ADVANCED SUSTAINABLE SYSTEMS

Early View

Online Version of Record before inclusion in an issue

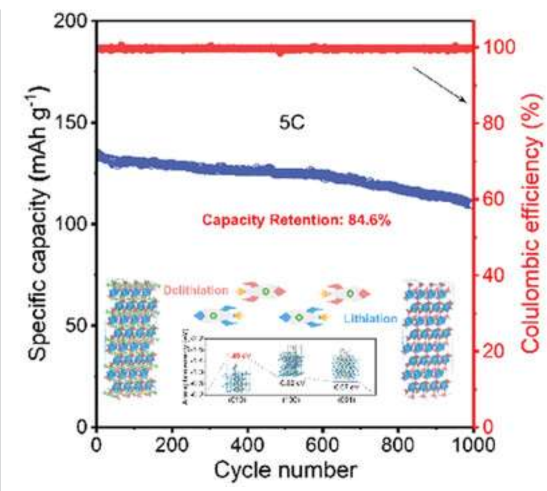
Export Citation(s)

Research Article

Achieving Fast Mn Redox Kinetics with Solvothermal Synthesized (010) Facet Preferential $LiMn_{0.5}Fe_{0.5}PO_4$ Nanoplates for Li-Ion Batteries

Wei Lin, Yulu Wu, Xinyu Hu, Peng Yang, Hong Wen, Tianfu Zhao, Lianbang Wang, Chaoqi Shen

Version of Record online: 06 January 2025



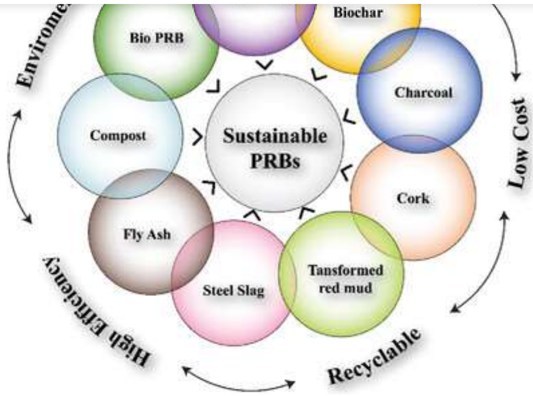
A solvothermal method to synthesize $LiMn_{0.5}Fe_{0.5}PO_4$ (LMFP) nanoplates with high exposure (010) facet and reducing defects. The improved lithium-ion diffusion, Mn redox kinetics, and electrochemical performance, deliver 130.7 mAh g^{-1} at 5C with 84.6% capacity retention after 1000 cycles. The study reveals an effective electrode structure design to realize long-life high rate batteries.

Abstract | **Full text** | **PDF** | **References** | **Request permissions**

α-Fe_2O_3 Nanocubes as High-Performance Anode for Supercapacitor

Umisha Singh, Mitali Patra, Amit K. Chakraborty, Shobha Shukla, Sumit Saxena

Version of Record online: 05 January 2025

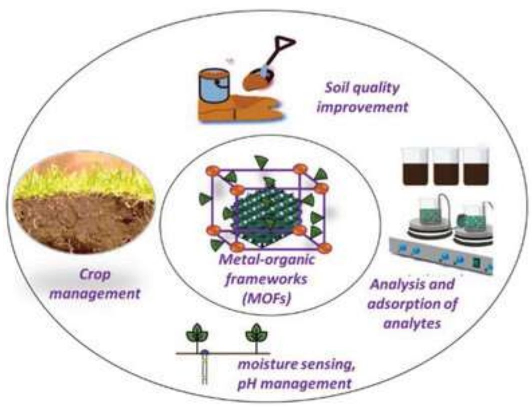


Abstract | Full text | PDF | References | Request permissions

Contaminants Removal and Monitoring: The Role of Hybrid MOFs in Agricultural Advancement and Soil Amendment

Brij Mohan, Harish Kumar Sharma, Stefan Ručman, Pisith Singjai, Armando J. L. Pombeiro

Version of Record online: 26 December 2024



Metal–organic frameworks (MOFs) have garnered interest due to their potential to improve soil quality through innovative methods. Advancements in MOF-based techniques may enhance soil quality and increase crop yields. Their unique properties as carriers release characteristics and analytical performance, which show promise in this field to pave the way for improved soil quality and a more sustainable agricultural industry.

Abstract | Full text | PDF | References | Request permissions

Research Article

Dual Molten Salt Synthesis of Oxygen Rich Hierarchical Porous Carbon as Cathode Materials for Zinc-Ion Hybrid Capacitor

Xinyang Zhang, Jun Ni, Weijian Chen, Hui Xu, Longfei Qiao, Rui Lu, Xiaoliang Wu

Version of Record online: 23 December 2024

ADVANCED SUSTAINABLE SYSTEMS
www.advsustainsys.com

Contaminants Removal and Monitoring: The Role of Hybrid MOFs in Agricultural Advancement and Soil Amendment

Brij Mohan, Harish Kumar Sharma, Stefan Ručman, Pisith Singjai, and Armando J. L. Pombeiro*

The interest in improving soil quality through innovative methods continues to grow in sustainable agriculture. Despite the emergence of new techniques, there has been limited research on methods based on metal-organic frameworks (MOFs). This review first addresses the current issues in the soil and agriculture industry and discusses recent approaches for improving soil quality. It then explores the latest advancements in MOF-based methods, which hold the potential to enhance soil quality and increase crop yields significantly. The unique properties and physicochemical mechanisms behind MOFs' applications and analytical performance are presented, highlighting their potential for more efficient and cost-effective soil enhancement solutions. The review reveals that these new MOF approaches show promise in enhancing soil quality through processes such as adsorption, extraction, analyte monitoring, fertilization, soil washing, and moisture sensing. This review can lead to a future with higher soil quality, ensuring better food production and a more sustainable agricultural industry.

1. Introduction

Metal–organic frameworks (MOFs) are hybrid materials of metal ions or clusters coordinated to organic ligands, forming a highly porous structure. These materials are known for their tunable surface areas and porosity, which can be adjusted during synthesis to meet specific application requirements. The unique structure of MOFs allows for excellent adsorption capabilities, making them ideal for various applications, including gas storage, separation processes, and catalysis. Their versatility and customizable properties make MOFs a significant area of research in materials science and chemistry.[1–4] MOFs possess properties like magnetism, porosity, self-tuning capability, and controlled pollutant uptake, making them superior to organic and inorganic materials for agricultural and soil improvement.[5–7]

Agriculture plays a crucial role in providing food, but it's essential to acknowledge the potential public health risks associated with soil and crop safety in this industry. With the growing population, the agriculture sector needs to increase food production, highlighting the importance of using proper soil amendments. Therefore, it is essential to understand and adopt safe agricultural practices to ensure that food is free from harmful contaminants and does not pose any health risks.[8–10] Soil is crucial for plant growth and development. It provides the necessary nutrients for their lifespan.[11,12] Soil is of utmost importance for agriculture because of the substantial demand for food production. It is crucial to prioritize optimizing crop yields while ensuring soil health preservation. Key crops such as wheat, rice, and corn are vital in meeting global food requirements. It is essential to have a comprehensive understanding of soil contaminants that can impact the quality and yield of these grains.[13–15] Grain contamination poses health risks due to chemical and biological impurities from soil and agrochemicals. Harmful residues threaten consumer safety. Fungi and bacteria in warm, humid conditions can spoil grains if not controlled.[16–18]

Agrochemicals have a negative impact on soil, food, the environment, health, and sustainability. It's important to limit their use and find sustainable alternatives proactively. Chemicals are classified based on toxicity, target, composition, formula, entry/action mode, and source. This classification depends on factors such as mode of action, toxicity level, target organism, and origin.[19,20] Agrochemicals encompass a wide variety of chemical substances, including pesticides (such as insecticides, fungicides, herbicides, algaecides, rodenticides, nematicides, and molluscicides), fertilizers (which provide essential macronutrients

B. Mohan, A. J. L. Pombeiro
Centro de Química Estrutural
Institute of Moleculars Sciences
Instituto Superior Técnico
Universidade de Lisboa
Av. Rovisco Pais, Lisboa 1049-001, Portugal
E-mail: brij.mohan@tecnico.ulisboa.pt
H. K. Sharma
Department of Chemistry
Kurukshetra University
Kurukshetra 136119, India
S. Ručman
Faculty of Liberal Arts
Maejo University
Chiang Mai 50290, Thailand
P. Singjai
Department of Physics and Materials Science
Faculty of Science
Chiang Mai University
Chiang Mai 50200, Thailand
The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adsu.202400637

DOI: 10.1002/adsu.202400637

Table 1. Various materials are used to remove, capture, and monitor contaminants.

Materials	Surface area [m^2 g^{-1}]	Effective for	Cost, regeneration, and stability	Efficiency range	Reference
Graphene	500–2630	Organic compounds	high	80–95%	[31]
Activated carbon	500–3000	organic compounds, chlorine, and heavy metals	moderate cost	85–95%	[32]
Mesoporous Silica	500–1000	mixtures	affordable cost and low reusability	85%–95%	[33]
Carbon nanotubes	250–500	Multiple analytes	Varying cost and stable and reusability	80%–97%	[34]
Metal nanoparticles	20–150	Metal ions and charged species	Costly and reusability & stability vary	70–90%	[35]
COFs	711–1590	Multiple analytes	Varying cost and high stability and reusability	80–95%	[36]
Polymer resigns	1–100	Heavy metal ions	cost-effective sorbents but less reusable	70–90%	[37]
MOFs	1000–7000	Multiple analytes	Varying cost and stable and reusable but less than COFs	85–95%	[38]

like nitrogen, phosphorus, and potassium), soil conditioners, liming agents (like calcium and magnesium), acidifying agents, and plant growth regulators. Each type of agrochemical serves a specific purpose and operates in a distinct way in agricultural production systems.[21,22]

Agriculture occupies 38% of the Earth's surface, and the use of hazardous agrochemicals is essential for protecting crops and significantly enhancing food production.[23] According to Next Move Strategy Consulting, the global agrochemical market was 275.4 million metric tons in 2021 and is projected to reach 296.6 million metric tons by 2030. Experts from AgriMarket Insight attribute this market growth to the increasing demand for agricultural products driven by population growth, farmers' need to enhance crop yields, and technological advancements.[24] In 2020, the total global use of pesticides in agriculture remained unchanged at 2.7 million tonnes (Mt) of active ingredients.[25] By 2050, Asia is expected to have the highest sales of agrochemicals worldwide, but there is a significant concern regarding the region's lack of capacity for effective chemical management.[26] Agrochemicals can lead to acute toxicity in humans and chronic illnesses, including cancer. Unregulated use can damage soil biodiversity, increase pest resistance, and waste resources. While fertilizers can boost crop yield, their lack of specificity raises environmental and production costs. Food waste exacerbates inefficiencies in food production, leading to environmental harm and health risks. Agri-food systems have interconnected impacts on water, food, nature, and human health.[26–28] Soil amendment is essential for producing high-quality food because it directly impacts crops' nutritional value and safety. Metal and nonmetallic materials have improved industrial processes in different environmental conditions, including soil. Nanomaterials, carbon and natural biomaterials, porous materials, and MOFs have provided advanced platforms for specific applications in soil improvement.[29,30] Various materials have been used to address contaminants that could enhance farming applications (**Table 1**).

MOFs have recently emerged as a promising technology in agriculture. MOFs are highly porous coordination polymers that consist of inorganic nodes and organic linkers, which assemble into multidimensional periodic lattices. This remarkable class of materials has found applications in eliminating agrochemicals through adsorption and photodegradation and in sensing. MOFs offer several advantages over traditional methods, including high surface area, tunable pore size, and selectivity towards specific molecules.[39,40] In addition to their potential use in agricultural applications, The versatility and flexibility of MOFs make them an exciting area of research with tremendous potential for future advancements.[41,42] Using MOF materials for soil amendment has also improved food production through various processes (**Figure 1**). It is necessary to prioritize soil quality amendment to ensure a sustainable and healthy food system.[43–45]

Previously critical reviews on MOFs in agriculture described sensing, delivery, removal, and pollutant degradation for sustainability and enhanced productivity.[46–48] In addition, multifunctional MOFs have been demonstrated for crop production, agrochemical delivery, and fundamental applications.[49–51] In addition to these meaningful reviews, there is a need to specifically focus on applying MOFs in soil amendment through the management of analytes and nutrients. The primary goal of this review is to examine how these methods can enhance soil quality and to explore new agricultural practices. This review emphasizes the importance of assessing soil quality to promote sustainable farming practices that benefit both the environment and human health. It also highlights the significance of monitoring soil quality and selecting appropriate amendments for agricultural use. Despite the emergence of new techniques for soil improvement, MOF-based methods have not received significant attention in research. Therefore, there is a pressing need to enhance productivity while minimizing negative environmental impacts. This review will focus on recent MOF-based techniques and their potential advantages in improving soil quality and increasing crop yields.

