reducing the leaching of nutrients, improving the availability of elements in the soil and minimizing the environmental impact of pesticides. One of the main problems of modern agriculture in fact concerns the waste of nutrients. Much of the nitrogen and phosphorus applied to soil is lost due to volatilization (50-70%), washing or insoluble (5-10%) generating economic costs and environmental damage [15,20]. At the same time, traditional phytosanitary treatments often suffer from poor efficiency (<10%), because the active ingredient is rapidly degraded by sun, moisture or microbiological decomposition, requiring repeated applications and high doses [45-47].

The possibility of designing porous materials capable of hosting nutrients or active molecules and releasing them gradually, or only in response to specific physico-chemical stimuli of the soil, opens the way to more targeted agricultural techniques with less impact. MOFs based on iron, zinc, zirconium and magnesium are getting attention due to their good stability, relative biocompatibility and potential biodegradability. In recent years, scientific production on the subject has grown rapidly. Several reviews and experimental articles published between 2018 and 2024 have shown encouraging results on the beneficial use of MOFs on model crops, showcasing both the advantages and the criticalities of such approaches. For instance, a review on MOFs as nano-carriers for agriculture highlights their promise of controlled nutrient release, environmental remediation, and sensing, while noting that practical deployment still faces hurdles in scaling up, cost, and environmental behavior [11]. Use of MOF-based slow-release fertilizers can be considered an attractive alternative to conventional fertilizers since they significantly improve nutrient use efficiency by controlling release rates and reducing leaching losses [22,48]. Several reviews have also reported that MOFs can serve as advanced vectors to reduce environmental dispersion compared to traditional formulations through encapsulation of pesticides and their release in a controlled manner [11, 47].

The use of MOFs in agriculture can be employed for fertilization and phytosanitary defense purposes (Fig. 1). In the first case, MOFs can act as nutrient reservoirs or vectors of essential micronutrients to improve their availability and reduce their dispersion. They can also act as delivery systems for pesticides, protect the active ingredient from degradation and permit their progressive release. The range of their applications can be expanded since MOFs can directly contribute to the destruction of pathogens or the degradation of contaminants, due to their catalytic properties [49,50].

In addition to these functions, MOFs have shown possible environmental remediation functions such as the removal of heavy metals, pesticide residues, and excess nutrients from soil and water. MOFs, with their high surface area and tunable adsorption capabilities, are very efficient in removing pollutants and can be applicable for soil remediation and the improvement of irrigation water quality [51]. This is particularly relevant to long-term accumulation of pollutants which can negatively impact soil health and crop yield. Furthermore, post-harvest application of MOFs in food packaging systems is increasingly being explored [7,8]. The ability of MOFs to absorb gases like ethylene (with uptake capacity of about 41 cm³ g⁻¹), regulate moisture, and deliver slow-release antimicrobial agents makes them well-suited for extending the shelf life of perishable foods like fruits, vegetables, and meat [52], thus reducing food waste in long-distance shipping. These applications extend the use of MOFs along the agricultural value chain with a synergy between crop production and storage.

Table 1
Representative MOFs commonly investigated for agricultural and environmental applications.

MOF	Metal node	Organic ligand	BET surface area (m ² g ⁻¹)	Structural Motif/ Lattice Type	Pore size (nm)	Controlled nutrient release suitability	Relative stability in soil	Key properties	Representative applications	Ref.
MIL-101 (Fe)	Fe ³⁺	Terephthalate (BDC)	3000–4100	Mesoporous MTN topology	2.9–3.4	Very Good	High	Strong Fe–O clusters, high porosity; good aqueous stability across moderate pH	Soil incubation/lab: Nutrient & pesticide delivery	[34,96, 97]
UiO-66	Zr ⁴⁺	Terephthalate (BDC)	1100–1500	12-connected fcu topology	~0.6	Excellent (slow, sustained release)	Very high	Strong Zr–O bonds; high node connectivity; exceptional hydrolytic resistance	Lab: Phosphate adsorption; pesticide encapsulation	[35,97, 98]
UiO-66-NH ₂	Zr ⁴⁺	Amino-BDC	900–1200	fcu topology (expanded linker)	1.1–2.2	Excellent	Very high	Robust Zr cluster, functionalized surface; improved adsorption affinity	Lab: Agrochemical delivery	[35,98, 99]
ZIF-8	Zn ²⁺	2-Methylimidazole	1400–1600	sodalite (SOD) topology	1.1–1.5	Moderate–Low	Moderate–Low	pH-responsive; degrades in acidic media	Lab: Pesticide delivery	[36, 97]
MIL-53 (Fe)	Fe ³⁺	Terephthalate (BDC)	1000–1500	Flexible “wine-rack” topology	Flexible	Good (responsive release possible)	Moderate–High	Breathing behavior; moisture sensitivity	Lab: Stimuli-responsive release systems	[97, 100]
Mg-MOF-74	Mg ²⁺	DOBDC (2,5-dihydroxyterephthalate)	630–1300	1D hexagonal channels	1.1–1.2	Moderate (fast release likely)	Low– Moderate	Open metal sites; acid-sensitive; biodegradable; strong adsorption	Lab: Mg release; soil amendment	[101, 102]
NH ₂ -MIL-125 (Ti)	Ti ⁴⁺	Aminoterephthalate	1200–1500	3D Ti–carboxylate	~0.7	Very Good	High	Strong Ti–O bonds; photocatalytic; moderate hydrolytic robustness	Lab: Antimicrobial/ phytosanitary applications	[103, 104]
HKUST-1	Cu ²⁺	Trimesate (BTC; 1,3,5-benzenetricarboxylate)	1200–1800	tbo topology	0.9–1.1	Poor (rapid collapse)	Very low	Open Cu sites; good porosity; moisture sensitivity reported in water/acidic conditions	Lab: Model MOF for stability studies	[102, 105]
MOF-177	Zn ₄ O clusters	BTB (1,3,5-benzenetricarboxylate)	3875–4500	Highly porous cubic net	mesoporous cages	Limited	Low	Ultra-high porosity; large cages; high surface area	Lab: High-capacity adsorption; benchmark in ultraporous MOF literature	[102, 106, 107]
NU-110	Cu ₂ paddlewheel	Acetylene-rich extended carboxylate linker	~7140	Low-density Zr framework	microporous, very high pore volume	Moderate	Low– Moderate	Very high BET areas; ultrahigh porosity	Lab: Benchmark ultrahigh surface area MOF; gas storage research	[107]
GR-MOF-27	Mg ²⁺	Fosfomycin-derived phosphate	-	Layered hybrid framework	-	Moderate	Moderate	Mg–O bonds weaker than Zr/Fe/Ti; stability enhanced by rigid linker	Greenhouse: Mg release and nutritional effect in plants	[53]

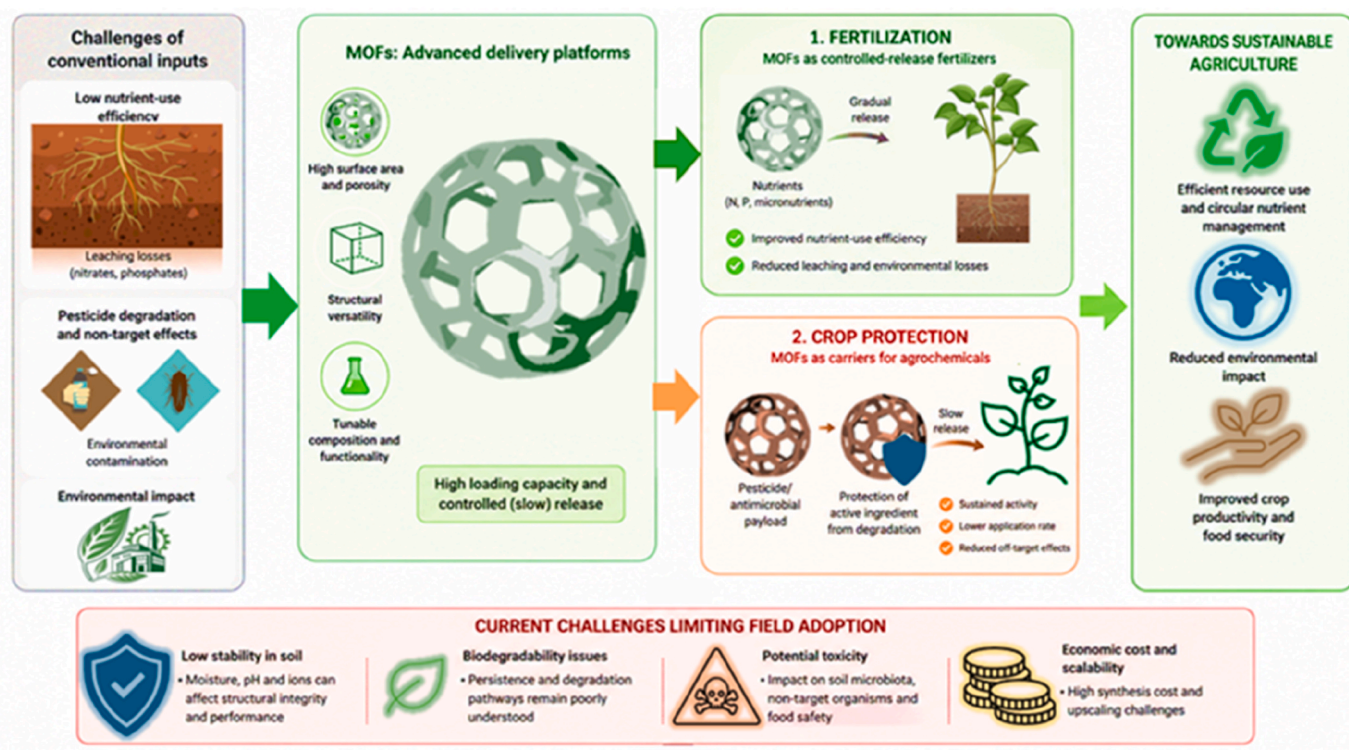


Fig. 1. Overview of the application of MOFs in agriculture.

Despite these advances, the use of MOFs in agriculture is still in the research and development phase, conducted through laboratory or pilot-scale studies. Issues regarding their stability, degradation/release rates and potential risks on soil microbiota, beneficial insects, and non-target organisms need to be addressed. Even though MOFs have indicated potential to become a valuable tool in the development of sustainable agricultural systems. An overview of the application of MOFs in agriculture showcasing their adoption as controlled release fertilizers, and carriers for agrochemicals towards a sustainable crop productivity and food security as well as challenges limiting field adoption is presented in Fig. 1.