2. Materials for Soil and Agriculture Development

Numerous robust methods and approaches have been developed to enhance soil quality and elevate agricultural productivity. Soil amendment techniques encompass a wide array of highly effective practices to modify the soil's physical, chemical, or

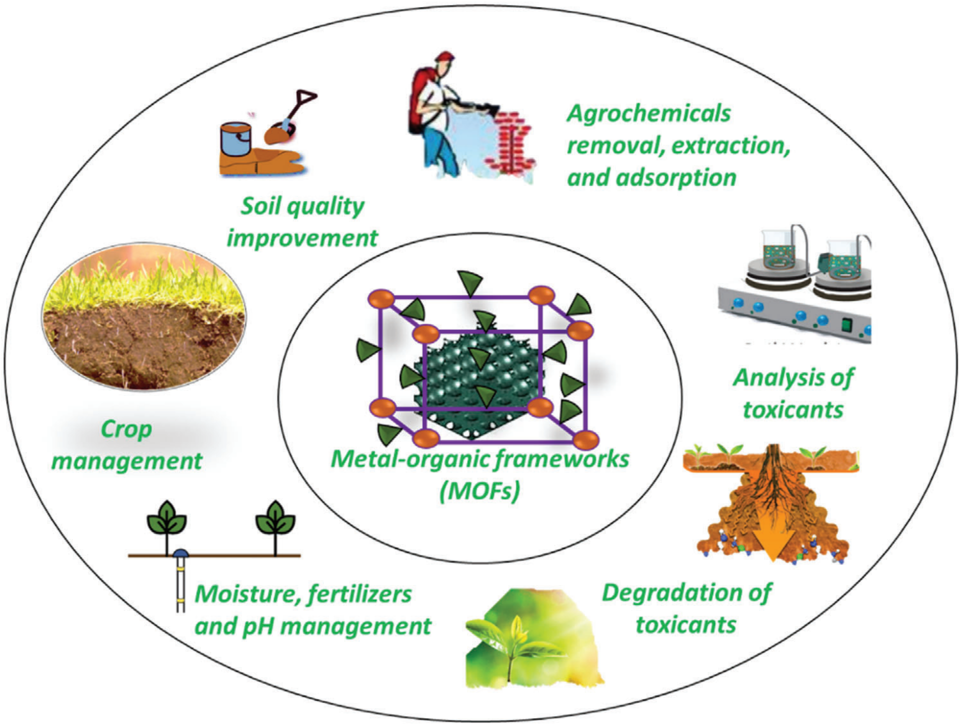


Figure 1. The schematic illustration of MOFs as emerging materials for agriculture and soil amendment. MOFs have recently emerged as promising candidates for use in agriculture and soil amendment. These highly porous materials are composed of metal ions or clusters linked by organic ligands and are shown to have potential applications in various agricultural areas.

biological properties to create an optimal environment for plant growth. These techniques include the strategic addition of organic matter such as compost or manure, the precise application of lime or fertilizers, and other proven strategies. It's important to note that the effectiveness of these techniques is backed by scientific evidence and can be influenced by various factors, including soil type, climate conditions, crop selection, and other environmental considerations.[52,53]

Compost is the most common traditional soil amendment made from decomposed organic matter like food waste, leaves, and grass clippings. It enhances soil fertility, structure, and water retention. Animal manure is another method for adding nutrients, but it should be aged or composted to prevent plant diseases and weed seeds. Peat moss improves soil structure and water-holding capacity, especially for acid-loving plants like blueberries and rhododendrons. Vermicomposting uses earthworms to create nutrient-rich compost that boosts soil health. Perlite, a lightweight volcanic rock, improves drainage and aeration while preventing soil compaction. Lastly, gypsum loosens heavy clay soils, enhancing their drainage ability.[54,55]

Green manure cover crops such as clover, rye, or buckwheat are explicitly grown to improve soil health by adding organic matter, nitrogen fixation, erosion control, weed suppression, pest management, etc.[56] Moreover, lime, known as calcium carbonate, has been used to raise the pH level of acidic soils, making them less acidic, which makes some nutrients more available for plant uptake.[57] In addition, rock phosphate, bone meal, Seaweed/kelp extracts, mushroom compost, and fish emulsion have played a role in soil quality.[58–60] A step ahead, materials science has gained interest in the growing awareness of the potential harm caused by agrochemical usage in agricultural production.[61,62] Nanomaterials, MOFs, biochar and clay materials, carbon nanotubes (CNTs), and activated porous materials have shown promising advancements in soil amendments (**Figure 2**). Moreover, nanomaterials have been used to improve soil fertility through the controlled release of nutrients and water retention. Metal and non-metallic frameworks offered high surface area for the adsorption of pollutants and onsite monitoring.[63–66] Also, silica and carbon materials showed applications as sensors for pH and moisture levels in the soil. The versatility of these materials makes them promising candidates for enhancing soil health and sustainability.[67–70] It has been seen that CNTs with $Fe_3O_4@SiO_2$-NH_2 are known for enhancing adsorption capacity for ecological and agricultural uses. Unique morphology and functional groups allow efficient adsorption of various analytes management.[71] MOFs possess high surface areas that enhance their effectiveness in catalytic reactions. They are highly efficient in promoting various chemical processes. In contrast, CNTs, silica, and carbon materials face limitations in surface functionalization, which restricts their versatility. MOFs can incorporate various metal ions and organic linkers, creating customized materials. Additionally, MOFs demonstrate exceptional adsorption capacities for removing water pollutants. While other materials have a rigid structure that limits their customization, MOFs are often preferred due to their porosity, larger surface area, and design flexibility.[34,72,73]

MOFs show great potential in agricultural applications by effectively removing and monitoring harmful substances in the

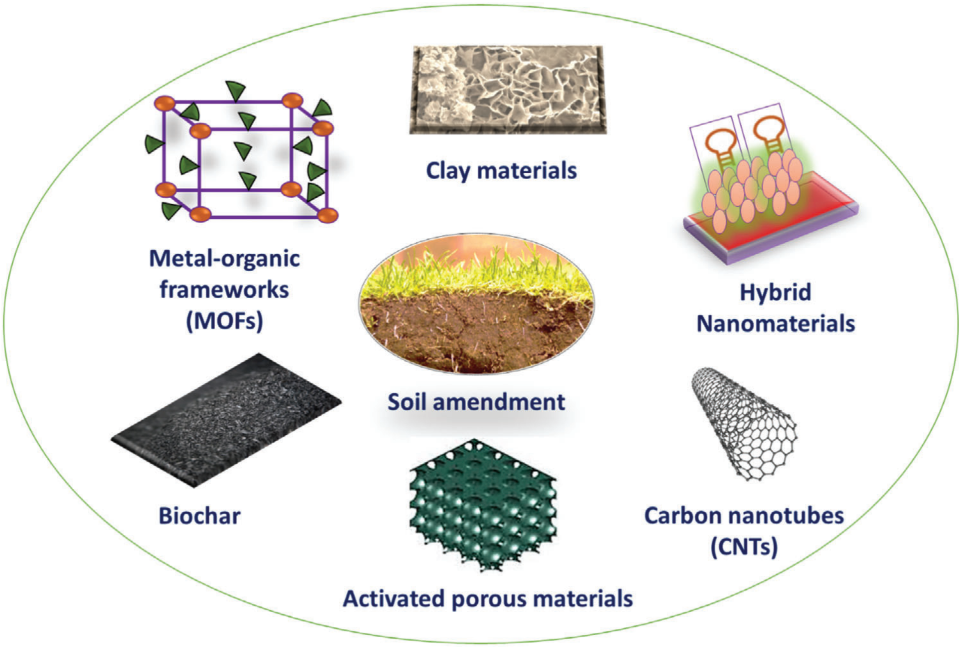


Figure 2. The materials used for soil amendment. Nanomaterials, MOFs, biochar and clay materials, carbon nanotubes (CNTs), and activated porous materials have advantages and have been modified at laboratory scales to farms for soil amendment applications.

soil. They can enhance soil health, boost crop yields, and reduce costs. MOFs also serve as sensors, providing real-time data on moisture levels, nutrient content, and pH balance. By leveraging these unique properties, agriculture can optimize crop production, minimize waste, and promote sustainability.[74–76] In this regard, the appreciable working capacity of MIL-101(Fe) in removing aflatoxin B1 (AFB1) has significantly improved. The higher loading capacity of 30.58 mg g^{-1} of MIL MOFs is due to its super-high porosity and excellent dispersion in liquid.[77]

Furthermore, the agricultural industry has extensively explored using MOF-based materials, employing various strategies to enhance crop quality. In particular, MOFs have been proposed for three primary purposes regarding agrochemicals.[49,78] First, they have been utilized for water remediation by adsorbing or degrading agrochemicals or their byproducts. Second, MOFs have been used to control agrochemicals' release. Third, they can serve as sensors to detect these molecules in both water and food. These remarkable properties of MOFs have demonstrated enormous potential in improving the efficiency and sustainability of agricultural practices by providing practical solutions to manage agrochemical residues and control their release into the environment. With these promising benefits, it is evident that MOFs are a valuable tool for advancing agricultural technology and promoting sustainable farming methods.[79,80] For example, Gan et al. studied different methods for removing organophosphorus herbicides from water, including adsorption and photodegradation. Glyphosate is a commonly used herbicide that can lead to excess in wastewater and soil. Zr-based MOF that features a meta-carborane carboxylate ligand (mCB-MOF-2) to investigate the potential of glyphosate (GP) adsorption and photodegradation. The study demonstrated that mCB-MOF-2 exhibited a maximum adsorption capacity of 11.4 mmol g^{-1} for GP. Additionally, when exposed to UV–vis light for 24 h, mCB-MOF-2 successfully converted 69% of GP into non-toxic sarcosine and orthophosphate. This conversion process effectively avoided the production of AMPA, which has similar toxicity levels to GP. These findings highlight the potential of mCB-MOF-2 as an effective material for removing and degrading GP from contaminated environments. The study provided a solution to the leading concentration of GP in soil and water.[81]

MOFs versatile nature and unique properties make them a valuable tool in modern agriculture, offering innovative approaches to address some of the most pressing challenges facing this sector today. The utilization of MOFs has shown promising potential in eradicating agrochemicals as pollutants in water. Additionally, MOFs have been explored for their ability to detect and measure these potentially hazardous molecules. However, a relatively new research field involving MOFs is their application as agrochemical delivery systems. This innovative approach holds great promise in the agricultural industry, as it could allow for more efficient and targeted delivery of chemicals to crops while minimizing environmental impact. The multifaceted uses of MOFs highlight their versatility and potential to address various challenges in different fields.[82]

Moreover, several techniques are utilized to eliminate soil pollutants, including biological processes like phytoremediation and bioremediation and physical processes such as adsorption, thermal desorption, soil vapor extraction, advanced oxidation processes (AOPs), and soil washing/soil flushing (SW/SF). It is crucial to consider the specific circumstances of the contaminated site to determine the method's effectiveness.[83–86] In comparison, it was found that thermal treatment eliminates contaminants and can destroy soil texture, creating concerns about highly volatile organic pollutants. AOPs are fast and efficient but generate toxic intermediates. Biological approaches are eco-friendly but require extra attention during analysis steps.

Phytoremediation methods have technical limitations for treating high concentrations of toxic substances. Soil remediation techniques like SW/SF are economically feasible ways of treating soil pollutants, offering soil regeneration and effective treatment methods. Soil treatment commonly uses AC, biochar, and clay minerals due to low cost and easy regeneration. CNTs offer rapid adsorption but have negative impacts on soil quality. MOFs are ideal for soil treatment as they have a large surface area and stability. Only a few MOFs were tested for soil pollutants, but coupling them with other nanomaterials can improve their application.

3. MOF Designs for Agriculture Uses

MOFs are versatile materials that have gained attention due to their potential applications in various fields, including agriculture.[87] MOFs' unique structure and properties make them suitable for various agricultural uses such as crop protection, soil improvement, and nutrient delivery. At present, there are various methods available for preparing MOFs. These techniques include sonochemical methodology, microwave synthesis, electrochemical approach, and solvothermal technique. For example, A stable, defect-free zirconium-based MOF layer was created using a two-step method. First, UiO-66-NH_2 MOF was grown in the voids of polydopamine-functionalized CM during solvothermal processing. Then, pressurized dead-end assembly facilitated the self-assembly of UiO-66-NH_2 with PDA.[88] A new method to create zeolite@MOF core-shell structures was designed by involving ion-exchange-induced crystallization and post-synthetic conversion, allowing exclusive growth of MOF on the zeolite surface. The method successfully created a CaA@ZIF-8 structure, which improved filler-polymer interfaces and resulted in defect-free membranes.[89]

Synthesis methods exhibit variations in efficiency, yield, and scalability. The sonochemical methodology uses high-frequency sound waves to promote chemical reactions between metal ions and organic ligands. Microwave synthesis utilizes microwave radiation to rapidly and uniformly heat the reaction mixture.[90,91] The electrochemical approach relies on applying an electric potential to drive the formation of MOFs on an electrode surface. The solvothermal technique utilizes high-pressure and high-temperature conditions in a solvent medium to facilitate the growth of MOF crystals. Researchers can tailor their synthesis strategies to meet specific application requirements and optimize performance characteristics by utilizing these diverse preparatory techniques for MOFs. These methods are influenced by various factors such as solvent type, pH level, linker substituent, concentration of metal ions, time duration, temperature range, and pressure conditions.[92–94]

MOFs are a promising material for toxicant adsorption using isothermal titration calorimetry (ITC) for quantifying in aqueous media and boosting tools for agriculture. Drou et al. demonstrated zirconium-based MOFs for the adsorption of organophosphorus agrochemicals. To commence this investigation, the development into the adsorption of glyphosate in NU-1000 using MOF comprised of Zr6-nodes and tetratopic pyrene-based linkers arranged into the csq topology, which showcases 1D hexagonal (31 Å) and triangular (12 Å) channels interlinked by orthogonal windows (10×8 Å) that are known as the c-pores. Eight linkers connect to each node, and four hydroxyl and water ligands maintain the node's charge. The ligands exhibited flexibility, allowing for pseudo-ion-exchange processes where oxyanions like perrhenate or phosphate-containing species can substitute a hydroxyl or water ligand. The designed model was one in which glyphosate could coordinate with the node. In addition, it was found that the carboxylic acid (pKa ≈ 2.6) can bind with the node; it is more likely for it to bind through the phosphonic acid (pKa ≈ 2.0), as inclined to be deprotonated (**Figure 3**).[95]

The unique properties of MOFs make them suitable for agriculture applications due to the presence of an aromatic linker. Nonetheless, researchers continue to explore ways to modify MOFs by combining them with high-conductive materials like carbon materials in different forms, including metal nanoparticles (MNPs) or conducting polymers (CPs).[96,97] This modification escalates the conductivity and enhances the electrochemical performance of MOFs while also imparting good stability. Diligent selection of metals, such as high-valent metal ions coupled with organic ligands like rigid ligands, can further improve water stability exhibited by MOFs. With their synergetic effects on high-conductive materials, MOFs find applications within sensing fields, including energy storage, capacitive deionization, catalysis, and drug delivery.[46,98]

MOFs design and use for agriculture applications are promising due to their effectiveness in agrochemicals' adsorption and controlled release process.[99] Mahmoud et al. developed MOFs UiO-66, UiO-66-NH_2, and UiO-67 to load and release the herbicide 2-methyl-4-chlorophenoxyacetic acid (MCPA). When combined with biodegradable polycaprolactone (PCL), the MCPA-loaded MOFs demonstrated up to 72 h of release, with UiO-66-NH_2 showing the highest efficiency: 0.056 mg mL^{-1} in ethanol and 0.037 mg mL^{-1} in water. Notably, the release capacity in water was greater than in ethanol. This suggests a promising application of MOFs in agriculture for the effective release of agrochemicals (**Figure 4**).[100]

4. MOF's Mechanism and Working in Agriculture

The physicochemical mechanisms behind MOFs' applications, stability, and activity in various soil environments offer valuable insights for improving crop production efficiency. MOFs with a high surface area and adjustable pore structures are excellent candidates for nutrient adsorption. They can effectively capture essential nutrients such as nitrogen, phosphorus, and potassium, enhancing soil fertility. The multifunctional sites within MOFs provide various interactions such as hydrogen bonding, noncovalent interactions, electrostatics interactions, and molecular interactions for processes like adsorption, controlled release, degradation, reduction, and oxidation, which assist in the transfer of nutrients to plants (**Figure 5**).[77,101]

Additionally, these structures enhance nutrient activity and are compatible with different fertilizers for synergistic nutrient delivery. The release of nutrients from MOFs is influenced by pH and soil moisture content.[4] For example, MOFs may exhibit slower nutrient release rates in acidic soils due to decreased solubility. Conversely, MOFs can release nutrients more efficiently in well-drained soils with neutral pH, promoting plant growth. MOFs can be susceptible to degradation in specific environments, such as those with high salinity. To address this challenge, researchers

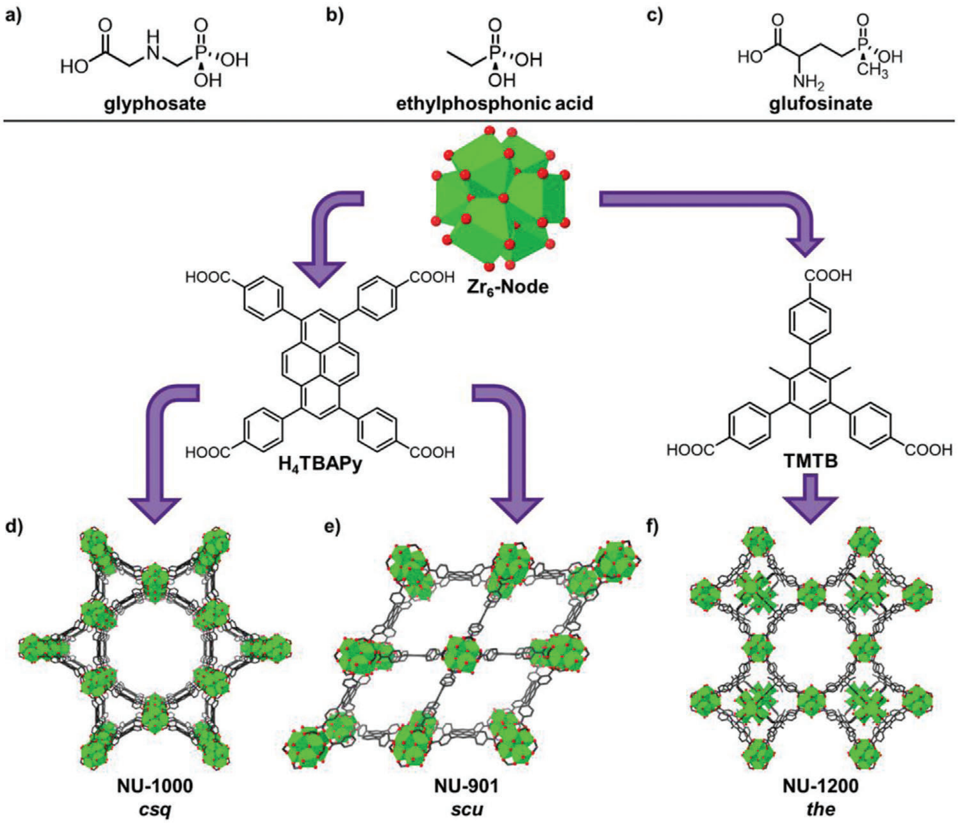


Figure 3. Structure of (a–c) glyphosate, ethylphosphonic acid, and glufosinate. MOF structures (d–f) NU-1000, NU-901, and NU-1200. Reproduced with permission.[95] Copyright 2020 American Chemical Society.

are exploring strategies such as surface modifications or encapsulation to improve the stability of MOFs.[102]

The controllable delivery of agrochemicals, like plant hormones, can enhance utilization, reduce pollution, and support precision agriculture. An intelligent system using MOFs and nanovalves efficiently loads and releases cargo in response to external stimuli, significantly promoting seed germination and plant growth. This innovative approach minimizes cargo loss and is environmentally friendly, making it a promising option for precision agriculture and controlled drug release.[42] The utilization of MOF-based materials in agriculture has been extensively studied and researched through several different approaches. Among these strategies, one popular method involves utilizing MOFs for water remediation purposes, a high benefit to agriculture.[103] This process removes agrochemicals or their byproducts from water through adsorption or degradation. For instance, Damacet et al. developed a method to control a MOF's crystal size and defect numbers at room temperature using a reaction-diffusion approach in an agar gel matrix. Adjusting the synthesis parameters, they created hierarchical MOF nanocrystals with tailored features. The largest and most defective crystals showed the highest adsorption capacity for methylene blue dye. This green synthesis technique allows for the engineering of MOF crystals with adjustable properties for various applications.[104]

Furthermore, MOFs have also been identified as potential carriers for the controlled release of agrochemicals. These materials can release specific amounts of chemicals over a set period, ensuring optimal crop growth and development while minimizing negative environmental impacts.[105] Additionally, MOFs have shown promise as sensors for detecting these molecules in water and food sources. By detecting the presence of agrochemicals, farmers can make informed decisions regarding crop management and ensure food safety for consumers. The use of MOF-type materials in agriculture has significant potential to revolutionize farming practices and promote sustainable agricultural development worldwide. For example, nanoporous bimetal MOFs using metals Ce, Fe, Al, and La were synthesized to remove F^- ions from drinking water. The best composition was Ce@Fe (1:1) with an adsorption capacity of 84.4 mg g^{-1} at 288 K. Ultrasonication improved the reaction kinetics, and the adsorption followed the pseudo-second-order model. Co-existing ions had little effect on fluoride adsorption, and the mechanism involved electrostatic attraction and ligand exchange processes.[106]

MOF materials promise for agrochemicals intelligent delivery formulations have efficiently reduced the environmental risk.[107] Ma et al. developed a hybrid material featuring a MOF using a zirconium-based MOF for pest and fungal management. This platform incorporates the fungicide tebuconazole (Teb) and the insecticide dinotefuran (DNF) at loadings of 8.59% and 6.87%, respectively. The study found that DNF was released in alkaline conditions, while Teb was released in acidic environments. The hybrid, termed DNF@UIO-ZIF@Teb, consists of a core-satellite structure where zirconium-based MOF nanoparticles (UIO)

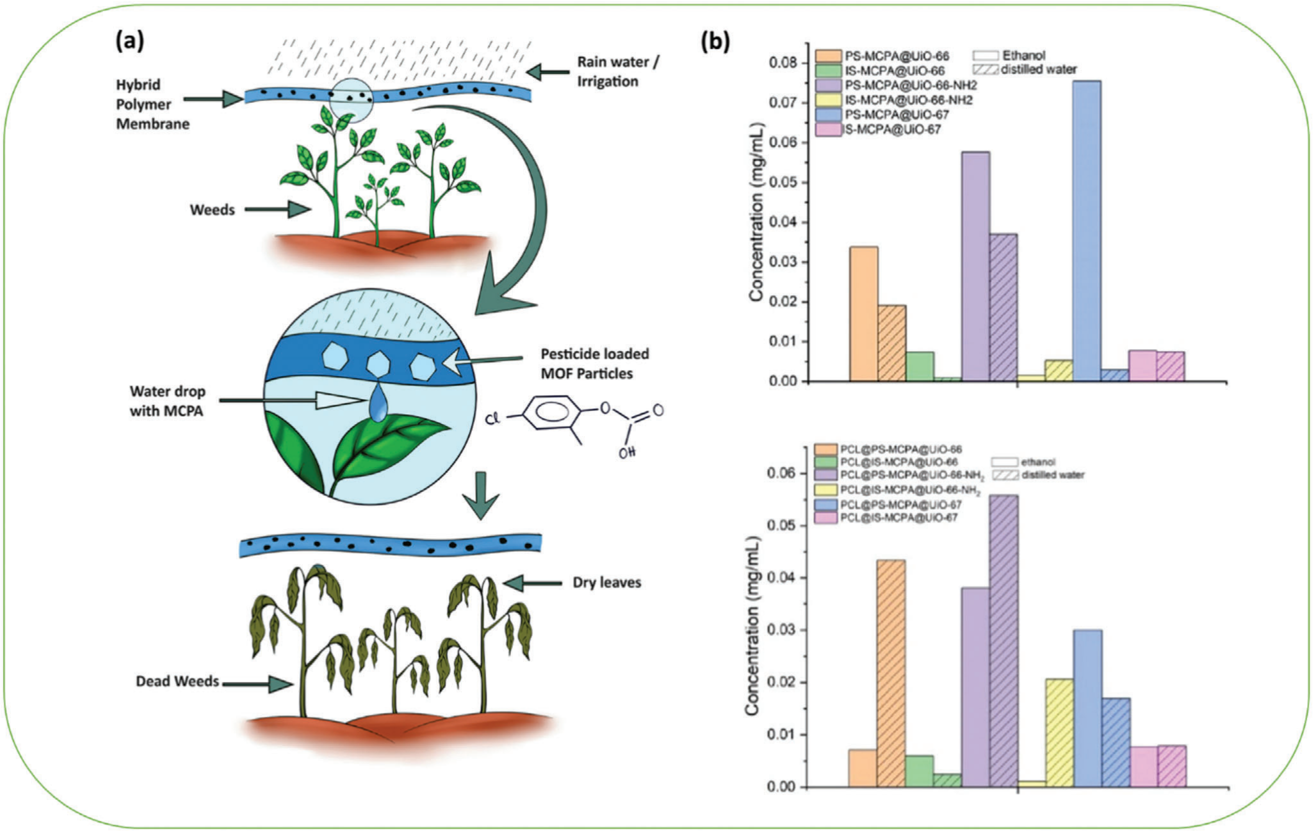


Figure 4. a) An illustration of polymer-MOF composite membrane application for the pesticide delivery in connection with weeds, facilitated by the rainwater or irrigation system b) MCPA concentrations released in 72 h for MOFs (top) and MOF-PCL composites (bottom) in ethanol and distilled water. Reproduced with permission.[100] Copyright 2022, The Authors and published by American Chemical Society.

encapsulate DNF. This design ensures stability and non-toxicity of the agrochemicals, enabling effective pest and fungal control. The results highlight the potential for future agricultural applications to protect crops from harmful diseases (**Figure 6**).[50]

MOFs are being used to measure total antioxidant capacity (TAC), which helps assess nutrition interventions. Recently, Xia et al. developed a Ce/Fe-MOF using microplasma for TAC determination. This framework showed improved catalyst efficiency due to oxygen vacancies and synergy between iron and cerium, displaying enzyme-like properties. They established a simple, cost-effective colorimetric assay for TAC in fruits and vegetables, which provides a rapid analysis time of just 15 min, a linear range of 5–60 μm, a low limit of detection (LOD) of 1.3 μM, and recovery rates of 91–107%. This research holds promise

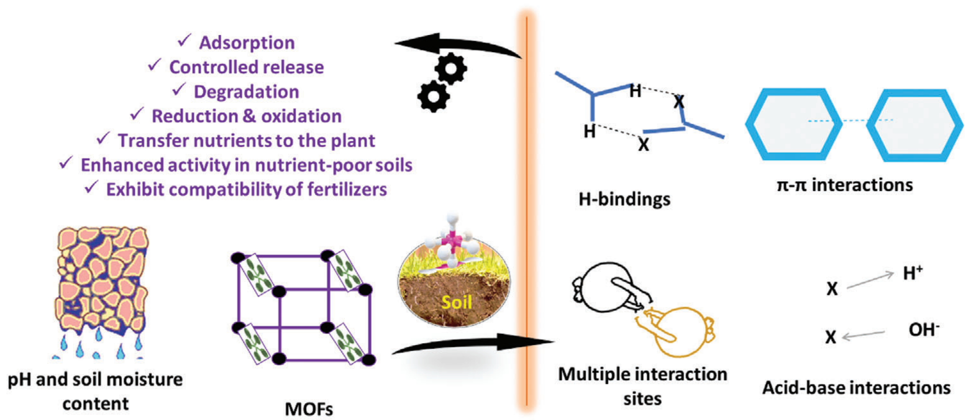


Figure 5. A schematic diagram for MOFs utility for soil amendment and common interaction forces used in various processes.