4.1. MOF for fertilization: controlled release of nutrients

The use of MOFs as smart fertilizers is based on their capacity to trap

essential plant nutrients within their porous structure through physical (van der Waals forces, hydrogen bonds) or chemical (coordination with metal centers) interactions and subsequently release them slowly into the soil. This mechanism is illustrated in Fig. 2. The strength of these interactions determines the load capacity of the material and the rate at which the compound can subsequently be released. This controlled-release approach directly addresses a major limitation of conventional fertilizers which is the tendency to discharge nutrients too quickly, leading to significant losses through leaching or volatilization and ultimately lowering the amount available for plant uptake.

The most studied nutrients in combination with MOF are nitrogen, phosphorus and micronutrients such as zinc, iron and magnesium [20, 22,53]. In some cases, MOFs can directly incorporate nutrient ions into their framework. For instance, iron- or magnesium-based MOFs are capable of releasing these elements gradually as the framework

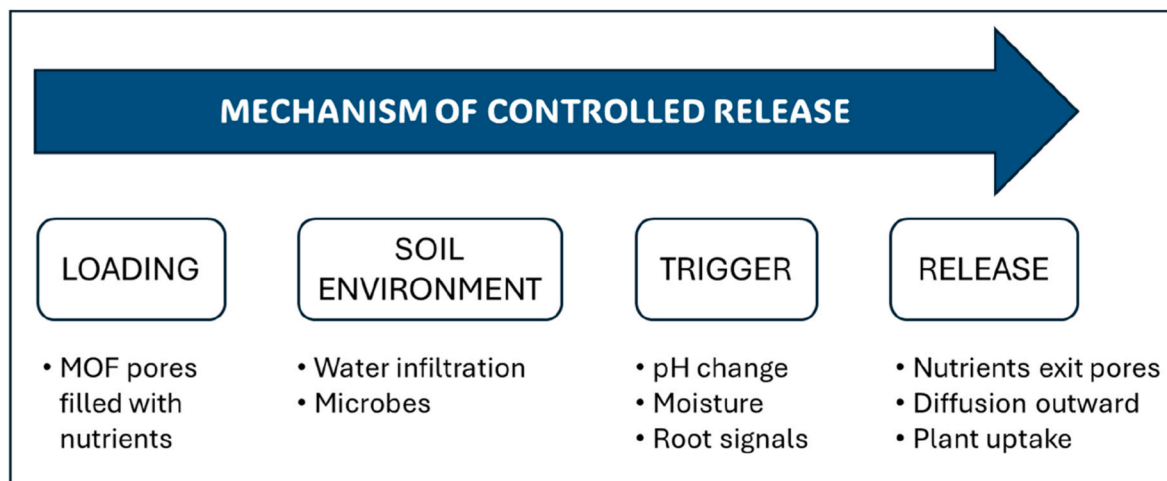


Fig. 2. Mechanism of controlled release of nutrients in soil-plant systems.

naturally breaks down in the soil [22]. Other MOFs can instead absorb nutrients such as ammonium, nitrate or phosphate inside the pores, retaining them through electrostatic or coordinating interactions [15]. Many MOFs break down faster under acidic conditions, such in the case of fertile, organic-rich soils. This pH-dependent degradation and nutrient release can be advantageous in slightly acidic environments where plant roots are more active. For instance, magnesium-based MOFs (Mg-MOF-74) dissolved more readily at pH values below 6, gradually releasing Mg^{2+} ions that support chlorophyll formation and photosynthesis [54]. Similarly, ZIF-8, a zinc-based framework, is more soluble in acidic soils, providing Zn^{2+} either as an essential micronutrient or as an enhancer of seed germination [55].

Recent experimental studies indicated that iron-based MOFs enriched with N, P, and Fe were successfully synthesized at both laboratory and pilot scales to gradually release N, P and Fe over 98 days when incubated in soil, with significantly slower release and reduced leaching compared to conventional soluble fertilizers, and improved rice yield under controlled conditions [22]. Similarly, in a field trial with a hydrothermally synthesized MOF rich in N, P, and Fe, about 50.9% of the MOF had degraded during the cropping season with soil analyses indicating sustained nutrient supply [20], demonstrating that MOF degradation can serve as a controlled-release mechanism under real soil conditions. Comparable results have been obtained with other MOF types: a citric acid-based MOF maintained slow nutrient release over 100 days in soil incubation [48]. And a magnesium-based MOF (GR-MOF-27) released Mg^{2+} over time, with treated plants showing greater Mg uptake (64.9%) and growth (13.1% dried weight) compared to conventional $MgSO_4$ fertilizer, confirming that MOF-based nutrient delivery is not limited to iron-based frameworks [53]. This progressive release of Mg^{2+} , especially under acidic soil conditions, improves the availability of this micronutrient, potentially contributing to the correction of soil acidity. Representative studies of MOF-mediated controlled release of plant nutrients are summarized in Table 2.

The ability to modulate the release of nutrients by adjusting the composition, functionalization or crystallinity of the MOF enables the fabrication of highly customizable fertilizers. In some cases, it has also been shown that the release can be stimulated by specific environmental conditions, such as pH variations, presence of anions in the soil or microbial activity, paving the way for “smart” systems capable of responding to the real needs of the plant. Laboratory and soil-microcosm studies further indicated that nanometric MOF formulations can interfere with soil microbial communities and transiently modify enzyme activities linked to the nitrogen cycle. For example, long-term soil exposure to an iron-based MOF nano pesticide (CF@MIL-101) altered the abundance and composition of nitrifying and denitrifying bacterial groups and changed N-cycling dynamics in soil and in earthworm gut microbiomes [56]. Changes in urease, dehydrogenase and nitrification activity depending on nanoparticle type, dose and soil texture have also been reported in other lab microcosm and shock-load experiments with MOF or metal-based nanoparticles further confirming that metal-based engineered nanoparticles can disrupt soil enzyme activities and N transformations [57,58].

4.2. MOF for phytosanitary defense: delivery of pesticides, fungicides and insecticides

The use of MOF in phytosanitary defense represents a significant evolution compared to traditional formulations of pesticides. Most of the pesticides and fungicides used today in agriculture have in fact well-documented problems ranging from poor stability to sunlight, rapid hydrolytic degradation, volatilization, and low biological efficiency, sometimes below 0.1% of the active ingredient applied [13,59]. The rest is lost in the environment, contributing to soil, water and air pollution, as well as increasing the risks for non-target organisms.

Research on MOFs as delivery systems for agro-chemicals arises precisely from the need to improve the efficiency of formulations,

Table 2
Controlled release of nutrients using MOFs.

MOF type	Nutrient (s) tested	System/test	Key result (concise)	Ref.
Fe-MOFs	N, P, Fe	Soil amendment; rice pot test	Gradual release of NH_4^+ , NO_3^- , P, Fe over 98 days; rice yield improved vs controls.	[22]
Citric-acid derived MOFs	N (from urea), P	Soil and water (laboratory-scale)	MOFs synthesized hydrothermally from ferric chloride, citric acid, phosphoric acid and urea; sustained nutrient release >100 days in soil.	[48]
Iron-based oxalate-phosphate-amine MOF	N, P	Soil (laboratory-scale)	Rapid urea hydrolysis; slow conversion of ammonium to nitrate; slow P mobilization; efficient N fertilizer.	[108]
Hydrothermal MOF (N, P, Fe rich MOF)	N, P, Fe	Field trial — wheat soil (field)	MOF framework degraded 50.9% over the wheat season; soil nutrient analyses indicated sustained N, available P and Fe supply during crop growth (evidence of controlled-release via framework degradation).	[20]
Core-shell MIL-100(Fe)/silica nanocarrier	Urea (N)	Laboratory-scale release tests	MIL-100(Fe)/silica core-shell loaded with urea: demonstrated controlled urea release and improved N-use metrics in model tests.	[109]
GR-MOF-27 (Mg-MOF)	Mg, P (co-released)	Plant growth tests (pot/greenhouse)	GR-MOF-27 released Mg^{2+} in controlled manner; plants had higher Mg uptake (64.9%) and better growth vs $MgSO_4$ control	[53]

reduce the frequency of treatments and reduce the chemical load dispersed in agricultural ecosystems. Among the most studied MOFs in the phytosanitary field, materials based on iron, zinc and zirconium stand out, chosen for their relative stability, lower toxicity and ability to maintain high levels of load of the active ingredient [13,15,60]. In many cases, the microporous structure of MOFs allows the pesticide to be retained due to physical interactions (adsorption, n-n, van der Waals) or chemical interactions (coordination with metallic sites), protecting it from photodegradation or leaching. An example is the use of MOF UiO-66, based on zirconium clusters, to convey fungicides such as carbendazim. Studies conducted in recent years have shown that UiO-66 can incorporate significant amounts of the active ingredient and release it gradually in the presence of water or in slightly acidic environments, typical conditions of agricultural soils. This controlled-release behavior enables the fungicide to remain effective over an extended period, reducing repeated applications compared to conventional formulations [60–62].

Zinc-based MOFs, such as ZIF-8 (zeolitic imidazolate framework), have also demonstrated strong potential as carriers of insecticidal compounds. ZIF-8 is relatively stable under neutral pH conditions but gradually breaks down in acidic environments, allowing the active ingredient to be released in a controlled manner. Thi@ZIF-8 (thiabendazole@ZIF-8) showed extended, pH-responsive release with

superior control of *Botrytis cinerea* and reduced soil leaching relative to free Thi [61], and CLO@ZIF-8 (clothianidin@ZIF-8) retained 70% efficacy against *Nilaparvata lugens* after water rinsing and maintained significantly higher residual activity than clothianidin solution over 10 days [62]. Similarly, within fungicide research, iron-based MOFs, such as MIL-101(Fe) have attracted considerable interest. Originally explored in pharmaceutical applications for the administration of bioactive molecules, this framework offers a high loading capacity and provides strong protection of the active ingredient against photodegradation. In a 2020 study, MIL-101(Fe) was used to convey diniconazole, a fungicide widely used in agriculture, with a loading content of 28.1% and a significant fungicidal bioactivity against *Fusarium graminearum* [63]. In addition, MOFs have also been used to control pests in stored food products [64]. Post-harvest losses due to insects, mites, and microbial contamination present a major concern in food systems. Their intrinsic antimicrobial activity, driven by reactive oxygen species generation and controlled release of bioactive compounds, enables effective inhibition of spoilage microorganisms and fungal pathogens. In addition, MOFs can adsorb and remove pesticide residues and toxins, with reported reductions below regulatory limits ($<10 \mu\text{g L}^{-1}$) [65], thereby improving food safety. This improves effectiveness, decreases active substance input, and limits exposure of food products to high concentrations of chemicals. Furthermore, the adsorption capabilities of MOFs may be exploited for the removal or controlled release of volatile compounds used in pest management, offering an alternative to conventional fumigation strategies.