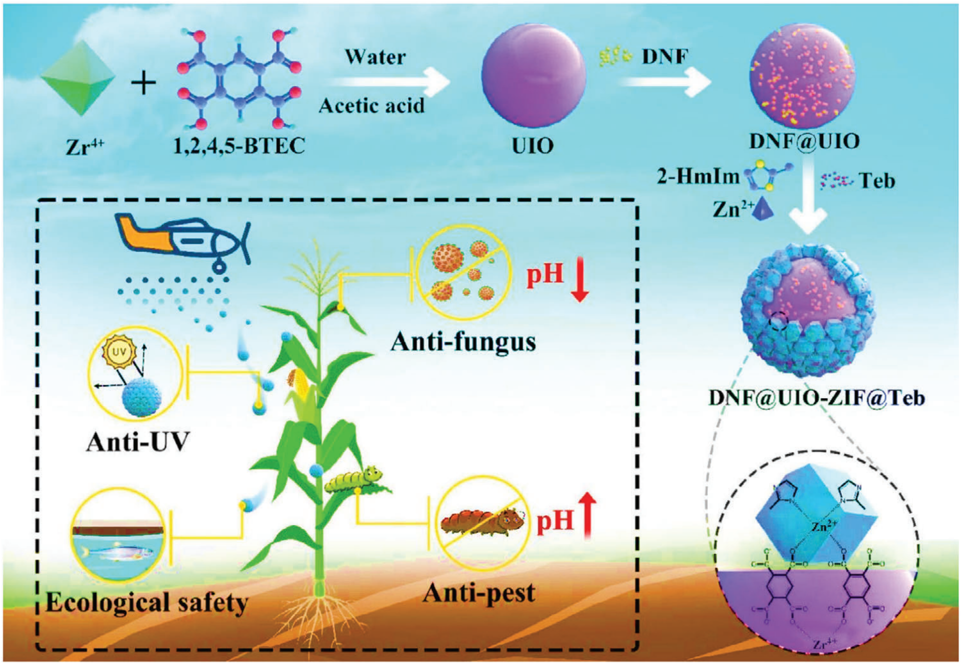


Figure 6. DNF@UIO-ZIF@Teb, a core-satellite MOF-on-MOF hybrid, could revolutionize sustainable agriculture by trapping and eliminating pests and fungi through various mechanisms. It is highly effective and versatile, providing comprehensive protection against agricultural threats. The system is sustainable and has precise targeting abilities, minimizing environmental impact. This hybrid system represents a significant step forward in sustainable agriculture, transforming modern farming practices for years. Reproduced with permission.[50]

for quick TAC assessment in agricultural products, potentially benefiting overall health outcomes.[108]

MOFs offer a promising solution for the efficient and selective extraction of sinapic acid from agricultural byproducts. Recently, Sun et al. developed raspberry-shaped imprinted polymers (CN@UiO-66-C = C@MIPs) using in-situ generated MOF composites to enhance the extraction process from squeezed rapeseed meal. These MOF-based platforms feature well-distributed particles, a template immobilization strategy, a specific surface area of 275 m^2 g^{-1}, and an average pore diameter of 2.78 nm. The adsorption process reaches equilibrium in just 10 minutes, with a capacity of 141.3 mg g^{-1} for sinapic acid. Additionally, the materials are stable after 6 h of sonication and can be regenerated up to eight times. CN@UiO-66-C = C@MIPs represent a significant advancement in sinapic acid extraction, providing a highly efficient, selective, stable, and reusable method (**Figure** 7).[109] Photocatalytic MOF membranes with a 2D heterostructure showed promise for removing and degrading agrochemicals. The 2D heterostructure MOF, graphitic carbon nitride (g-C_3N_4) nanosheets, demonstrate improved photocatalytic activity, expediting radical attack and pollutant interception. The membrane exhibits an enhanced removal rate of 89–98% for agricultural pollutants, along with good stability and reusability. This technology highlights the potential of MOF composites to effectively remove agrochemicals, serving as an essential tool for soil protection.[110]

MIL MOFs have shown promising applications in agriculture and soil amendment. They can be utilized as carriers for the controlled release of fertilizers, pesticides, and herbicides. For instance, encapsulating nutrients within MIL MOF particles can enhance plant nutrient uptake, which leads to improved crop yields. Additionally, the porous structure of these materials allows for the slow release of pesticides, reducing environmental contamination and improving crop protection.[111] Recently, Oladipo developed a sunlight-driven $AgIO_3$/MIL-53 (Fe) nanohybrid composite that effectively degrades two organophosphate pesticides. The degradation rates of the pesticides were influenced by factors such as pH, catalyst dosage, and initial concentration. Approximately 78–90% of chlorpyrifos (CP) and methyl parathion (MP) were degraded individually in tap and distilled water within 60 minutes. Around 70% mineralization was achieved within 180 minutes in a binary mixture. This innovative MOF could be particularly effective in agriculture due to its carrier separation capabilities, surface hydroxyl groups, and specific surface area.[112]

MIL-100 can remediate contaminated soils by adsorbing and removing heavy metals and organic pollutants in soil amendment. By incorporating MIL-100 into soil amendments, such as compost or biochar, the effectiveness of soil remediation processes can be enhanced. This can be particularly beneficial in areas with high levels of soil contamination, restoring soil health and promoting plant growth.[113] Shaghaleh et al. designed a new strategy using multiple-pulse water soil flushing with aminated cellulose nanofibers and AEM/AM@MIL-100(Fe) nanocomposite hydrogel effectively removed Cr(VI) from agricultural soil. The hydrogel's adsorption capacity was 338.24 mg g^{-1} at pH 6.8. A five-day simulation trial demonstrated a 98.9% Cr(VI) removal efficiency after lowering soil pH, with treated soil meeting permissible limits after three reuse cycles of the hydrogel. Importantly, chromium bioaccumulation in wheat

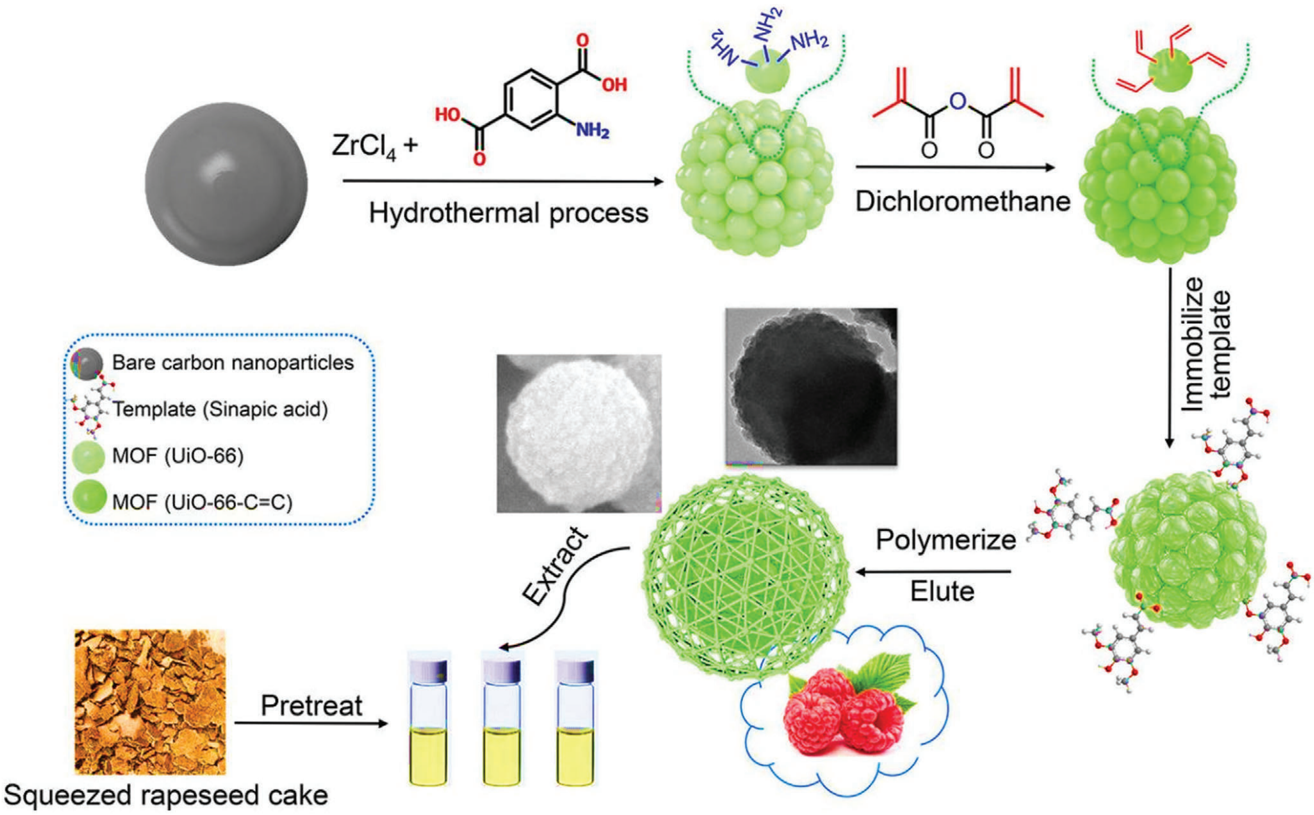


Figure 7. A new raspberry-shaped adsorbent made from MOF composites can selectively extract sinapic acid from agricultural waste. This provides a new way to extract phenolic acid from complex samples.[109]

plants remained below 0.1 ppm, while soil quality, microbial diversity, and ecological functions improved, offering a sustainable solution for soil remediation.[114]

5. MOFs for Soil Applications

MOFs in agriculture have been used for soil and crop protection by encapsulating pesticides and herbicides, protecting water-holding capacity, nutrient retention, and overall fertility.[115,116] The unique properties of MOFs lead to increased crop yields and improved soil health. In addition, MOFs have the potential for nutrient delivery in agriculture by loading nutrients such as nitrogen or phosphorus into MOFs that have delivered essential elements directly to plant roots. Using soil-water extraction, catalytic, absorption, and release technology has provided promising solutions for high-quality agriculture management and amendment.[117–119] Meng et al. designed ZIF-8-derived nanostructured carbon composited with wood sponge based in a double-layer solar evaporator using a one-step brush-printing process for soil-water extraction. ZIF-8 carbon coating has a rough morphology, enhancing photothermal conversion. The wood sponge has hydrophilic channels for efficient water extraction. The solar evaporator has high sunlight absorbance, low thermal conductivity, strong capillary force, and rapid water transport. As a result, water-evaporation of 1.42 kg m^{-2} h^{-1} and soil water-extraction rates of 0.57 kg $m^{-2}h^{-1}$ reached under a one-sun light intensity. The study demonstrated the use of ZIF-8-based wood sponge material for efficient evaporation and soil water extraction. It can be concluded that this innovative technology of soil-water extraction based on ZIF-8-based wood sponge offered an effective method for obtaining clean drinking water in remote and poor inland areas with its high sunlight absorption rate and low thermal conductivity.[120]

Zhang et al. developed a method for preparing magnetic ZIF-7@graphene oxide (mag-ZIF-7@GO) composites using polydopamine and assessing their ability to extract fungicides from environmental water and soil samples. The combination of ZIF units and GO layers enhanced the preconcentration of the fungicides, making them easier to detect. To determine the presence of seven specific fungicides (pyrimethanil, triadimenol, elutriator, tebuconazole, hexaconazole, difenoconazole, and bioethanol), a sensitive magnetic solid-phase extraction method based on mag-ZIF-7@GO coupled with LC-MS was developed. This involved optimizing salt concentration, pH levels, extraction time, and desorption time. The method exhibited good linearity, repeatability, and reproducibility under optimal conditions, with LODs ranging from 0.58 to 2.38 ng L^{-1} and limits of quantification ranging from 1.95 to 7.94 ng L^{-1} for the seven fungicides tested. This new method was then applied to determine trace amounts of these same fungicides in environmental water and soil samples. Recoveries were found to be between 81.8% and 96.7% for pond water samples, between 87.2% and 96.3% for river water samples, and between 82.4% and 93.4% for soil samples—indicating that this method has great potential for

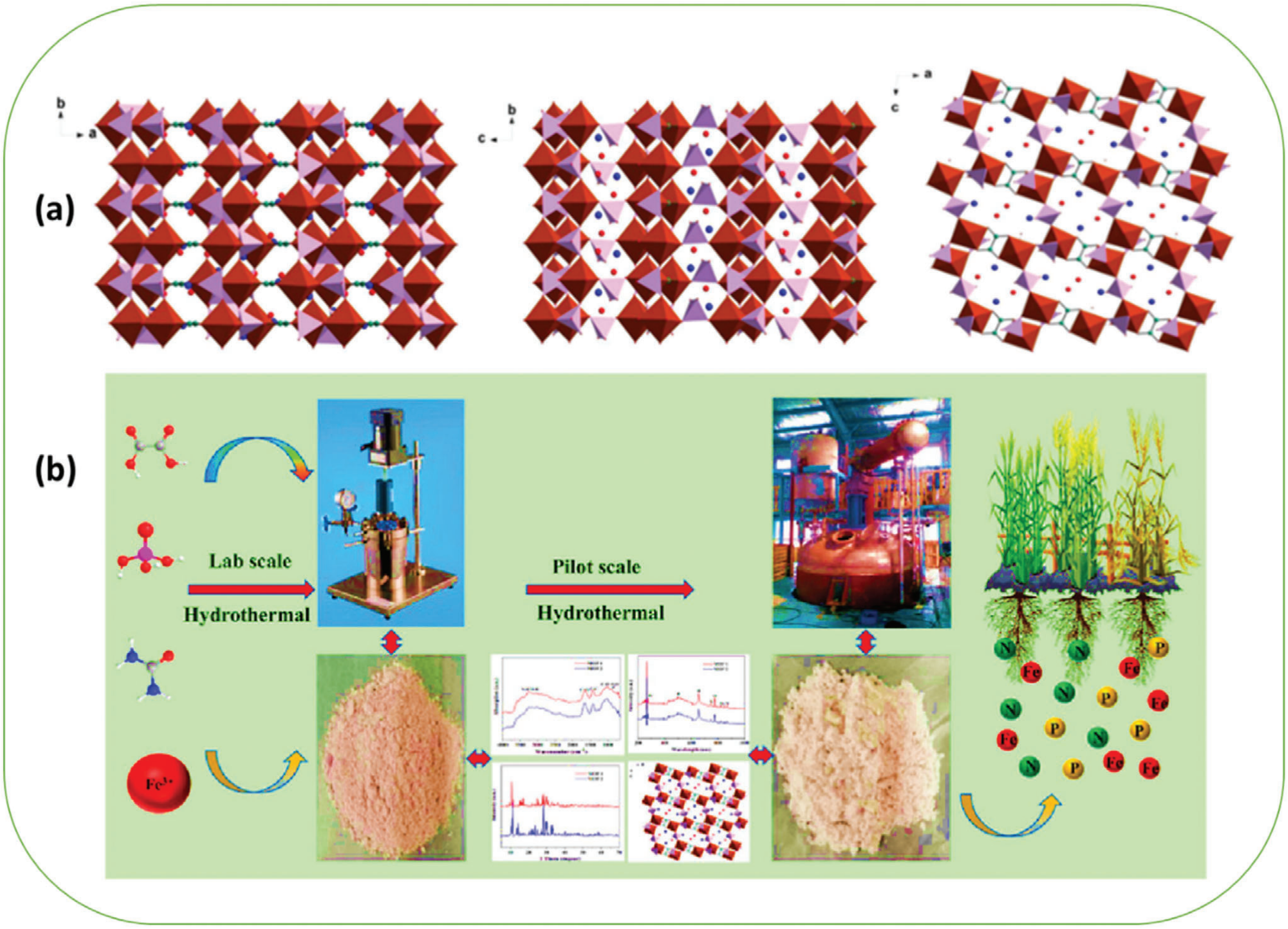


Figure 8. a) Fe-MOFs' crystal structure comprises red octahedral FeO6 units, purple tetrahedral PO_4 units, blue NH_4^+ spheres, and green C atoms. Red spheres represent H_2O molecules. b) Fe-based MOFs are an innovative solution for managing the release of fertilizer nutrients. These MOFs comprise Fe ions and organic linkers, forming a porous structure that traps and holds nutrients until plants need them. This controlled release mechanism ensures that nutrients are released gradually over time, reducing the risk of leaching or runoff into the environment. Additionally, Fe-based MOFs have improved plant nutrient uptake and utilization efficiency, leading to higher crop yields. Reproduced with permission.[122] Copyright 2022, The Authors. Published by American Chemical Society.

use in trace analysis of pollutants in complex environmental matrices.[121] It can be observed that MOF composites prepared using polydopamine can be used as an effective tool for extracting trace amounts of fungicides from environmental samples.

MOFs have amended soils with novel properties as fertilizers. Recently, Wu et al. designed Fe-MOFs that were utilized for practical crop production and connected with the soil amendment process. The main scale-up was focused on heat and energy transfer. Hydrothermally synthesized Fe-MOFs at pilot and laboratory scale with yields around 27%. The MOF was laced with nutrients N, P, and Fe with 6.03%, 14.48%, and 14.69%, suitable for nutrient release patterns with the promotion of trice yield growth. It is worth noting that using environmentally sustainable compounds such as Fe-MOFs can pave the way for their industrial production and application as a groundbreaking fertilizer, offering distinct benefits, including diverse nutrients and regulated discharge. This approach could enhance crop yield and promote eco-friendliness, making it a promising solution for sustainable agriculture (**Figure 8**).[122]

MOFs are utilized in soil-washing processes to remove pollutants from contaminated soil. The process starts with excavating the soil and transporting it to a treatment site, where it is mixed with a washing solution and agitated to release the contaminants. A significant challenge in these methods is treating the washing effluents that contain high concentrations of surfactants and polycyclic aromatic hydrocarbons (PAHs). Zhang et al. Developed a bimetallic MOF modified with molecularly imprinted polymers called Al/Co-MOFs@MIP to address the treatment of washing effluents. The aim was to activate peroxymonosulfate (PMS) for the targeted degradation of phenanthrene from soil-washing effluents and to recover biosurfactants. The Al/Co-MOFs@MIP showed stability and high catalytic performance with excellent selective recognition. The study demonstrates the improved phenanthrene adsorption and reduces oxidative free radicals on rhamnolipids for higher degradation efficiency. Both free and non-free radicals contribute to phenanthrene degradation through two pathways: $SO_4^{Å\cdot-}$and $^1O_2$ attack, causing oxalic acid loss, ring cleavage, and mineralization. The study revealed that selective phenanthrene degradation could be achieved using the MOF composite system due to its synergistic effects, such as selective adsorption and catalysis. MOFs-based innovative approach has promising potential for efficiently treating washing effluents containing high concentrations of surfactants and PAHs in surfactant-enhanced soil washing processes.[123]

MOFs with objectives to create a fast, highly selective, reusable, and effective process for the simultaneous detection of alachlor, acetochlor, and pretilachlor in field soil have shown high efficiencies. For example, Cai et al. developed and observed the performance of MIL-101 to optimize SPE. The results indicated that MIL-101(Cr) had exceptional adsorption performance compared to other commercial materials such as C18, PSA, and Florisil for amide herbicides. Method validation was carried out, which demonstrated excellent method performance. The MOF-based model showed linearities d with $r^2 \geq 0.9921$, LOD between 0.25–0.45 μg kg^{-1}, enrichment factors ≥ 89%, recoveries between 86.3% and 102.4%. This method was then applied successfully to determine amide herbicides in soil samples taken from wheat, corn, and soybean fields at various depths. The results showed that alachlor, acetochlor, and pretilachlor concentrations ranged from 0.62–8.04 μg kg^{-1} in the soil samples analyzed. Interestingly enough, it was discovered that the deeper the soil sample was taken from, the lower the concentration of these three amide herbicides became—this novel finding is significant as it proposes a new method for detecting amide herbicides in agriculture and food industry applications.[124] The findings revealed a practical approach for analyzing lachlor, acetochlor, and pretilachlor herbicides in soils. MOFs have provided a valuable pathway for monitoring herbicide presence levels over time or assessing potential environmental impacts associated with their use in agricultural practices.[124]

MOFs have been developed to tackle the environmental issue of soil organic matter pollution, which threatens the safety of food, water, and air. For example, Liu et al. created a MIL-101(Fe)/g-C_3N_4 MOF-based material to catalyze the degradation of peroxynitrite in 2-chlorophenol in soil. They optimized the reaction parameters using a mathematical model, enhancing the understanding of the mechanisms involved. The hydrothermal synthesis of MIL-101(Fe)/g-C_3N_4 improved the degradation process with sodium persulfate. Response surface methodology (RSM) indicated that this material achieved an impressive 91.2% removal rate of 2-chlorophenol, thanks to its catalytic properties and g-C_3N_4's effective adsorption. Furthermore, the research revealed that sulfate radicals ($SO_4^{\bullet-}$) were the dominant reactive species, enabling the interconversion of Fe^{2+} and Fe^{3+}. Analyzing degradation pathways provided insights for future studies on MOFs in soil pollutant removal. The authors have demonstrated a significant step in addressing soil organic matter pollution and protecting human environments.[125] MOFs have been identified as promising for producing fertilizers and enhancing soil quality for use in agriculture and horticulture applications.[126] These porous materials have a high surface area, improving nutrient absorption and retention in the soil. Wu et al. developed MOF(Fe)@NaAlg aerogels through a simple ion cross-linking process. Their model indicates that the aerogels can act as slow-release fertilizers (SRF), with an ammonium adsorption capacity of 29.4 mg g^{-1} and a swelling capacity of 73 g g^{-1}. The study showed that the optimal sample, MOF(Fe)@NaAlg(2:10), achieved the highest swelling capacity, while the SRF formulation demonstrated excellent water-retention capabilities in soil. Cumulative release studies confirmed that the release behavior was consistent with Non-Fickian diffusion. MOF(Fe)@NaAlg aerogels show great potential for use in agricultural and horticultural fertilizers due to their effective slow-release properties and improved water retention (**Figure 9**).[127]

MOFs have reached the ongoing trend of industrialization worldwide to pose a substantial environmental challenge.[128] MOFs serve as effective sensing materials for soil-moisture monitoring due to their sensitivity and performance. Alsadun et al. utilized MOFs as the receptor layer in capacitive sensors for moisture sensing in different soil types, finding that Cr-soc-MOF-1 exhibited the highest sensitivity (≈24 000 pF) among the tested MOFs. It showed increased sensitivity at 500 Hz by approximately 450% in clayey soil, with a response time of around 500 seconds. This demonstrates the significant potential of MOFs for soil-moisture applications, which could enhance sustainable water use and crop yields. The study evaluated three MOFs: Zr-fum-fcu-MOF, Al-ABTC-soc-MOF, and Cr-soc-MOF-1, confirming the efficacy of MOF-based sensors in improving irrigation and water-saving practices (**Figure 10**).[129]

MOF composites with other porous frameworks have shown enhanced applications in extracting and enriching analytes from contaminated environmental samples.[130] MOFs have been effectively used to analyze polycyclic aromatic hydrocarbons (PAHs) in contaminated soil samples through techniques like solid-phase microextraction (SPME). Koonani et al. developed Zn-MOF/COF-based SPME fibers coupled with gas chromatography-flame ionization detection (GC-FID) for improved analysis. Using a Box-Behnken design (BBD), they optimized the extraction process, which included heating the soil sample to 85 °C for 30 min at a moisture level of 23 μL g^{-1}. The method demonstrated linear responses for six PAHs ranging from 1 to 20000 ng g^{-1} and detection limits between 0.1 and 1 ng g^{-1}. The study also showed intra-fiber RSDs of 2.2% to 6.6% and inter-fiber RSDs of 5.2% to 11.6%. Relative recovery values for real soil samples ranged from 91.1% to 110.2%. The Zn-MOF/COF fiber proved to be more cost-effective and efficient in extracting PAHs than existing commercial and homemade adsorbents.[131]

Soil pollution from heavy metal ions has adversely affected ecosystems, reducing soil fertility and hindering plant growth. This, in turn, impacts the food chain, as plants are essential for animal nutrition. In this regard, Lu et al. developed ZVI@MOF-g-DCUF, a multifunctional fertilizer made from zerovalent iron-doped MOF (Mg)-74, coated with dialdehyde carboxymethylcellulose urea-formaldehyde (DCUF). This MOF enhances soil quality and water retention. Studies showed that nZVI@MOF-g-DCUF effectively releases nutrients over 35 days and positively impacts the growth of Chinese cabbage. Remediation tests indicated that adding 1% of the MOF to chromium (Cr)-polluted soil achieved significant removal rates for Cr(VI) of 84.40% and 76.83%. This efficiency results from the immobilization of Cr(VI) through hydrogen bonding, reduction, precipitation, and complexation. This MOF-based approach shows strong potential for long-term nutrient release and Cr(VI) immobilization, addressing environmental concerns linked to chemical fertilizers while improving soil quality for agriculture.[132]