Some MOFs can act as antimicrobial photocatalysts, by generating reactive oxygen species (ROS) under exposure to UV or visible light thereby damaging the membranes and enzymes of pathogens [66,67]. Materials such as NH_2 -MIL-125, have been tested and shown to achieve 99% antibacterial efficiency against *Staphylococcus aureus* and *Escherichia coli* within 20 min of white light irradiation [68]. In such applications, the MOF not only provides a physical barrier that moderates the release of fungicides but also contributes actively through photocatalytic degradation of pathogens, significantly broadening its functional utility. A growing interest in stimuli-responsive MOFs, which are engineered to discharge their active compounds under specific environmental signals, has been noted. Some studies have proposed MOFs that degrade more quickly in the presence of enzymes secreted by pathogenic fungi, releasing the active ingredient only near infection. Although it is still at a preliminary stage, this strategy could lead to the development of “smart” formulations that can drastically reduce the overall dosage needed. Table 3 summarizes key empirical studies on MOF-based phytosanitary systems, highlighting the types of MOFs employed, the active compounds loaded, and observed outcomes.

4.3. Sensing with MOF in agriculture

In addition to the more traditional roles of nutrient and pharmaceutical carriers, MOFs emerge as a promising platform for agricultural sensing, due to their highly porous structure, chemical modularity and functionalization possibilities. They are being adopted as tools to create sensors capable of detecting various critical analytes, such as soil moisture, fertilizer ions (for example nitrates) and also traces of pesticides, with high sensitivity and selectivity.

A particularly interesting example is the development of MOF-based soil moisture sensors [69], wherein a MOF (Cr-soc-MOF-1) with high water absorption capacity was applied to an interdigitized electrode and inserted into the ground, the water enters the pores of the MOF, replacing the initial air and modifies the dielectric constant (capacity) of the material, which can be measured electronically. This sensor showed a very high sensitivity (450% response increase) in clay soils, with response times in the order of a few hundred seconds [69]. Such sensors are directly relevant to irrigation management, where real-time moisture data can inform water application schedules and reduce overuse. It has also been shown that electrochemical sensors based on Ag-MOF can simultaneously detect nitrites and nitrates with very low detection limits ($0.045 \mu\text{M}$ for nitrite, $12 \mu\text{M}$ for nitrate), making them useful for monitoring nutrient availability in the soil or water used for irrigation [70]. This capability can be coupled with fertilizer application strategies to improve nutrient use efficiency and minimize leaching losses. Beyond nutrients and moisture, MOF-based optical sensors have been explored for detecting agrochemical contaminants. Fluorescent lanthanide-based MOFs (e.g., with Tb) are capable of detecting phosphates in pesticides such as glyphosate with limit detection of $0.0144 \mu\text{M}$ or other agrochemical molecules exhibiting micromolar or nanomolar sensitivity through estimation of light emission change in the presence of the analyte [71,72]. Likewise, Han et al. [73] developed a fluorescent sensing system based on UiO-67 to detect carbendazim residues in fruits and vegetables through determination of a ratiometric signal (UiO-67 emission quenching + carbendazim emission) with a detection limit of $0.003 \mu\text{M}$.

MOFs structure and properties further facilitate the design of multifunctional sensors that can be integrated with low-power electronics to develop IoT devices for online monitoring [74,75]. This use of MOF can be employed in precision agriculture for continuous, in situ monitoring of humidity, nutrients and contaminants, in order to optimize the use of resources (water, fertilizers) and reduce the environmental footprint.

Table 3
Empirical studies on MOFs for phytosanitary.

MOF (type)	Active ingredient (AI)	Loading/release behavior (key data)	Test system/outcome	Ref.
ZIF-67 (nanocarrier)	Boscalid (fungicide)	High loading (18%); pH-triggered release (faster in acidic conditions); enhanced antifungal efficacy vs free boscalid	Lab: in vitro antifungal tests (<i>Botrytis cinerea</i>); improved activity, reduced toxicity	[110]
pH-responsive MOF	Thiabendazole (fungicide)	Stimulus (pH) responsive release; sustained delivery and protection in simulated plant environment	Lab/plant protection assays; demonstrated sustained release and improved disease control	[61]
Polymer–MOF composites (UiO-66, UiO-66-NH ₂ ⁺ biodegradable polymer)	2,4-dichlorophenoxyacetic acid (2,4-D) (herbicide)	High loading (45 wt%); controlled, sustained release vs soluble 2,4-D; composite improves handling and biodegradability	Lab/greenhouse: reduced runoff potential and sustained herbicidal availability	[111]
ZIF-8, ZIF-67 and others	Various pesticides (multiple AIs across studies)	Reports many stimuli-responsive release profiles (pH, moisture, redox); improved stability and tunable kinetics	Lab and greenhouse studies summarized; most work pre-field scale	[60]
Various MOFs (survey)	Multiple: pesticides and agrochemicals	Collated experimental instances of targeted loading and controlled release; protective effect vs photodegradation noted	Review of experimental literature; includes references to specific encapsulation studies	[13]
MOFs@MPN nanocarrier (pH-responsive)	Pesticides (general)	pH-triggered release demonstrated; enhanced bioactivity and environmental stability	Lab tests: sustained-release behavior and improved efficacy	[112]

5. Limitations and stability challenges of MOFs

Despite the advantages of MOFs in agriculture, several steps are needed for their widespread adoption. One major issue is their stability under field conditions. MOFs that are stable in the laboratory may be degraded in soils, due to high moisture, humic substances, or temperature alterations. As summarized in Fig. 3, the stability of MOF is strongly dependent on environmental conditions. For instance, ZIF-8 and MIL-53 (Fe) are easily hydrolysed in humid and acidic ($\text{pH} < 5$) environments [55,76,77]. Oxidation of redox metals, such as Fe^{2+} or Cu^{2+} , may affect MOFs stability. In oxygenated environments or under solar radiation, these metal centers may oxidize and alter the coordination geometry and weaken the MOFs structure. Exposure to UV light can also induce photodegradation, particularly in the existence of aromatic binders such as terephthalate or imidazolates [78]. UV-induced cleavage of C-C or C-O bonds may occur in foliar applications, where the MOF is directly exposed to sunlight. Some researchers have developed photostable MOFs to mitigate such effects by replacing binders with aliphatic rings or by introducing surface coatings [79,80].

In addition, the possible release of metals such as Zr, Zn or Fe deserves further evaluation to avoid unwanted accumulations in the soil. Some zirconium- or copper-based MOFs may gradually leach small amounts of metals which, at elevated concentrations, could harm soil microbiota and fauna or aquatic life. For example, Zr-MOFs have been shown to leach Zr and linker species in buffered or photochemical environments, and UiO-66-type materials can release zirconium under aggressive conditions [81,82]. Likewise, Cu-MOFs such as HKUST-1 are hydrolytically labile and may release Cu^{2+} when exposed to water or acidic media [83].

The consistency and scalability of MOF synthesis are also major drawbacks. These materials require controlled manufacturing conditions, which rely on expensive reagents, organic solvents and energy-intensive processes. Despite the recent advances in water-based and biodegradable “green” synthesis methods, the production of MOFs at large scale with uniform quality is still difficult. This can lead to variations in synthesis and framework properties, and in uncertain behavior in field applications. Consequently, production costs remain high, which presently limits the realistic application of MOFs as commercial fertilizers or agro-products, although progress in cheaper and greener synthesis techniques could attenuate these barriers.

Analytical characterization poses another issue to address. Accurate measurement of active ingredients, load of MOF carries, porosity, and release rate and mechanism in complex environments such as soil,

require advanced instrumentation. Techniques such as BET surface area analysis, TGA, DRIFT spectroscopy, and ICP-MS are often necessary to obtain reliable data, however, these tools are not commonly available in standard agronomy laboratories.

6. Challenges and future prospects

The introduction of MOFs in agriculture may raise concerns about their possible effects on human health, animals' welfare, and environmental quality. MOFs are nanoscale materials with hybrid organic-inorganic structures that can release both metal ions and organic fragments during degradation, therefore thorough environmental assessment is prior to real-scale applications. Such assessment must consider the toxicity of constituent metals, the biodegradability of organic binders and their persistence in the soil, bioaccumulation aspects, and the effects on soil microbial communities and fauna. Most agricultural MOFs use relatively biocompatible metals such as Fe, Mg, Zn or Zr, which are generally assimilable and show low toxicity, but some also include Cu, Co or Ni, which can be cytotoxic at low concentrations [15,84]. Although metals such as Zn may become toxic at concentration levels above $200\text{--}300 \text{ mg kg}^{-1}$ [84] and highly persistent Zr-based frameworks could interfere with soil microbiota, if accumulated, current studies suggest low risk at realistic agronomic doses. Application rates of MOFs reported in soil systems are generally low ($<50 \text{ mg kg}^{-1}$), and most functional studies have been conducted at $\leq 20\text{--}30 \text{ mg kg}^{-1}$ [85,86]. However, long-term field studies are needed to fully assess environmental risk posed by Zr-based frameworks, given their persistence and potential for bioaccumulation. While there is no direct evidence that Zn-MOFs such as ZIF-8 affect *Rhizobium* symbiosis, studies with free Zn^{2+} and ZnO nanoparticles show that elevated Zn concentrations or nanoparticulate Zn can inhibit *R. leguminosarum* growth, delay nodulation, and reduce nitrogen fixation [87]. Although ZIF-8 is primarily used as an adsorbent (and not as catalyst as ZnO), similar effects cannot be excluded since Zn^{2+} may be released from ZIF-8 [88], thus deserving further investigation before field deployment.

Organic binders based on terephthalate, fumarate or imidazolate are gradually mineralized in soil, with reported half-lives typically ranging from 2 to 8 weeks, producing metabolites already present in soil chemistry, while newer bio-based linkers further improve biodegradability [11,89]. Fe- and Mg-based MOFs tend to degrade within weeks, whereas Zr- and Ti-based materials may persist longer; nevertheless, complete degradation within one or two crop cycles is considered desirable to avoid long-term accumulation [15,90–92]. Due to their nanoscale size (50–500 nm), attention is required regarding bioaccumulation, but available evidence indicates that most biodegradable MOFs remain largely localized in the rhizosphere and show low toxicity in plant and animal models. Ecotoxicity studies generally report limited and reversible effects on earthworms, pollinators and soil microbiota, with only transient shifts in microbial enzyme activity [56].