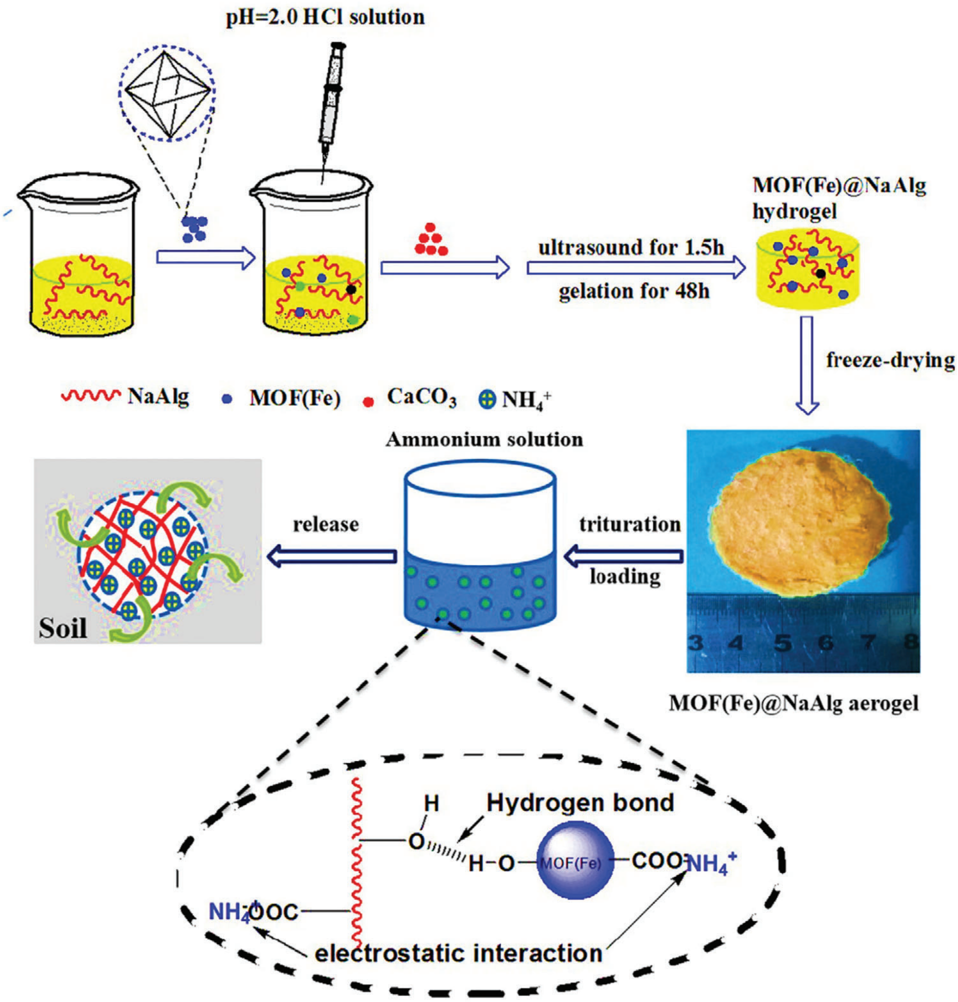


Figure 9. The MOF(Fe)@NaAlg composite aerogel is prepared by selecting appropriate materials and synthesizing the MOF(Fe) and NaAlg separately. The platform was designed by combing through impregnation, drying, and exhibiting unique gas storage and separation properties. The pathway offers new possibilities for addressing global challenges such as climate change and energy sustainability. Reproduced with the permission of[127] © 2019 Elsevier B.V. All rights reserved.

Shaghaleh et al. developed an eco-friendly, reusable nanocomposite hydrogel adsorbent, TO-NFCs/lignin/AM@MIL-100(Fe) (NCLMH), for removing hazardous lead (Pb) and copper (Cu) from contaminated agricultural soils. The hydrogel achieved a removal capacity of 416.39 mg g^{-1} for Pb and 133.98 mg g^{-1} for Cu at pH 6.5 through complexation, electrical attraction, and ion exchange. Three remediation strategies were explored: soil stabilizer (SA@NCLMH) and two soil flushing methods—continuous flushing (CF@NCLMH) and multiple-pulse flushing (MF@NCLMH). Continuous flushing removed 89.5% Pb and 77.2% Cu in 24 hours, while multiple-pulse flushing achieved 96.5% Cu and 84.5% Pb removal over five days. The model demonstrated excellent stability and reusability, making it a promising solution for heavy metal remediation in agricultural soils.[133]

Ma et al. developed a heterostructured membrane based on Fe(III)-MOF, carboxymethyl cellulose (CMC), and silver nanowires (AgNWs) that was used for catalytic separation activity to treat roots in the soil to transport water. The membrane exhibited electrostatic force and hydrogen bonding interaction between CMC and AgNWs as the “root” connected to NH_2-MIL-88B(Fe). The resulting AgNWs/CMC@NMB membrane displayed remarkable selective wettability, with water contact angles (WCAs) of approximately 0° and underwater oil contact angles (UWOCAs) exceeding 155°. It also exhibited excellent removal efficiency (>99%) for insoluble oils under a 1343 L m^{-2} h^{-1} bar^{-1} separation flux. The porous filter structure of the soil-root-like heterostructure allowed for concurrent treatment of both insoluble oils and soluble dyes via one-step efficient filtration. Notably, the disposal efficiency for anionic and cationic dyes reached over 96.7% due to the unique structure. The study revealed that AgNWs filter and stabilize water, aiding electron transfer in the Fe-MOF photo-Fenton system. This improves the degradation of organic contaminants and regenerates fouled membranes through photo-catalysis.[134]

MOF-based materials have gained a new approach for detecting organophosphorus pesticides. Guselnikova et al. designed MOF with surface plasmon-polariton (SPP)-supported gold

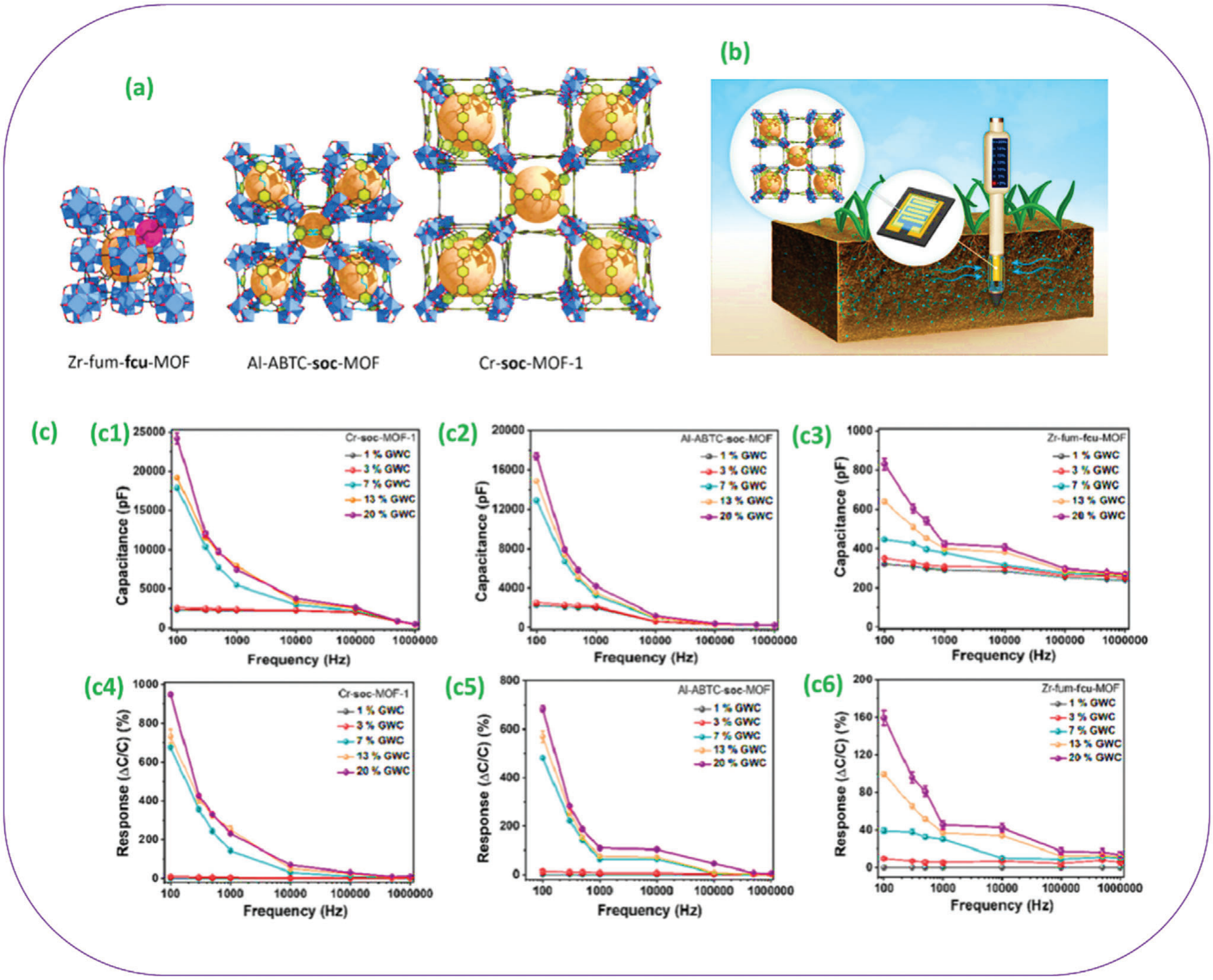


Figure 10. a) This study employed schematic representations of Zr-fum-fcu-MOF, Al-ABTC-soc-MOF, and Cr-soc-MOF-1. b) MOF is designed as a sensor image for soil deployment. c) Selectivity of the sensor on the clayey and loamy sand soil on exposing 10% GWC with different water content for c1,c4) Cr-soc-MOF-1, c2, 5) Al-ABTC-soc-MOF, and c3,c6) Zr-fum-fcu-MOF. Reproduced with permission.[129] Copyright 2023, American Chemical Society.

grating surface as a SERS chip. The platform was designed in two steps to grow thin MOF-5 film. Firstly, the covalently grafted using 4-carboxyphenyl groups, and secondly, the immersion of samples in the mother liquid of MOF-5. The proposed SERS chip has proven to be an ideal analytical probe for detecting organophosphorus pesticides with high reliability and a low LOD of up to 10^{-12} M.[135] The MOF-based materials applications in soil amendment have successfully shown the ability to selectively detect, degrade, release, and adsorb various significant contaminants. MOFs also revealed that when combining the high affinity of contaminants with excellent chemical and physical forces that supported structure for developing an ideal platform. The findings suggested a promising solution for soil amendment in different strategies for using MOFs and composites as reliable tools in various settings.[135]

Hybrid MOFs have shown promising agricultural potential, particularly in soil amendment applications. These materials combine the advantages of both organic and inorganic components, offering unique properties for enhancing soil quality and plant growth. The current status of Hybrid MOFs in agriculture indicates a growing interest, and research is focusing on their practical applications. In practical scenarios, Hybrid MOFs have been utilized as soil amendments to improve soil structure, water retention, and nutrient availability. It can't be denied that incorporating Hybrid MOFs into the soil can enhance cation exchange capacity, leading to better retention and release of essential nutrients for plant uptake. Additionally, these materials have shown the ability to reduce soil compaction and increase microbial activity, promoting healthier soil ecosystems.

6. Challenges

MOFs are a promising class of porous materials with numerous applications in agriculture and soil amendment. Despite their potential, MOFs face several challenges regarding their use in agriculture and soil amendment.

i. A significant obstacle in developing and utilizing MOFs in agriculture and soil amendment is their requirement to maintain stability and functionality despite harsh environmental conditions. This includes exposure to high temperatures and acidic soils, which can seriously threaten their efficacy. As such, any MOFs utilized in agricultural settings must be carefully designed and tested to ensure their resilience under these challenging circumstances.
ii. To be effective, MOFs must be able to selectively capture and release essential plant nutrients, including nitrogen and phosphorus. This is paramount as it ensures that these vital nutrients remain within the plant's ecosystem without being lost through processes such as leaching or volatilization. Therefore, MOFs must be designed with this important consideration in mind to maximize their potential benefits for agricultural applications.
iii. One of the obstacles faced in producing MOFs for agricultural purposes is the issue of cost-effectiveness, particularly in large-scale production. This presents a challenge that must be addressed to make MOFs a viable option for widespread use in agriculture and soil amendment. The need to balance cost with effectiveness and efficiency is crucial, as it will ultimately determine whether or not MOFs can be implemented on a larger scale. Finding ways to optimize production processes and reduce costs without sacrificing quality or efficacy will be vital in overcoming this hurdle.
iv. One major issue is the need for more research on their practical implementation for soil decontamination. While MOFs show promise in theory, their application in real-world settings still needs to be tested. For example, when attempting to remediate contaminated soil from industrial sites, MOFs could potentially adsorb harmful contaminants. However, there is a lack of empirical data regarding their effectiveness in various soil conditions. Additionally, the complexity of soil ecosystems—including differences in soil composition, pH, and microbial activity—affects the performance of MOFs. This complexity requires tailored strategies for each specific environment. Although MOFs' theoretical potential for soil detoxification is significant, the absence of practical applications and supporting data limits their broader use. Addressing these challenges through field trials and collaborative research is crucial to unlocking the full potential of MOFs in soil decontamination.

The application of MOFs has gained attention as a potential solution to various challenges in agriculture. However, there is a significant gap in research regarding the long-term effects of MOF application on soil health and crop productivity. Without proper investigation and understanding of these impacts, the successful integration of MOFs into sustainable agriculture practices remains uncertain. Therefore, addressing these challenges through rigorous research and experimentation will be crucial for ensuring the safe and effective use of MOFs in agriculture. It is essential to recognize that sustainable agricultural practices are critical for maintaining global food security while minimizing negative environmental impacts. Therefore, it is necessary to prioritize a thorough investigation of the potential benefits and drawbacks associated with MOF application in agriculture to make informed decisions about its use.

7. Conclusion and Outlooks

MOFs are highly versatile materials with many potential applications in agriculture and soil improvement. Their use as fertilizers has been shown to impact plant growth and yield significantly. Additionally, MOFs can enhance the effectiveness of pesticide delivery systems, reducing the required amount of chemicals and minimizing environmental damage. Another promising application is their ability to effectively remove pollutants and contaminants from soil, making them ideal for maintaining healthy soil quality while minimizing environmental impact.

MOFs have demonstrated their ability to store and release nutrients over time, improving soil quality and providing crops with sustained nutrition throughout the growing season. This represents a significant step towards improving crop yields while minimizing environmental harm. MOFs' versatility makes them an invaluable tool for sustainable agriculture practices. Further exploration of MOFs in agriculture is needed to unlock their full potential in achieving sustainable and responsible farming practices.

Development trends in Hybrid MOFs for soil amendment involve exploring novel synthetic strategies to tailor their properties to specific agricultural needs. Researchers are investigating the use of functionalized ligands and metal nodes to enhance the performance of these materials in different soil types and crop systems. Moreover, efforts are being made to scale up production processes to make Hybrid MOFs more accessible to farmers and agricultural industries. Applying Hybrid MOFs in agriculture for soil amendment is a rapidly evolving field with significant potential. By leveraging the unique properties of these materials, researchers aim to address challenges in modern agriculture, such as soil degradation and nutrient deficiencies. As research progresses and technology advances, Hybrid MOFs are poised to play a crucial role in sustainable farming practices.

In conclusion, the versatile applications of MOFs in agriculture and soil amendment can benefit farmers and the environment. As research on MOFs progresses, there may be even more innovative ways these adaptable materials can enhance crop production and promote sustainability efforts. The versatility of MOFs makes them a promising prospect for the future of agriculture, as they can aid in reducing environmental impact and optimizing crop yields. Therefore, it is imperative to continue exploring the potential of these materials to revolutionize agricultural practices and pave the way toward a more sustainable future.

Acknowledgements

The authors gratefully acknowledge the Fundação para a Ciência e a Tecnologia (FCT), Portugal, through projects UIDB/00100/2020 (DOI:10.54499/UIDB/00100/2020), UIDP/00100/2020 (DOI:10.54499/UIDP/00100/2020), and LA/P/0056/2020 (DOI:10.54499/LA/P/0056/2020) of Centro de Química Estrutural.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

Ariculture, Analysis, Loading release, Metal-organic frameworks, Soil amendment

Received: August 25, 2024
Revised: November 29, 2024
Published online:

[1] K. S. Aldren Usman, J. W. Maina, S. Seyedin, M. T. Conato, L. M. Payawan Jr, L. F. Dumée, J. M. Razal, *NPG Asia Mater* **2020**, *12*, 58.
[2] Z. Han, K. Wang, Y. Guo, W. Chen, J. Zhang, X. Zhang, G. Siligardi, S. Yang, Z. Zhou, P. Sun, W. Shi, P. Cheng, *Nat. Commun.* **2019**, *10*, 5117.
[3] J. Abdi, G. Mazloom, *Sci. Reports* **2022**, *12*, 16458.
[4] C. G. Song, Y. Q. Liu, G. Ding, J. Yang, C. Y. Wang, J. R. Wu, G. Wu, M. H. Li, L. P. Guo, J. C. Qin, Y. W. Yang, *ACS Appl. Nano Mater.* **2022**, *5*, 18930.
[5] D. J. Cerasale, D. C. Ward, T. L. Easun, *Nat. Rev. Chem.* **2021**, *6*, 9.
[6] Q. Xie, Y. Li, Z. Lv, H. Zhou, X. Yang, J. Chen, H. Guo, *Sci. Reports* **2017**, *7*, 3316.
[7] F. Ke, C. Peng, T. Zhang, M. Zhang, C. Zhou, H. Cai, J. Zhu, X. Wan, *Sci. Reports* **2018**, *8*, 939.
[8] S. J. Cusworth, W. J. Davies, M. R. McAinsh, A. S. Gregory, J. Storkey, C. J. Stevens, *Commun. Earth Environ.* **2024**, *5*, 7.
[9] G. R. Gois, *Ann. Am. Assoc. Geogr.* **2023**, *113*, 1589.
[10] S. H. Ali, *Nat. Mater.* **2018**, *17*, 1052.
[11] A. Yudina, Y. Kuzyakov, *Geoderma* **2023**, *434*, 116478.
[12] H. Wang, Y. Chen, F. Guo, P. Dong, W. Liang, J. Cheng, *Sci. Reports* **2024**, *14*, 5407.
[13] R. Lal, *Farming Syst* **2023**, *1*, 100002.
[14] M. Fernández-Huarte, J. G. Elphinstone, I. P. Adams, J. G. Vicente, A. Bhogal, C. A. Watson, F. Dussart, E. A. Stockdale, J. Walshaw, S. McGreig, R. W. Simmons, L. Mašková, L. K. Deeks, M. R. Goddard, *Soil Biol. Biochem.* **2023**, *184*, 109104.
[15] E. Collado, M. Piqué, J. Coello, J. de-Dios-García, C. Fuentes, L. Coll, *For. Ecol. Manage.* **2023**, *549*, 121457.
[16] S. Li, X. X. Wang, M. Li, C. Wang, F. Wang, H. Zong, B. Wang, Z. Lv, N. Song, J. Liu, *Ecotoxicol. Environ. Saf.* **2024**, *271*, 116013.
[17] N. Atta, M. Shahbaz, F. Farhat, M. F. Maqsood, U. Zulfiqar, N. Naz, M. M. Ahmed, N. U. Hassan, N. Mujahid, A. E. Z. M. A. Mustafa, M. S. Elshikh, T. Chaudhary, *Sci. Reports* **2024**, *14*, 456.
[18] A. Sieprawska, E. Rudolphi-Szydło, M. Skórka, A. Telk, M. Filek, *Sci. Reports* **2024**, *14*, 3121.
[19] L. Li, C. Xu, J. Zou, Z. Deng, S. You, Q. Wang, *J. Agric. Food Chem.* **2023**, *72*, 6684.
[20] J. Feng, N. Wei, Z. Chen, C. Hou, Q. Liang, Y. Tan, *J. Environ. Chem. Eng.* **2024**, *12*, 112406.
[21] N. K. Pandey, A. Murmu, P. Banjare, B. W. Matore, J. Singh, P. P. Roy, *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 12371.
[22] R. Gill, M. Naeem, A. A. Ansari, A. Kumar, A. Kumar, A. Chhikara, J. F. J. Bremont, N. Tuteja, S. S. Gill, *Agrochem. Soil Environ. Impacts Remediat.* **2022**, *3*.
[23] P. Meidl, A. Lehmann, M. Bi, C. Breitenreiter, J. Benkrama, E. Li, J. Riedo, M. C. Rillig, *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 11995.
[24] Global agrochemical market volume 2021–2030 | Statista.
[25] F. A. Brief, *FAOSTAT Analytical Briefs* **2022**, *46*, https://www.statista.com/statistics/1254514/global-agrochemical-market-size.
[26] L. de Graaf, M. Bresson, M. Boulanger, M. Bureau, Y. Lecluse, P. Lebailly, I. Baldi, *Sci. Total Environ.* **2024**, *919*, 170816.
[27] A. Nipers, I. Pilvere, I. Upite, A. Krievina, A. Pilvere, *Resour. Environ. Sustain.* **2024**, *15*, 100145.
[28] A. R. Pimentão, A. P. Cuco, C. Pascoal, F. Cássio, B. B. Castro, *Environ. Pollut.* **2024**, *347*, 123678.
[29] J. Yang, X.-Y. Lou, D. Dai, J. Shi, Y.-W. Yang, *Chinese Chem. Lett.* **2025**, *36*, 109818.
[30] C. Y. Wang, J. C. Qin, Y. W. Yang, *J. Agric. Food Chem.* **2023**, *71*, 5953.
[31] E. Deveci, Madenli, C. A., R. Zan, *Int. J. Environ. Sci. Technol.* **2024**, *16*, 9308.
[32] Z. Tigrine, O. Benhabiles, L. Merabti, N. Chekir, M. Mellal, S. Aoudj, N. A. Abdeslam, D. Tassalit, S. E. I. Lebouachera, N. Drouiche, *Sustain.* **2024**, *16*, 9308.
[33] S. F. Farzam, F. Shemirani, S. Karimi, *Talanta* **2024**, *272*, 125744.
[34] M. Shah, P. Kolhe, S. Gandhi, *Chemosphere* **2023**, *321*, 138148.
[35] G. Dubourg, Z. Pavlović, B. Bajac, M. Kukkar, N. Finčur, Z. Novaković, M. Radović, *Sci. Total Environ.* **2024**, *928*, 172048.
[36] X. Sun, M. Di, J. Liu, L. Gao, X. Yan, G. He, *Small* **2023**, *19*, 2303757.
[37] L. Delitsyn, R. Kulumbegov, O. Popel, Y. Kosivtsov, M. Sulman, *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1212*, 012024.
[38] L. Hu, W. Wu, M. Hu, L. Jiang, D. Lin, J. Wu, K. Yang, *Nat. Commun.* **2024**, *15*, 3204.
[39] P. Kumar, Z. Abbas, P. Kumar, D. Das, S. M. Mobin, *Langmuir* **2023**, *40*, 5040.
[40] L. H. T. Nguyen, M. T. Le Nguyen, T. N. Ha, H. T. Hoang, N. K. Pham, Y. Kawazoe, D. Nguyen-Manh, T. L. H. Doan, *J. Sci. Adv. Mater. Devices* **2024**, *9*, 100661.
[41] B. F. Rivadeneira-Mendoza, L. S. Quiroz-Fernández, F. F. da Silva, R. Luque, A. M. Balu, J. M. Rodríguez-Díaz, *Environ. Sci. Nano* **2024**, *11*, 1543.
[42] J. Yang, D. Dai, Z. Cai, Y. Q. Liu, J. C. Qin, Y. Wang, Y. W. Yang, *Acta Biomater.* **2021**, *134*, 664.
[43] Z. Suo, R. Liang, R. Liu, M. Wei, B. He, L. Jiang, X. Sun, H. Jin, *Anal. Chim. Acta* **2023**, *1239*, 340714.
[44] X. Tao, Z. Yang, J. Feng, S. Jian, Y. Yang, C. T. Bates, G. Wang, X. Guo, D. Ning, M. L. Kempher, X. J. A. Liu, Y. Ouyang, S. Han, L. Wu, Y. Zeng, J. Kuang, Y. Zhang, X. Zhou, Z. Shi, W. Qin, J. Wang, M. K. Firestone, J. M. Tiedje, J. Zhou, *Nat. Commun.* **2024**, *15*, 1178.
[45] M. C. Heuermann, D. Knoch, A. Junker, T. Altmann, *Nat. Commun.* **2023**, *14*, 5783.
[46] S. Rojas, A. Rodríguez-Diéguez, P. Horcajada, *ACS Appl. Mater. Interfaces* **2022**, *14*, 16983.
[47] X. Lu, K. Jayakumar, Y. Wen, A. Hojjati-Najafabadi, X. Duan, J. Xu, *Microchim. Acta* **2023**, *191*, 58.
[48] H. Karimi-Maleh, M. Ghalkhani, Z. Saberi Dehkordi, M. Mohsenpour Tehran, J. Singh, Y. Wen, M. Baghayeri, J. Rouhi, L. Fu, S. Rajendran, *J. Ind. Eng. Chem.* **2024**, *129*, 105.
[49] C. Y. Wang, J. C. Qin, Y. W. Yang, *J. Agric. Food Chem.* **2023**, *71*, 5972.
[50] S. Ma, X. Yang, Y. Wang, X. Yang, Y. Li, S. Lü, *Appl. Surf. Sci.* **2023**, *624*, 157129.
[51] Z. Cui, Y. Li, O. V. Tsyusko, J. Wang, J. M. Unrine, G. Wei, C. Chen, *J. Agric. Food Chem.* **2024**, *72*, 8890.
[52] K. Jhajharia, P. Mathur, S. Jain, S. Nijhawan, *Procedia Comput. Sci.* **2023**, *218*, 406.
[53] Q. Liu, Y. Zhao, T. Li, L. Chen, Y. Chen, P. Sui, *Appl. Soil Ecol.* **2023**, *186*, 104815.
[54] E. A. Minato, F. M. Brignoli, M. E. Neto, M. R. Besen, B. M. A. R. Cassim, R. S. Lima, C. A. Tormena, T. T. Inoue, M. A. Batista, *Soil Tillage Res* **2023**, *234*, 105860.
[55] H. Green, P. Larsen, J. Koci, W. Edwards, P. N. Nelson, *Soil Tillage Res* **2023**, *233*, 105780.
[56] O. Özbolat, V. Sánchez-Navarro, R. Zornoza, M. Egea-Cortines, J. Cuartero, M. Ros, J. A. Pascual, C. Boix-Fayos, M. Almagro, J. de Vente, E. Díaz-Pereira, M. Martínez-Mena, *Geoderma* **2023**, *429*, 116218.
[57] J. Nan, D. Chang, J. Liu, H. Chen, J. S. Lee, S. Y. Kim, *Transp. Geotech.* **2024**, *44*, 101175.