A comparison of some key characteristics of MOFs with conventional porous materials commonly used today in agriculture, namely natural zeolites, pumice and other mineral soil conditioners is summarized in Table 4. These conventional materials have been extensively utilized owing to their affordability and natural abundance. While these materials possess passive adsorption and ion exchange capabilities, they lack the tunable and selective release functionality of MOFs for controlled and stimuli-responsive release kinetics. Although considerably more expensive than conventional fertilizers, the improved nutrient use efficiency, lower leaching losses, and multifunctionality of MOFs has the potential to mitigate the economic limitation through reduced application frequency and subsequently improve overall agronomic performance. Moreover, MOFs provide greater opportunities for modulation of release rates and nutrient delivery compared to traditional materials that predominantly display a fixed diffusion-controlled release behavior. Mineral materials such as zeolites and pumice are characterized by high stability and low ecotoxicity; on the other hand, MOFs exhibit variable

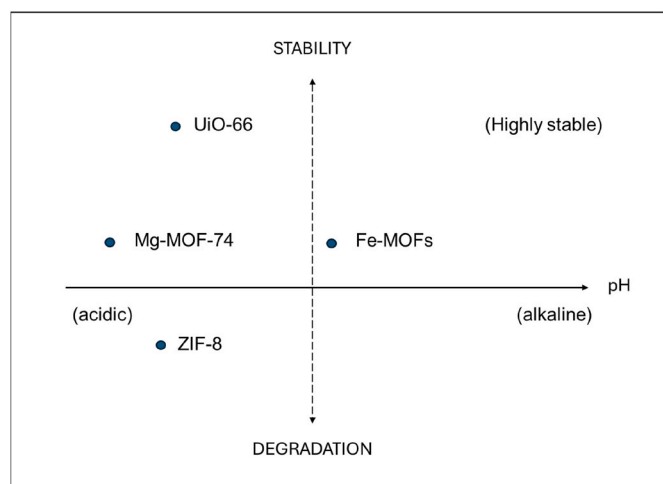


Fig. 3. Stability and degradation behavior of representative MOFs under varying environmental conditions relevant to agricultural soils. This system is acted upon and significantly influenced by moisture and exposure to UV light.

Table 4
Cost Benefits Analysis of MOFs and Conventional Porous Materials used in Agriculture.

Material	Typical cost (USD/kg)	Surface area (m ² /g)	Functionality	Controlled release capability	Stability in soil	Ecotoxicity risk	Advantages	Limitations	Ref.
MOFs	10–100+	500–7000	Highly tunable; multifunctional	Excellent (stimuli-responsive)	Variable (depends on type)	Moderate (metal-dependent)	High efficiency; reduced leaching; smart delivery	High cost; scalability issues	[107,113]
Natural zeolites (clinoptilolite)	0.1–0.5	50–300	Ion exchange (NH ₄ ⁺ , K ⁺ retention)	Moderate (diffusion-based)	High	Low	Very cheap; widely available; soil conditioning	Limited tunability; lower capacity	[114]
Synthetic zeolites (e.g., 13X)	0.5–30	300–800	Adsorption, ion exchange	Moderate	High	Low–moderate	Higher purity and performance than natural zeolites	Limited functionality	[113]
Pumice/volcanic materials	0.05–0.3	<10	Physical water retention	Low	Very high	Very low	Extremely cheap; improves aeration	No active nutrient control	[115,116]
Activated carbon/biochar	1–5	500–1500	Adsorption of organics, nutrients	Moderate	High	Low–moderate	Improves soil structure; carbon sequestration	Limited selectivity	[117–119]

biodegradability depending on metal nodes and organic linkers, thus, their use as soil amendments in agriculture should be done with caution.

From an economic point of view, the recent cost for MOFs production is one of the main barriers for wide adoption in agriculture. Techno-economic analysis by Severino et al. (2021) estimated the production cost of MIL-160(Al) at about 55 US\$ kg⁻¹ at an industrial scale of 100 t yr⁻¹, which is higher than the cost of conventional fertilizers such as urea or ammonium nitrate (typically <1 US\$ kg⁻¹). Earlier cost assessments for MOFs such as HKUST-1 and MOF-5 projected large-scale manufacturing costs of 35–71 US\$ kg⁻¹ using solvothermal routes, and potentially 13–36 US\$ kg⁻¹ with low-solvent or aqueous synthesis [10]. While low application rates are anticipated for MOFs compared to conventional fertilizers (estimated around 20–30 kg ha⁻¹ vs 150–300 kg ha⁻¹ for conventional nitrogen fertilizers) [93], these values remain system dependent and have not been standardized across different crops and formulations yet. Conventional urea fertilizers typically cost about

50–150 US\$ ha⁻¹, whereas polymer-coated controlled-release fertilizers (with generally superior efficiency) could increase costs to about 150–400 US\$ ha⁻¹ due to higher market prices. However, production and application costs for MOF-based fertilizers such as ZIF-8 and UiO-66, are likely to reach up to a maximum of 1000 US\$ ha⁻¹. Although, a change in material composition like the use of Mg and Ca can result in lower production costs and lower application rates, reaching an overall cost of 100–200 US\$ ha⁻¹, which can be even more reduced with the further adoption of the MOF technology.

The economic competitiveness of MOF depends on future advances in scalability and low-cost synthesis. MOFs can be synthesized using different techniques, such as conventional solvothermal and hydrothermal methods [40]. Solvothermal methods, most often utilizing organic solvents like N,N-dimethylformamide (DMF) or N,N-diethylformamide (DEF) under high temperature and pressure, are the most widely used due to their ability to produce highly crystalline

Table 5
Conventional vs Greener and Scalable MOF Synthesis Strategies.

Synthesis approach	Key principle	Main advantages	Scalability potential	Reaction time	Agricultural applications	Ref.
Solvothermal synthesis	Reaction in organic solvents (e.g., DMF, DEF) at elevated temperature and pressure	High crystallinity; well-defined and reproducible structures; widely applicable	Moderate (limited by solvent cost, energy demand, and scale-up constraints)	12–72 h	High-performance MOFs for pesticide encapsulation; mechanistic studies of nutrient adsorption and release	[6, 120]
Hydrothermal synthesis	Reaction in water under elevated temperature and autogenous pressure	Safer solvent system; good crystallinity; reduced toxicity compared to organic solvents	Moderate to high (more scalable than solvothermal but still energy-intensive)	6–48 h	Controlled-release fertilizers with moderate cost and good structural stability	[120, 121]
Mechanochemical synthesis	Solvent-free ball milling or grinding	Minimizes solvent use, fast synthesis, low environmental footprint	High	10–60 min	Large-scale production of fertilizers; soil amendments; cost-sensitive applications	[122, 123]
Liquid-assisted grinding	Trace green solvent added during milling	Improves crystallinity, still low solvent consumption	Moderate to high	10–120 min	Improved-quality MOFs for controlled-release fertilizers and agrochemical delivery where moderate crystallinity is required	[124, 125]
Water-based synthesis	MOFs grown in pure water instead of DMF/DEF	Non-toxic, cheaper solvent system, eco-friendly	High	2–24 h	Environmentally friendly fertilizers; applications requiring low toxicity	[126, 127]
Seed-assisted aqueous growth	Crystalline MOF “seeds” guide low-energy nucleation	Lower temperature, fast growth, better reproducibility	High	1–12 h	Uniform MOFs for reproducible nutrient delivery systems	[128, 129]
Biomass-derived linkers	Use of natural acids (citric, lactic, fumaric)	Renewable feedstock, reduced cost, improved biodegradability	Moderate to high	-	Biodegradable fertilizers; sustainable and eco-friendly agricultural inputs	[130]
Waste-derived precursors	Use of PET plastics or industrial waste as organic linkers or metal sources	Circular economy approach, lower raw-material costs	Moderate	-	Low-cost fertilizers; circular economy-based agricultural systems	[24]
Microwave-assisted synthesis	Rapid heating via microwave irradiation	Short reaction times, energy efficient	Moderate	5–60 min	Rapid production of MOFs for time-sensitive or pilot-scale applications	[131, 132]

materials with well-defined structures. However, these approaches tend to be highly energy-intensive, require long reaction times, and raise environmental concerns in relation to solvent use (Table 5). In recent years, significant progress has been made to reduce costs. Techniques such as water synthesis or mechanochemical synthesis (solvent-free) offer prospects in reducing both economic and environmental impact of production [94,95], particularly for large-scale agricultural applications where solvent use and energy consumption are critical constraints. In addition, the possibility of using agro-industrial waste precursors (such as citric acid or lactic acid from biomass) to create natural linkers may further improve economic sustainability [24,94]. Use of agricultural residues and low-cost metal ions may further reduce MOFs production cost. Table 5 presents an overview of these greener and scalable strategies for MOF synthesis, highlighting some of their foremost attributes and applicability.

A critical limitation across current studies is that most findings were derived from laboratory or controlled greenhouse experiments, such as soil incubations and pot trials, with only a very few field-scale trials to support the underlying mechanisms (e.g., Wu et al., 2019, 2022). Hence, there remains a considerable gap between laboratory scale performance and the field, specifically with contrasting soil types, climate variability, and multi-season cultivation cycles. Most specifically, the lack of long-term field data over several growing seasons makes it practically impossible to comprehensively evaluate the stability, nutrient release behavior, and fate of MOFs in environment when assessed under realistic agricultural settings. This remains a key barrier to practical agricultural adoption and scaling.

An emerging area is that of “intelligent” MOFs, capable of reacting to environmental stimuli such as pH, humidity, temperature or the presence of specific ions. These “responsive” materials could modulate the release of nutrients based on the real physiological needs of the plant or soil conditions, integrating perfectly with precision agriculture and digital soil monitoring systems. Meanwhile, there is still a lack of long-term data on the ecological impacts, poor standardization of assessment protocols and the complexity of the toxicity tests required for placing on the market. In addition, the stability of MOFs under field conditions (rain, solar radiation, pH variations), as well as the need for safety throughout food web, are key issues to be addressed.

Future progress in the use of MOFs in agriculture will depend on the synergy between materials chemistry, biotechnology, and agronomy. By reducing production costs and addressing environmental footprint issues, MOFs could become one of the most promising materials for sustainable, efficient and low-impact agriculture.

7. Conclusion

Metal-Organic Frameworks represent one of the most promising compounds of materials chemistry applied to agriculture. Their hybrid nature, consisting of metal ions and organic binders, results in the synthesis of functional material of high surface area and porosity. These features make MOFs ideal for nutrient storage and controlled release of nutrients or bioactive compounds in agricultural systems. Thus, MOFs can permit the controlled release of nutrients based on plant physiology and soil nutrient content, thereby permitting the efficient use of resources and improving environmental quality. Moreover, their ability to incorporate key macro- and micronutrients, including Fe, Zn, Mg, and P, provides new opportunities for sustainable, targeted, crop nutrition.

Experimental evidence to date demonstrates clear agronomic advantages, including improved nitrogen use efficiency, and significant reduction in nutrient leaching. MOFs have also been successfully explored as pesticide carriers for targeted application, in order to lower the quantity of bioactive ingredients required while extending its protective effect. These applications represent the most realistic near-term uses of MOFs in agriculture and are already supported by laboratory and pilot-scale studies. These advances align with global policy frameworks for reduced fertilizer and pesticide use.

However, the scale-up from laboratory innovation to field application is a challenging issue. Economic scalability, regulatory clarity, long-term ecotoxicological validation, and the design of materials that balance functional stability with safe use and complete biodegradation are prerequisites for wide adoption in agriculture. Current advances in “green MOFs,” made from nutrient metals like Fe, Mg, Ca and natural organic linkers such as citric or tartaric acid, materials designed to biodegrade within the timeframe of typical crop cycles, represent an essential step toward resolving these challenges.

The development of multifunctional MOFs, capable of responding to environmental or biological stimuli, can be integrated into modern precision agriculture systems. In combination with sensors, drones and digital platforms, these advanced materials could provide a new generation of adaptive, targeted, fertilizers, capable of optimizing plant nutrition in real time, simultaneously reducing environmental footprint and maximizing plant productivity, although such applications still require validation under field conditions.

MOFs represent a paradigm shift in how nutrients and protection agents can be provided in agro-ecosystems in a targeted and controlled manner. Current applications are likely to focus on controlled-release fertilizers, agrochemical delivery systems, and pollutant adsorption technologies, while advanced smart agricultural systems remain a longer-term goal. Bridging the gap between laboratory-scale innovation and field-scale implementation will be critical, and will require interdisciplinary efforts across materials science, agronomy, environmental safety assessment, and policy development. Addressing these challenges will determine whether MOFs can transition from promising research materials to practical tools for improving agricultural productivity and environmental sustainability.

CRedit authorship contribution statement

Oluwatoyosi Oyebiyi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Felice Modugno:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Konstantinos C. Christoforidis:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation. **Panagiota Stathopoulou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation. **George Tsiamis:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Data curation. **Spyridon Ntougias:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Data curation, Conceptualization. **Antonio Scopa:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Marios Drosos:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Funding

This research was funded by the project “Integrated Approaches at Local Scale for Enhancing Water Reuse Efficiency and Sustainable Soil Fertilization from Wastewater's Recovered Nutrients (CIRQUA)”, Grant agreement No. 2321, Call 2023 Section 1 Management of Water IA, that is part of the PRIMA program in the European Union Horizon 2020. The content reflects only the authors' view. The PRIMA Foundation is not responsible for any use that may be made of the information it contains.

Declaration of competing interest

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

Data availability

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

References

- [1] A. Kumar, G. Antoniella, E. Blasi, T. Chiti, Recent advances in regenerative sustainable agricultural strategies for managing soil carbon and mitigating climate change consequences, *Catena* 258 (2025) 109208, <https://doi.org/10.1016/j.catena.2025.109208>.
- [2] E.W. Kamau, R. Gitau, H.K. Bett, Effects of adoption of ecological farming practices on farm income in rural households: evidence from central Kenya, *Heliyon* 10 (2024) e34610, <https://doi.org/10.1016/j.heliyon.2024.e34610>.
- [3] FAO, *The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction*, FAO, Rome, 2019.
- [4] D. Li, A. Yadav, H. Zhou, K. Roy, P. Thanasekaran, C. Lee, Advances and applications of metal-organic frameworks (MOFs) in emerging technologies: a comprehensive review, *Glob. Chall.* 8 (2023) 2300244, <https://doi.org/10.1002/gch.202300244>.
- [5] O.M. Yaghi, H. Li, C. Davis, D. Richardson, T.L. Groy, Synthetic strategies, structure patterns, and emerging properties in the chemistry of modular porous solids, *Acc. Chem. Res.* 31 (1998) 474–484, <https://doi.org/10.1021/ar970151f>.
- [6] O.M. Yaghi, M. O'Keeffe, N.W. Ockwig, H.K. Chae, M. Eddaoudi, J. Kim, Reticular synthesis and the design of new materials, *Nature* 423 (2003) 705–714, <https://doi.org/10.1038/nature01650>.
- [7] W. Sun, Y. Huo, X. Feng, L. Wei, X. Lu, S. Liu, Z. Gao, Recent advances in metal-organic frameworks (MOFs)-based colorimetric sensors for visual detection of food freshness, *Coord. Chem. Rev.* 535 (2025) 216638, <https://doi.org/10.1016/j.ccr.2025.216638>.
- [8] D. Yan, M. Yang, F. Cheng, Y. Sun, Novel antimicrobial agents prepared on the basis of metal-organic frameworks (MOFs) and their applications in the food field, *Trends Food Sci. Technol.* 161 (2025) 105070, <https://doi.org/10.1016/j.tifs.2025.105070>.
- [9] P.A. Sampaio, E.C.V. Pereira, P.G.S. Sá, J.M.T. Alencar Filho, L.R.M. Ferraz, R.H. V. Nishimura, A.S. Ferreira, P.J. Rolim Neto, E.S. Araújo, L.A. Rolim, A review on metal-organic frameworks as technological excipients: synthesis, characterization, toxicity, and application in drug delivery systems, *Compounds* 5 (2025) 1, <https://doi.org/10.3390/compounds5010001>.
- [10] D. DeSantis, J.A. Mason, B.D. James, C. Houchins, J.R. Long, M. Veenstra, Techno-economic analysis of metal-organic frameworks for hydrogen and natural gas storage, *Energy Fuel.* 31 (2017) 2024–2032, <https://doi.org/10.1021/acs.energyfuels.6b02510>.
- [11] S. Basak, P. Bhattacharyya, R.N. Pudake, P.E. Lokhande, U. Rednam, S. Chakrabarti, Metal-organic framework as nanocarriers for agricultural applications: a review, *Front. Nanotechnol.* 6 (2024) 1385981, <https://doi.org/10.3389/fnano.2024.1385981>.
- [12] R.M. Abdelhameed, R.E. Abdelhameed, H.A. Kamel, Iron-based metal-organic frameworks as fertilizers for hydroponically grown *Phaseolus vulgaris*, *Mater. Lett.* 237 (2019) 72–79, <https://doi.org/10.1016/j.matlet.2018.11.072>.
- [13] L.A.M. Mahmoud, R.A. dos Reis, X. Chen, V.P. Ting, S. Nayak, Metal-organic frameworks as potential agents for extraction and delivery of pesticides and agrochemicals, *ACS Omega* 7 (2022) 45910–45934, <https://doi.org/10.1021/acsomega.2c05978>.
- [14] H.A. Masood, T. Ahmed, M.K. Zahid, M. Noman, M.A. Yousaf, H.M. Ali, B. Li, S. Han, Metal-organic frameworks as versatile platforms for sustainable crop disease management: a comprehensive review of mechanisms and applications, *Environ. Sci. Nano* 12 (2025) 3425–3441, <https://doi.org/10.1039/d5en00042d>.
- [15] S. Rojas, A. Rodríguez-Diéguez, P. Horcajada, Metal-organic frameworks in agriculture, *ACS Appl. Mater. Interfaces* 14 (2022) 16983–17007, <https://doi.org/10.1021/acsaami.2c00615>.
- [16] D. Zhao, G. Yu, M. Ge, M. Han, H. Meng, W. Xiong, L. Wen, Post-modified linker functionalization of metal organic frameworks for high-efficiency adsorption and quantification of trace organophosphorus pesticides in environmental water, *Sep. Purif. Technol.* 346 (2024) 127470, <https://doi.org/10.1016/j.seppur.2024.127470>.
- [17] M. Kalaj, S.M. Cohen, Postsynthetic modification: an enabling technology for the advancement of metal-organic frameworks, *ACS Cent. Sci.* 6 (2020) 1046, <https://doi.org/10.1021/acscentsci.0c00690>.
- [18] G. Deffo, A.K. Tamo, C.G. Fotsop, H.H.B. Tchoumi, D.E.N. Talla, C.G. Wabo, M.C. N. Deussi, R.C.T. Temgoua, G. Doungmo, E. Njanja, et al., Metal-organic framework-based materials: from synthesis and characterization routes to electrochemical sensing applications, *Coord. Chem. Rev.* 536 (2025) 216680, <https://doi.org/10.1016/j.ccr.2025.216680>.
- [19] D. Chauhan, R.A. Omar, R.V. Mangalaraja, M. Ashfaq, N. Talreja, Metal-organic framework as an emerging material: a novel plant growth stimulant, in: *Nanotechnology-Based Sustainable Alternatives for the Management of Plant Diseases*, Elsevier, 2022, pp. 323–339, <https://doi.org/10.1016/b978-0-12-823394-8.00015-9>.
- [20] K. Wu, C. Du, F. Ma, Y. Shen, D. Liang, J. Zhou, Degradation of metal-organic framework materials as controlled-release fertilizers in crop fields, *Polymers* 11 (2019) 947, <https://doi.org/10.3390/polym11060947>.
- [21] R.C. Alves, V.C. Luna, C.J. Baco, A.J. Terezo, M. Castilho, A.B. Siqueira, Emerging applications of nano-metal-organic frameworks for sustainable agriculture: a critical review, *Plant Nano Biol* 12 (2025) 100159, <https://doi.org/10.1016/j.plana.2025.100159>.
- [22] K. Wu, X. Xu, F. Ma, C. Du, Fe-based metal-organic frameworks for the controlled release of fertilizer nutrients, *ACS Omega* 7 (2022) 35970–35980, <https://doi.org/10.1021/acsomega.2c05093>.
- [23] R.A. dos Reis, M.A. Fernández-Baldo, R.S. Nunes, A.B. Seabra, Metal-organic frameworks: an overview of a possible solution for modern agriculture, *Microporous Mesoporous Mater.* 391 (2025) 113609, <https://doi.org/10.1016/j.micromeso.2025.113609>.
- [24] K. Boukayouh, L. Bazzi, S. El Hankari, Sustainable synthesis of metal-organic frameworks and their derived materials from organic and inorganic wastes, *Coord. Chem. Rev.* 478 (2023) 214986, <https://doi.org/10.1016/j.ccr.2022.214986>.
- [25] M.I. Severino, E. Gkaniatsou, F. Nouar, M.L. Pinto, C. Serre, MOFs industrialization: a complete assessment of production costs, *Faraday Discuss.* 231 (2021) 326–341, <https://doi.org/10.1039/d1fd00018g>.
- [26] U. Mueller, M. Schubert, F. Teich, H. Puetter, K. Schierle-Armdt, J. Pastré, Metal-organic frameworks—Prospective industrial applications, *J. Mater. Chem.* 16 (2006) 626–636, <https://doi.org/10.1039/b511962f>.
- [27] K.H. Ernst, F.R.W.P. Wild, O. Blacque, H. Berke, Alfred Werner's coordination chemistry: new insights from old samples, *Angew. Chem. Int. Ed.* 50 (2011) 10780–10787, <https://doi.org/10.1002/anie.201104477>.
- [28] H. Furukawa, K.E. Cordova, M. O'Keeffe, O.M. Yaghi, The chemistry and applications of metal-organic frameworks, *Science* 341 (2013), <https://doi.org/10.1126/science.1230444>.
- [29] B.F. Hoskins, R. Robson, Infinite polymeric frameworks consisting of three dimensionally linked rod-like segments, *J. Am. Chem. Soc.* 111 (1989) 5962–5964, <https://doi.org/10.1021/ja00197a079>.
- [30] R. Robson, The historical development of the concepts underlying the design and construction of targeted coordination polymers/MOFs: a personal account, *Chem. Rec.* 24 (2024), <https://doi.org/10.1002/tcr.202400038>.
- [31] T.R. Cook, Y.R. Zheng, P.J. Stang, Metal-organic frameworks and self-assembled supramolecular coordination complexes: comparing and contrasting the design, synthesis and functionality of metal-organic materials, *Chem. Rev.* 113 (2012) 734, <https://doi.org/10.1021/cr3002824>.
- [32] H. Li, M. Eddaoudi, M. O'Keeffe, O.M. Yaghi, Design and synthesis of an exceptionally stable and highly porous metal-organic framework, *Nature* 402 (1999) 276–279, <https://doi.org/10.1038/46248>.
- [33] S. Kitagawa, R. Kitaura, S.I. Noro, Functional porous coordination polymers, *Angew. Chem. Int. Ed.* 43 (2004) 2334–2375, <https://doi.org/10.1002/anie.200300610>.
- [34] C. Férey, C. Mellot-Draznieks, C. Serre, F. Millange, J. Dutour, S. Surlblé, I. Margiolaki, A chromium terephthalate-based solid with unusually large pore volumes and surface area, *Science* 309 (2005) 2040–2042, <https://doi.org/10.1126/science.1116275>.
- [35] J.H. Cavka, S. Jakobsen, U. Olsbye, N. Guillou, C. Lamberti, S. Bordiga, K. P. Lillerud, A new zirconium inorganic building brick forming metal organic frameworks with exceptional stability, *J. Am. Chem. Soc.* 130 (2008) 13850–13851, <https://doi.org/10.1021/ja8057953>.
- [36] K.S. Park, Z. Ni, A.P. Côté, J.Y. Choi, R. Huang, F.J. Uribe-Romo, H.K. Chae, M. O'Keeffe, O.M. Yaghi, Exceptional chemical and thermal stability of zeolitic imidazolate frameworks, *Proc. Natl. Acad. Sci. USA* 103 (2006) 10186–10191, <https://doi.org/10.1073/pnas.0602439103>.
- [37] J.L.C. Rowsell, O.M. Yaghi, Metal-organic frameworks: a new class of porous materials, *Microporous Mesoporous Mater.* 73 (2004) 3–14, <https://doi.org/10.1016/j.micromeso.2004.03.034>.
- [38] V.R. Remya, M. Kurian, Synthesis and catalytic applications of metal-organic frameworks: a review on recent literature, *Int. Nano Lett.* 9 (2018) 17–29, <https://doi.org/10.1007/s40089-018-0255-1>.
- [39] A. Carné-Sánchez, I. Imaz, K.C. Stylianou, D. Maspoeh, Metal-organic frameworks: from molecules/metal ions to crystals to superstructures, *Chemistry* 20 (2014) 5192–5201, <https://doi.org/10.1002/chem.201304529>.
- [40] F. Zeggai, Z. Ait-Touchente, K. Bachari, A. Elaissari, Investigation of metal-organic frameworks (MOFs): Synthesis, properties, and applications – an in-depth review, *Chem. Phys. Impact* 10 (2025) 100864, <https://doi.org/10.1016/j.chphi.2025.100864>.
- [41] M. Karimi, Z. Mehrabadi, M. Farsadrooh, R. Bafkary, H. Derikvandi, P. Hayati, K. Mohammadi, Metal-organic framework, *Interface Sci. Technol.* 33 (2021) 279–387, <https://doi.org/10.1016/b978-0-12-818805-7.00010-2>.
- [42] D. Zhao, D.J. Timmons, D. Yuan, H.C. Zhou, Tuning the topology and functionality of metal-organic frameworks by ligand design, *Acc. Chem. Res.* 44 (2011) 123–133, <https://doi.org/10.1021/ar100112y>.
- [43] G. Férey, C. Serre, Large breathing effects in three-dimensional porous hybrid matter: facts, analyses, rules and consequences, *Chem. Soc. Rev.* 38 (2009) 1380–1399, <https://doi.org/10.1039/b804302g>.
- [44] A. Schneemann, V. Bon, I. Schwedler, I. Senkovska, S. Kaskel, R.A. Fischer, Flexible metal-organic frameworks, *Chem. Soc. Rev.* 43 (2014) 6062–6096, <https://doi.org/10.1039/c4cs00101j>.
- [45] K. Fenner, S. Canonica, L.P. Wackett, M. Elsner, Evaluating pesticide degradation in the environment: blind spots and emerging opportunities, *Science* 341 (2013) 752–758, <https://doi.org/10.1126/science.1236281>.
- [46] M. Arias-Estévez, E. López-Periago, E. Martínez-Carballo, J. Simal-Gándara, J. C. Mejuto, L. García-Río, The mobility and degradation of pesticides in soils and the pollution of groundwater resources, *Agric. Ecosyst. Environ.* 123 (2008) 247–260, <https://doi.org/10.1016/j.agee.2007.07.011>.

- [47] R.S. Kookana, A.B.A. Boxall, P.T. Reeves, R. Ashauer, S. Beulke, Q. Chaudhry, G. Cornelis, T.F. Fernandes, J. Gan, M. Kah, et al., Nanopesticides: guiding principles for regulatory evaluation of environmental risks, *J. Agric. Food Chem.* 62 (2014) 4227–4240, <https://doi.org/10.1021/jf500232f>.
- [48] K. Wu, C. Du, F. Ma, Y. Shen, J. Zhou, Optimization of metal–organic (citric acid) frameworks for controlled release of nutrients, *RSC Adv.* 9 (2019) 32270–32277, <https://doi.org/10.1039/c9ra06939a>.
- [49] M.S. Khan, Y. Li, D.S. Li, J. Qiu, X. Xu, H.Y. Yang, A review of metal–organic framework (MOF) materials as an effective photocatalyst for degradation of organic pollutants, *Nanoscale Adv.* 5 (2023) 6318–6348, <https://doi.org/10.1039/d3na00627a>.
- [50] D. Terrón, A. Sanromán, M. Pazos, Metal–organic frameworks: next-generation materials for environmental remediation, *Catalysts* 15 (2025) 244, <https://doi.org/10.3390/catal15030244>.
- [51] G.A. Udourioh, I.I. Alikali, M.M. Solomon, C.O. Matthews-Amune, Environmental remediation using metal–organic frameworks: recent progress in adsorption capacities, mechanisms, and practical applications, *J. Mol. Struct.* 1351 (2026) 144167, <https://doi.org/10.1016/j.molstruc.2025.144167>.
- [52] Y. Fu, D. Yang, Y. Chen, J. Shi, X. Zhang, Y. Hao, Z. Zhang, Y. Sun, J. Zhang, MOF-Based active packaging materials for extending post-harvest shelf-life of fruits and vegetables, *Materials* 16 (2023) 3406, <https://doi.org/10.3390/ma16093406>.
- [53] S. Morales-Cámara, L. Cardona-Carrascosa, P. Salcedo-Abraira, A. Rodríguez-Diéguez, S. Rojas, Controlled magnesium release and nutritional effect of a novel metal-organic framework on plants, *Cryst. Growth Des.* 25 (2025) 4685–4689, <https://doi.org/10.1021/acscgd.5c00080>.
- [54] A.A. Voskanyan, V.G. Goncharov, N. Novendra, X. Guo, A. Navrotsky, Thermodynamics drives the stability of the MOF-74 family in water, *ACS Omega* 5 (2020) 13158–13163, <https://doi.org/10.1021/acsomega.0c01189>.
- [55] H. Zhang, M. Zhao, Y. Yang, Y.S. Lin, Hydrolysis and condensation of ZIF-8 in water, *Microporous Mesoporous Mater.* 288 (2019) 109568, <https://doi.org/10.1016/j.micromeso.2019.109568>.
- [56] H. Chen, L. Yang, S. Zhao, H. Xu, Z. Zhang, Long-term toxic effects of iron-based metal-organic framework nanopesticides on earthworm-soil microorganism interactions in the soil environment, *Sci. Total Environ.* 917 (2024) 170146, <https://doi.org/10.1016/j.scitotenv.2024.170146>.
- [57] A. Kedves, Ç. Yavuz, O. Kedves, H. Haspel, Z. Kónya, The response to shock loads of Ni-MOF and NiO nanoparticles on aerobic granular sludge and algal-bacterial aerobic granular sludge, *Heliyon* 10 (2024) e40796, <https://doi.org/10.1016/j.heliyon.2024.e40796>.
- [58] B. Asadishad, S. Chahal, A. Akbari, V. Cianciarelli, M. Azodi, S. Ghoshal, N. Tufenkji, Amendment of agricultural soil with metal nanoparticles: effects on soil enzyme activity and microbial community composition, *Environ. Sci. Technol.* 52 (2018) 1908–1918, <https://doi.org/10.1021/acs.est.7b05389>.
- [59] D.G. Crosby, The fate of pesticides in the environment, *Annu. Rev. Plant Physiol.* 24 (1973) 467–492, <https://doi.org/10.1146/annurev.pp.24.060173.002343>.
- [60] S. Hu, C. Yan, Q. Fei, B. Zhang, W. Wu, MOF-based stimuli-responsive controlled release nanopesticide: mini review, *Front. Chem.* 11 (2023) 1272725, <https://doi.org/10.3389/fchem.2023.1272725>.
- [61] S. Yang, F. Lü, L. Wang, S. Liu, Z. Wu, Y. Cheng, F. Liu, pH-responsive metal–organic framework for targeted delivery of fungicide, release behavior, and sustainable plant protection, *Molecules* 29 (2024) 5330, <https://doi.org/10.3390/molecules29225330>.
- [62] Y. Ma, K. Zhao, Y. Ding, S. Wu, X. Liao, X. Yin, Z. Li, R. Li, Y. Long, F. Du, A facile one-pot route to fabricate clothianidin-loaded ZIF-8 nanoparticles with biocompatibility and long-term efficacy, *Pest Manag. Sci.* 79 (2023) 2603–2610, <https://doi.org/10.1002/ps.7440>.
- [63] Y. Shan, C. Xu, H. Zhang, H. Chen, M. Bilal, S. Niu, L. Cao, Q. Huang, Polydopamine-modified metal-organic frameworks, NH₂-Fe-MIL-101, as pH-sensitive nanocarriers for controlled pesticide release, *Nanomaterials* 10 (2020) 2000, <https://doi.org/10.3390/nano10102000>.
- [64] S. Sonowal, R. Prasad, Exploring the recent advancement of MOFs in agriculture and food technology, *Next Mater.* 9 (2025) 101016, <https://doi.org/10.1016/j.nxmate.2025.101016>.
- [65] X. Guo, L. Wang, L. Wang, Q. Huang, L. Bu, Q. Wang, Metal-organic frameworks for food contaminant adsorption and detection, *Front. Chem.* 11 (2023) 1116524, <https://doi.org/10.3389/fchem.2023.1116524>.
- [66] P. Li, J. Li, X. Feng, J. Li, Y. Hao, J. Zhang, H. Wang, A. Yin, J. Zhou, X. Ma, et al., Metal-organic frameworks with photocatalytic bactericidal activity for integrated air cleaning, *Nat. Commun.* 10 (2019) 2177, <https://doi.org/10.1038/s41467-019-10218-9>.
- [67] H.A. Bicalho, V. Quezada-Novoa, A.J. Howarth, Metal–organic frameworks for the generation of reactive oxygen species, *Chem. Phys. Rev* 2 (2021), <https://doi.org/10.1063/5.0060141>.
- [68] Y. Luo, B. Li, X. Liu, Y. Zheng, E. Wang, Z. Li, Z. Cui, Y. Liang, S. Zhu, S. Wu, Simultaneously enhancing photocatalytic and photothermal effect of NH₂-MIL-125-GO-Pt ternary heterojunction for rapid therapy of bacteria-infected wounds, *Bioact. Mater.* 18 (2022) 421–432, <https://doi.org/10.1016/j.bioactmat.2022.03.035>.
- [69] N. Alsadun, S. Surya, K. Patle, V.S. Palaparthi, O. Shekha, K.N. Salama, M. Eddaoudi, Institution of metal–organic frameworks as a highly sensitive and selective layer in-field integrated soil-moisture capacitive sensor, *ACS Appl. Mater. Interfaces* 15 (2023) 6202–6208, <https://doi.org/10.1021/acsaami.2c20141>.
- [70] C. Arul, G. Veerapandi, C. Sekar, Selective and simultaneous electrochemical detection of nitrite and nitrate ions using Ag-MOF: food and water analyses, *Food Chem.* 484 (2025) 144457, <https://doi.org/10.1016/j.foodchem.2025.144457>.
- [71] D. Zhao, S. Yu, W.J. Jiang, Z.H. Cai, D.L. Li, Y.L. Liu, Z.Z. Chen, Recent progress in metal-organic framework-based fluorescent sensors for hazardous materials detection, *Molecules* 27 (2022) 2226, <https://doi.org/10.3390/molecules27072226>.
- [72] Y. Li, S. Wu, Y. Zhang, Z. Ma, M. Zhu, E. Gao, A lanthanide metal–organic framework as ratio fluorescence probe to detect pesticides in water, *Inorg. Chim. Acta.* 528 (2021) 120632, <https://doi.org/10.1016/j.ica.2021.120632>.
- [73] Y. Han, X. He, W. Yang, X. Luo, Y. Yu, W. Tang, T. Yue, Z. Li, Ratiometric fluorescent sensing carbendazim in fruits and vegetables via its innate fluorescence coupling with UiO-67, *Food Chem.* 345 (2021) 128839, <https://doi.org/10.1016/j.foodchem.2020.128839>.
- [74] W. Akram, S. Iqbal, Z. Abbas, S. Mansoor, I. Shah, A. Ullah, W. Xu, W.Y. Kim, Metal organic framework-based humidity sensing: stability, performance, and IoT integration, *J. Sci. Adv. Mater. Devices* (2025) 100972, <https://doi.org/10.1016/j.jsamd.2025.100972>.
- [75] J.F. Olorunoyi, S.T. Geh, R.A. Caruso, C.M. Doherty, Metal–organic frameworks for chemical sensing devices, *Mater. Horiz.* 8 (2021) 2387–2419, <https://doi.org/10.1039/d1mh00609f>.
- [76] S. Tanaka, Y. Tanaka, A simple step toward enhancing hydrothermal stability of ZIF-8, *ACS Omega* 4 (2019) 19905, <https://doi.org/10.1021/acsomega.9b02812>.
- [77] J. López, A.M. Chávez, A. Rey, P.M. Álvarez, Insights into the stability and activity of MIL-53(Fe) in solar photocatalytic oxidation processes in water, *Catalysts* 11 (2021) 448, <https://doi.org/10.3390/catal11040448>.
- [78] D. Mateo, A. Santiago-Portillo, J. Albero, S. Navalón, M. Álvaro, H. García, Long-term photostability in terephthalate metal–organic frameworks, *Angew. Chem. Int. Ed.* 58 (2019) 17843–17848, <https://doi.org/10.1002/anie.201911600>.
- [79] P.A. Demakov, Properties of aliphatic ligand-based metal–organic frameworks, *Polymers* 15 (2023) 2891, <https://doi.org/10.3390/polym15132891>.
- [80] F. Mahmoudi, L.G. Bachas, Application of metal–organic framework-based composite materials for photodegradation of dye pollutants in wastewater, *Water* 16 (2024) 3051, <https://doi.org/10.3390/w16213051>.
- [81] M. Bhattacharya, K.J. Chandler, J. Geary, C.T. Saouma, The role of leached Zr in the photocatalytic reduction of CO₂ to formate by derivatives of UiO-66 metal organic frameworks, *Dalton Trans.* 49 (2020) 4751–4757, <https://doi.org/10.1039/d0dt00524j>.
- [82] D. Bůžek, S. Adamec, K. Lang, J. Demel, Metal–organic frameworks vs. buffers: case study of UiO-66 stability, *Inorg. Chem. Front.* 8 (2021) 720–734, <https://doi.org/10.1039/d0qi00973c>.
- [83] M. Mazaj, T. Čendak, G. Buscarino, M. Todaro, N. Zabukovec Logar, Confined crystallization of HKUST-1 within mesostructured silica with enhanced water resistance, *J. Mater. Chem. A* 5 (2017) 22305–22315, <https://doi.org/10.1039/c7ta04959e>.
- [84] A. Kabata-Pendias, Trace Elements in Soils and Plants, fourth ed., CRC Press, 2010 <https://doi.org/10.1201/b10158>.
- [85] T.A. Makhetha, S.C. Ray, R.M. Moutloali, Zeolitic imidazolate framework-8 encapsulated Ag/Cu composites supported on graphene oxide: synthesis and antibacterial activity, *ACS Omega* 5 (2020) 9626–9640, <https://doi.org/10.1021/acsomega.9b03215>.
- [86] P. Pillai, S. Dharaskar, S. Sasikumar, M. Khalid, ZIF-8 nanoparticle: a promising adsorbent for fluoride removal, *Appl. Water Sci.* 9 (2019) 150, <https://doi.org/10.1007/s13201-019-1030-9>.
- [87] Y.C. Huang, R. Fan, M.A. Grusak, J.D. Sherrier, C.P. Huang, Effects of nano-ZnO on Rhizobium-legume symbiosis, *Sci. Total Environ.* 497–498 (2014) 78–90, <https://doi.org/10.1016/j.scitotenv.2014.07.100>.
- [88] P. Goyal, P. Soppina, S.K. Misra, E. Valsami-Jones, V. Soppina, S. Chakraborty, Toxicological impact and in vivo tracing of rhodamine functionalised ZIF-8 nanoparticles, *Front. Toxicol.* 4 (2022) 917749, <https://doi.org/10.3389/ftox.2022.917749>.
- [89] D. Aksu, C. Vural, B. Karabey, G. Ozdemir, Biodegradation of terephthalic acid by activated sludge microorganisms, *Braz. Arch. Biol. Technol.* 64 (2021) e21200002, <https://doi.org/10.1590/1678-4324-2021200002>.
- [90] L. Chen, W. Pan, K. Li, M. Chen, P. Li, Y. Liu, Z. Li, H. Lu, University of Oslo-66: a versatile Zr-based MOF for water purification through adsorption and photocatalysis, *Processes* 13 (2025) 1133, <https://doi.org/10.3390/pr13041133>.
- [91] X. Liu, X. Wang, F. Kapteijn, Water and metal–organic frameworks: from interaction toward utilization, *Chem. Rev.* 120 (2020) 8303–8377, <https://doi.org/10.1021/acs.chemrev.9b00746>.
- [92] H.T.N. Thi, K.N.T. Thi, N.B. Hoang, B.T. Tran, T.S. Do, C.S. Phung, K.O.N. Thi, Enhanced degradation of rhodamine B by metallic organic frameworks based on NH₂-MIL-125(Ti) under visible light, *Materials* 14 (2021) 7741, <https://doi.org/10.3390/ma14247741>.
- [93] R. Gil-Ortiz, M.Á. Naranjo, A. Ruiz-Navarro, M. Caballero-Molada, S. Atares, C. García, O. Vicente, Agronomic assessment of a controlled-release polymer-coated urea-based fertilizer in maize, *Plants* 10 (2021) 594, <https://doi.org/10.3390/plants10030594>.
- [94] S. Kumar, S. Jain, M. Nehra, N. Dilbaghi, G. Marrazza, K.H. Kim, Green synthesis of metal–organic frameworks: a state-of-the-art review of potential environmental and medical applications, *Coord. Chem. Rev.* 420 (2020) 213407, <https://doi.org/10.1016/j.ccr.2020.213407>.
- [95] S. Glowniak, B. Szczęśniak, J. Choma, M. Jaroniec, Mechanochemistry: toward green synthesis of metal–organic frameworks, *Mater. Today* 46 (2021) 109–124, <https://doi.org/10.1016/j.mattod.2021.01.008>.
- [96] S. Bhattacharjee, C. Chen, W.S. Ahn, Chromium terephthalate metal–organic framework MIL-101: synthesis, functionalization, and applications for adsorption and catalysis, *RSC Adv.* 4 (2014) 52500–52525, <https://doi.org/10.1039/c4ra11259h>.

- [97] N.C. Burtch, H. Jasuja, K.S. Walton, Water stability and adsorption in metal-organic frameworks, *Chem. Rev.* 114 (2014) 10575–10612, <https://doi.org/10.1021/cr5002589>.
- [98] A.J. Howarth, Y. Liu, P. Li, Z. Li, T.C. Wang, J.T. Hupp, O.K. Farha, Chemical, thermal and mechanical stabilities of metal-organic frameworks, *Nat. Rev. Mater.* 1 (2016) 15018, <https://doi.org/10.1038/natrevmats.2015.18>.
- [99] M.J. Katz, Z.J. Brown, Y.J. Colón, P.W. Siu, K.A. Scheidt, R.Q. Snurr, J.T. Hupp, O.K. Farha, A facile synthesis of UiO-66, UiO-67 and their derivatives, *Chem. Commun.* 49 (2013) 9449–9451, <https://doi.org/10.1039/c3cc46105j>.
- [100] C. Serre, S. Bourrelly, A. Vimont, N.A. Ramsahye, G. Maurin, P.L. Llewellyn, M. Daturi, Y. Filinchuk, O. Leynaud, P. Barnes, et al., An explanation for the very large breathing effect of a metal-organic framework during CO₂ adsorption, *Adv. Mater.* 19 (2007) 2246–2251, <https://doi.org/10.1002/adma.200602645>.
- [101] S.R. Caskey, A.G. Wong-Foy, A.J. Matzger, Dramatic tuning of carbon dioxide uptake via metal substitution in a coordination polymer with cylindrical pores, *J. Am. Chem. Soc.* 130 (2008) 10870–10871, <https://doi.org/10.1021/ja8036096>.
- [102] D. Britt, D. Tranchemontagne, O.M. Yaghi, Metal-organic frameworks with high capacity and selectivity for harmful gases, *Proc. Natl. Acad. Sci. USA* 105 (2008) 11623, <https://doi.org/10.1073/pnas.0804900105>.
- [103] Y.H. Fan, S.W. Zhang, S. Qin, X.S. Li, S.H. Qi, Enhanced adsorption of organic dyes onto NH₂-functionalized titanium-based metal-organic frameworks and mechanism investigation, *Microporous Mesoporous Mater.* 263 (2018) 120–127, <https://doi.org/10.1016/j.micromeso.2017.12.016>.
- [104] M. Dan-Hardi, C. Serre, T. Frot, L. Rozes, G. Maurin, C. Sanchez, G. Férey, A new photoactive crystalline highly porous titanium(IV) dicarboxylate, *J. Am. Chem. Soc.* 131 (2009) 10857–10859, <https://doi.org/10.1021/ja903726m>.
- [105] S.S.Y. Chui, S.M.F. Lo, J.P.H. Charmant, A.G. Orpen, I.D. Williams, A chemically functionalizable nanoporous material [Cu₃(TMA)₂(H₂O)₃]_n, *Science* 283 (1999) 1148–1150, <https://doi.org/10.1126/science.283.5405.1148>.
- [106] H.K. Chae, D.Y. Siberio-Pérez, J. Kim, Y.B. Go, M. Eddaoudi, A.J. Matzger, M. O'Keeffe, O.M. Yaghi, A route to high surface area, porosity and inclusion of large molecules in crystals, *Nature* 427 (2004) 523–527, <https://doi.org/10.1038/nature02311>.
- [107] O.K. Farha, I. Eryazici, N.C. Jeong, B.G. Hauser, C.E. Wilmer, A.A. Sarjeant, R. Q. Snurr, S.T. Nguyen, A.Ö. Yazaydin, J.T. Hupp, Metal-organic framework materials with ultrahigh surface areas: is the sky the limit? *J. Am. Chem. Soc.* 134 (2012) 15016–15021, <https://doi.org/10.1021/ja3055639>.
- [108] M. Anstoetz, T.J. Rose, M.W. Clark, L.H. Yee, C.A. Raymond, T. Vancov, Novel applications for oxalate-phosphate-amine metal-organic frameworks (OPA-MOFs): can an iron-based OPA-MOF be used as slow-release fertilizer? *PLoS One* 10 (2015) e0144169, <https://doi.org/10.1371/journal.pone.0144169>.
- [109] K. Wu, W. Li, F. Ma, F. Gan, J. Zhou, H. Zeng, C. Du, Urea-loaded core-shell MOF/silica nanocarriers for continuous nitrogen release to crops, *ACS Appl. Nano Mater.* 7 (2024) 11645–11654, <https://doi.org/10.1021/acsnm.4c01187>.
- [110] X. Zhang, X. Tang, C. Zhao, Z. Yuan, D. Zhang, H. Zhao, N. Yang, K. Guo, Y. He, Y. He, et al., A pH-responsive MOF for site-specific delivery of fungicide to control citrus disease of botrytis cinerea, *Chem. Eng. J.* 431 (2022) 133351, <https://doi.org/10.1016/j.cej.2021.133351>.
- [111] R.A. dos Reis, L.A.M. Mahmoud, E.H. Ivanovska, R. Telford, M.A. Addicoat, L. R. Terry, V.P. Ting, S. Nayak, Biodegradable polymer-metal-organic framework composites for controlled and sustainable pesticide delivery, *Adv. Sustain. Syst.* 7 (2023) 2300269, <https://doi.org/10.1002/advsu.202300269>.
- [112] Y. Hou, Y. Zhang, Y. Huang, A. Zhou, J. Han, K. Yang, Y. Zhao, J. Zhou, J. Wang, G. Chen, et al., A pH-responsive MOFs@MPN nanocarrier with enhancing antifungal activity for sustainable controlling myclobutanil release, *Chem. Eng. J.* 497 (2024) 155713, <https://doi.org/10.1016/j.cej.2024.155713>.
- [113] A.H. Farmahini, S. Krishnamurthy, D. Friedrich, S. Brandani, L. Sarkisov, Performance-based screening of porous materials for carbon capture, *Chem. Rev.* 121 (2021) 10666–10741, <https://doi.org/10.1021/acs.chemrev.0c01266>.
- [114] T. Kurniawan, N. Nuryoto, Characterization and application of bayah natural zeolites for ammonium capture: isotherm and kinetic, *Mater. Sci. Forum* 988 (2020) 51–64, <https://doi.org/10.4028/www.scientific.net/msf.988.51>.
- [115] J. Abedi-Koupai, R. Mollaei, S.S. Eslamian, Use of pumice or willow-based biochar amendments to decrease soil salinity under arid conditions, *Environ. Technol. Innov.* 24 (2021) 101849, <https://doi.org/10.1016/j.ecohyd.2015.05.001>.
- [116] M. Stromberg, *Biotreatment Soil Media and Specification: Current Research on Trees and Water Quality Treatment*, 2016.
- [117] C. Kong, M. Camps-Arbestain, B. Clothier, Influence of physical properties of pumice and biochar amendments on soil water dynamics, *Soil Res.* 60 (2022) 234–241, <https://doi.org/10.1017/sr20327>.
- [118] L. Gao, Z. Dong, Y. Xu, L. Zhao, X. Xing, Z. Han, M. Jin, X. Li, X. Zhang, Z. Zhang, Advancements in biochar research methods for soil pollution remediation, *ACS Omega* 10 (2025) 9854–9868, <https://doi.org/10.1021/acsomega.4c10533>.
- [119] T. Wang, D. Wiltse, F. Viskupić, A. Oyeibanji, Promoting awareness and adoption of biochar as a soil amendment: effect of message framing, *Renew. Agric. Food Syst.* 41 (2026) e5, <https://doi.org/10.1017/s1742170526100258>.
- [120] P. Chandra, S. Sahoo, P.K. Pandey, R.K. Dey, R.P. Biswal, D.K. Pati, K. Tiwari, C. Chakraborty, S. Chakraborty, Copper-based metal-organic frameworks for sustainable catalysis: mechanistic insights, stability, and emerging research directions, *ACS Omega* 11 (2026) 8911–8939, <https://doi.org/10.1021/acsomega.5c10345>.
- [121] N. Stock, S. Biswas, Synthesis of metal-organic frameworks (MOFs): routes to various MOF topologies, morphologies, and composites, *Chem. Rev.* 112 (2012) 933–969, <https://doi.org/10.1021/cr200304e>.
- [122] M. Klimakow, P. Klobes, A.F. Thünemann, K. Rademann, F. Emmerling, Mechanochemical synthesis of metal-organic frameworks: a fast and facile approach toward quantitative yields and high specific surface areas, *Chem. Mater.* 22 (2010) 5216–5221, <https://doi.org/10.1021/cm1012119>.
- [123] J.M. Marrett, F. Effaty, X. Ottenwaelder, T. Frišić, Mechanochemistry for metal-organic frameworks and covalent-organic frameworks (MOFs, COFs): methods, materials, and mechanisms, *Adv. Mater.* (2025) 2418707, <https://doi.org/10.1002/adma.202418707>.
- [124] S.A. Salami, M.H. Manyeruke, C.I. Ezekiel, U.N. Ndagano, J.B. Safari, S. O. Amusat, R.W.M. Krause, Recent advances in liquid assisted grinding chemistry: towards sustainable synthesis, results, *Chem* 18 (2025) 102675, <https://doi.org/10.1016/j.rechem.2025.102675>.
- [125] C. Jia, J. Wang, X. Feng, Q. Lin, W. Yuan, Efficient vapour-assisted aging and liquid-assisted grinding synthesis of a microporous copper-adeninate framework, *CrystEngComm* 16 (2014) 6552–6555, <https://doi.org/10.1039/c4ce00533c>.
- [126] Y. Yu, Z. Liu, X. Chen, S. Liu, C. Duan, H. Xi, Water-based synthesis of nanoscale hierarchical metal-organic frameworks: boosting adsorption and catalytic performance, *Nano Mater. Sci.* 5 (2023) 361–368, <https://doi.org/10.1016/j.nanoms.2022.09.002>.
- [127] Z. Chen, X. Wang, R. Cao, K.B. Idrees, X. Liu, M.C. Wasson, O.K. Farha, Water-based synthesis of a stable iron-based metal-organic framework for capturing toxic gases, *ACS Mater. Lett.* 2 (2020) 1129–1134, <https://doi.org/10.1021/acsmaterlett.0c00264>.
- [128] H.Q. Xu, K. Wang, M. Ding, D. Feng, H.L. Jiang, H.C. Zhou, Seed-mediated synthesis of metal-organic frameworks, *J. Am. Chem. Soc.* 138 (2016) 5316–5320, <https://doi.org/10.1021/jacs.6b01414>.
- [129] H.T. An, X. Zhang, C. Dong, M.Y. Lu, R. Li, Y. Xie, L.H. Xie, J.R. Li, Seed-aided green synthesis of metal-organic frameworks in water, *Green Chem. Eng.* 4 (2023) 64–72, <https://doi.org/10.1016/j.gce.2022.04.004>.
- [130] D. Chakraborty, A. Yurdusen, G. Mouchaham, F. Nouar, C. Serre, Large-scale production of metal-organic frameworks, *Adv. Funct. Mater.* 34 (2024) 2309089, <https://doi.org/10.1002/adfm.202309089>.
- [131] A. Ramos Corona, J. Rodríguez López, R. Rangel Segura, M.M. Martínez García, E. Flores, G. Rodríguez Gattorno, J.J. Alvarado Gil, Microwave-assisted synthesis of CdS-MOF MIL-101 (Fe) composite: characterization and photocatalytic performance, *Inorg. Chem.* 63 (2024) 19536–19552, <https://doi.org/10.1021/acs.inorgchem.4c02104>.
- [132] S.K. Khalid Rahaman, T. Chatterjee, S.M. Alam, Microwave-assisted synthesis of metal-organic frameworks, in: *Synthesis of Metal-Organic Frameworks via Water-based Routes: a Green and Sustainable Approach*, 2024, pp. 51–72, <https://doi.org/10.1016/b978-0-323-95939-1.00009-5>.