[58] Y. Z. Liu, R. D. Fan, S. Y. Liu, C. Z. Zhang, J. W. Sun, *Constr. Build. Mater.* **2023**, *404*, 133188.
[59] B. T. Dang, R. Ramaraj, K. P. H. Huynh, M. V. Le, I. Tomoaki, T. T. Pham, V. Hoang Luan, P. Thi Le Na, D. P. H. Tran, *Bioresour. Technol.* **2023**, *375*, 128830.
[60] H. Wang, Y. Lv, J. Bao, Y. Chen, L. Zhu, *J. Hazard. Mater.* **2024**, *466*, 133600.
[61] Z. P. Xu, *ACS Agric. Sci. Technol.* **2022**, *2*, 232.
[62] P. M. Singh, A. Tiwari, D. Maity, S. Saha, *J. Mater. Sci.* **2022**, *57*, 10836.
[63] P. Krištuf, M. P. Janovský, J. Turek, J. Horák, L. Ferenczi, M. Hejcman, *J. Archaeol. Sci.* **2023**, *160*, 105881.
[64] P. Huang, Y. Zhang, N. Hussain, T. Lan, G. Chen, X. Tang, O. Deng, C. Yan, Y. Li, L. Luo, W. Yang, X. Gao, *Environ. Pollut.* **2024**, *341*, 122890.
[65] M. O. Karkush, A. D. Almurshedi, H. H. Karim, *Arab. J. Sci. Eng.* **2023**, *48*, 665.
[66] C. Ma, L. Han, H. Shang, Y. Hao, X. Xu, J. C. White, Z. Wang, B. Xing, *Curr. Opin. Environ. Sci. Heal.* **2023**, *31*, 100432.
[67] I. Mohiuddin, R. Singh, V. Kaur, *J. Environ. Chem. Eng.* **2023**, *11*, 109067.
[68] C. Dietzen, M. T. Rosing, *Int. J. Greenh. Gas Control* **2023**, *125*, 103872.
[69] H. Lv, G. Zhang, W. Yang, X. Dai, Y. Huang, J. Ni, Q. Wang, *J. Electroanal. Chem.* **2023**, *930*, 117141.
[70] M. Mazarji, M. T. Bayero, T. Minkina, S. Sushkova, S. Mandzhieva, T. V. Bauer, A. Soldatov, M. Sillanpää, M. H. Wong, *Sci. Total Environ.* **2023**, *880*, 163330.
[71] M. Behpour, M. Shadi, S. Nojavan, *Food Chem.* **2023**, *407*, 135067.
[72] A. Karnwal, A. Dohroo, T. Malik, *Biomed Res. Int.* **2023**, *2023*, 6911851.
[73] D. Rudakiya, Y. Patel, U. Chhaya, A. Gupte, *Nanotechnol. Agric. Adv. Sustain. Agric.* **2023**, *880*, 163330.
[74] D. W. Sun, L. Huang, H. Pu, J. Ma, *Chem. Soc. Rev.* **2021**, *50*, 1070.
[75] Z. Guo, J. J. Richardson, B. Kong, K. Liang, *Sci. Adv.* **2020**, *6*, 330.
[76] X. Mao, Z. Yang, *J. Nanoparticle Res.* **2023**, *25*, 198.
[77] Y. Q. Liu, C. G. Song, G. Ding, J. Yang, J. R. Wu, G. Wu, M. Z. Zhang, C. Song, L. P. Guo, J. C. Qin, Y. W. Yang, *Adv. Mater. Interfaces* **2022**, *9*, 2102480.
[78] R. Yousefi, S. Asgari, A. Banitalebi Dehkordi, G. Mohammadi Ziarani, A. Badiei, F. Mohajer, R. S. Varma, S. Iravani, *Environ. Res.* **2023**, *226*, 115664.
[79] C. Yue, L. Chen, H. Zhang, J. Huang, H. Jiang, H. Li, S. Yang, *Environ. Sci. Water Res. Technol.* **2023**, *9*, 669.
[80] H. Kaur, N. Devi, S. S. Siwal, W. F. Alsanie, M. K. Thakur, V. K. Thakur, *ACS Omega* **2023**, *8*, 9004.
[81] L. Gan, M. T. Nord, J. M. Lessard, N. Q. Tufts, A. Chidambaram, M. E. Light, H. Huang, E. Solano, J. Fraile, F. Suárez-García, C. Viñas, F. Teixidor, K. C. Stylianou, J. G. Planas, *J. Am. Chem. Soc.* **2023**, *145*, 13730.
[82] T. Sakthi Priya, T.-W. Chen, S.-M. Chen, T. Kokulnathan, B.-S. Lou, T. saad Algarni, W. A. Al-onazi, M. S. Elshikh, *Carbon N. Y.* **2024**, *223*, 119026.
[83] S. Wang, F. Cheng, Z. Shao, B. Wu, S. Guo, *Sci. Total Environ.* **2023**, *857*, 159405.
[84] Y. Xue, L. Chen, L. Xiang, Y. Zhou, T. Wang, *J. Environ. Manage.* **2023**, *328*, 117200.
[85] C. Ye, J. Sima, D. Zhou, Y. Chen, J. Yang, Y. Yan, *Water. Air. Soil Pollut.* **2023**, *234*, 642.
[86] F. Rassaei, *Environ. Prog. Sustain. Energy* **2024**, *43*, e14251.
[87] K. G. Froudas, M. Vassaki, K. Papadopoulos, C. Tsangarakis, X. Chen, W. Shepard, D. Fairen-Jimenez, C. Tampaxis, G. Charalambopoulou, T. A. Steriotis, P. N. Trikalitis, *J. Am. Chem. Soc.* **2023**, *146*, 8961.
[88] J. Usman, S. I. Abba, N. Baig, N. Abu-Zahra, S. W. Hasan, I. H. Aljundi, *ACS Appl. Mater. Interfaces* **2024**, *16*, 16271.
[89] H. L. Choi, Y. Jeong, H. Lee, T. H. Bae, *JACS Au* **2024**, *4*, 253.
[90] Y. Liu, X. He, Y. Wang, Z. Cheng, Z. Yao, J. Zhou, Y. Zuo, R. Chen, Y. Lei, R. Tan, P. Chen, *Small* **2023**, *19*, 2302633.
[91] K. J. Fernández-Andrade, A. A. Fernández-Andrade, L. Á. Zambrano-Intriago, L. E. Arteaga-Perez, S. Alejandro-Martin, R. J. Baquerizo-Crespo, R. Luque, J. M. Rodríguez-Díaz, *Chemosphere* **2023**, *314*, 137664.
[92] M. Shi, D. Lin, R. Huang, W. Qi, R. Su, Z. He, *Ind. Eng. Chem. Res.* **2020**, *59*, 13220.
[93] F. Huang, X. Lu, L. Kuai, Y. Ru, J. Jiang, J. Song, S. Chen, L. Mao, Y. Li, B. Li, H. Dong, J. Shi, *J. Am. Chem. Soc.* **2024**, *146*, 3186.
[94] I. Akpinar, X. Wang, K. Fahy, F. Sha, S. Yang, T. Kwon, P. J. Das, T. Islamoglu, O. K. Farha, J. F. Stoddart, *J. Am. Chem. Soc.* **2024**, *146*, 5108.
[95] R. J. Drout, S. Kato, H. Chen, F. A. Son, K. I. Otake, T. Islamoglu, R. Q. Snurr, O. K. Farha, *J. Am. Chem. Soc.* **2020**, *142*, 12357.
[96] T. De Villenoisy, X. Zheng, V. Wong, S. S. Mofarah, H. Arandiyan, Y. Yamauchi, P. Koshy, C. C. Sorrell, T. De Villenoisy, X. Zheng, V. Wong, S. S. Mofarah, P. Koshy, C. C. Sorrell, H. Arandiyan, Y. Yamauchi, *Adv. Mater.* **2023**, *35*, 2210166.
[97] D. W. Junior, B. M. Hryniewicz, L. T. Kubota, *Chemosphere* **2024**, *352*, 141479.
[98] Y. Wang, Y. Gui, S. He, J. Yang, *Compos. Part A Appl. Sci. Manuf.* **2023**, *173*, 107692.
[99] L. Jiao, J. Y. R. Seow, W. S. Skinner, Z. U. Wang, H. L. Jiang, *Mater. Today* **2019**, *27*, 43.
[100] L. A. M. Mahmoud, R. Telford, T. C. Livesey, M. Katsikogianni, A. L. Kelly, L. R. Terry, V. P. Ting, S. Nayak, *ACS Appl. Bio Mater.* **2022**, *5*, 3972.
[101] C. L. Song, Z. Li, Y. N. Zhang, G. Zhang, Y. W. Yang, *Supramol. Mater.* **2023**, *2*, 100035.
[102] C. Y. Wang, Y. Q. Liu, C. Jia, M. Z. Zhang, C. L. Song, C. Xu, R. Hao, J. C. Qin, Y. W. Yang, *Chinese Chem. Lett.* **2023**, *34*, 108400.
[103] S. Ghosh, D. Mal, S. Biswas, *Environ. Sci. Nano* **2024**, *11*.
[104] P. Damacet, K. Hannouche, A. Gouda, M. Hmadeh, *ACS Appl. Mater. Interfaces* **2023**.
[105] J. Li, Q. Lv, L. Bi, F. Fang, J. Hou, G. Di, J. Wei, X. Wu, X. Li, *Coord. Chem. Rev.* **2023**, *493*, 215303.
[106] S. Sikha, B. Mandal, *ACS Appl. Nano Mater.* **2024**, *7*, 866.
[107] X. Xu, H. Li, Z. Xu, *Chem. Eng. J.* **2022**, *436*, 135028.
[108] Y. Xia, J. He, L. Tang, M. Hu, J. Zhou, Y. Y. Xiao, Z. C. Jiang, X. Jiang, *Food Chem. X* **2024**, *21*, 101247.
[109] Y. Sun, P. Li, E. Guo, C. Wang, Y. Zhang, *Microchem. J.* **2024**, *199*, 110193.
[110] Z. Wang, M. He, H. Jiang, H. He, J. Qi, J. Ma, *Chem. Eng. J.* **2022**, *435*, 133870.
[111] H. Chen, L. Yang, P. Wu, P. Liu, H. Xu, Z. Zhang, *Chem. Eng. J.* **2024**, *488*, 151193.
[112] A. A. Oladipo, R. Vaziri, M. A. Abureesh, *J. Taiwan Inst. Chem. Eng.* **2018**, *83*, 133.
[113] K. Wu, W. Li, F. Ma, F. Gan, J. Zhou, H. Zeng, C. Du, *ACS Appl. Nano Mater.* **2024**, *7*, 11645.
[114] H. Shaghaleh, Y. Alhaj Hamoud, Q. Sun, M. S. Sheteiwy, H. AbdElgawad, *Sep. Purif. Technol.* **2025**, *353*, 128440.
[115] X. le Deng, J. qing Li, J. ming Yi, R. jie Lian, Z. yang Zhang, J. hong Li, S. He, L. yang Bai, *Pest Manag. Sci.* **2023**, *79*, 5237.
[116] C. Xu, L. Cao, T. Liu, H. Chen, Y. Li, *Environ. Sci. Nano* **2023**, *10*, 2578.
[117] K. Guo, X. Deng, Y. Peng, N. Yang, K. Qian, L. Bai, *Environ. Sci. Nano* **2023**, *10*, 1016.
[118] K. Pandey, R. A. Omar, N. Verma, G. Gupta, *Environ. Sci. Nano* **2024**, *11*, 1597.

[119] H. Chen, Y. Shan, C. Xu, M. Bilal, P. Zhao, C. Cao, H. Zhang, Q. Huang, L. Cao, *ACS Agric. Sci. Technol.* **2023**, *3*, 190.
[120] T. Meng, Z. Li, Z. Wan, J. Zhang, L. Wang, K. Shi, X. Bu, S. M. Alshehri, Y. Bando, Y. Yamauchi, D. Li, X. Xu, *Chem. Eng. J.* **2023**, *452*, 139193.
[121] S. Zhang, W. Yao, C. Zhou, J. Wang, H. Zhao, *Int. J. Environ. Anal. Chem.* **2021**, *101*, 621.
[122] K. Wu, X. Xu, F. Ma, C. Du, *ACS Omega* **2022**, *7*, 35970.
[123] X. Zhang, X. Zhang, Y. Cai, S. Wang, *Chem. Eng. J.* **2022**, *443*, 136412.
[124] Y. Cai, L. Li, J. Zhang, Z. Li, F. Zhang, Y. Xu, Z. Tai, *Environ. Monit. Assess.* **2023**, *195*, 569.
[125] Q. Liu, J. Yu, Y. Jiang, C. Zhong, S. Ding, P. Zhou, Y. Jin, *J. Soils Sediments* **2022**, *22*.
[126] S. Chopra, S. Dhumal, P. Abeli, R. Beaudry, E. Almenar, *Postharvest Biol. Technol.* **2017**, *130*, 48.
[127] C. Wu, Y. Dan, D. Tian, Y. Zheng, S. Wei, D. Xiang, *Int. J. Biol. Macromol.* **2020**, *145*, 1073.
[128] L. Guo, J. Hurd, M. He, W. Lu, J. Li, D. Crawshaw, M. Fan, S. Sapchenko, Y. Chen, X. Zeng, M. Kippax-Jones, W. Huang, Z. Zhu, P. Manuel, M. D. Frogley, D. Lee, M. Schröder, S. Yang, *Commun. Chem.* **2023**, *6*, 55.
[129] N. Alsadun, S. Surya, K. Patle, V. S. Palaparthy, O. Shekhah, K. N. Salama, M. Eddaoudi, *ACS Appl. Mater. Interfaces* **2023**, *15*, 6202.
[130] C. Altintas, I. Erucar, S. Keskin, *CrystEngComm* **2022**, *24*, 7360.
[131] S. Koonani, A. Ghiasvand, *Talanta* **2024**, *267*, 125236.
[132] J. Lu, C. Wu, C. Tian, L. Wang, W. Li, B. Liu, *Surfaces and Interfaces* **2024**, *46*, 104039.
[133] H. Shaghaleh, Y. Alhaj Hamoud, Q. Sun, *Environ. Pollut.* **2024**, *360*, 124623.
[134] L. Ma, T. Wang, Y. Wan, G. Zhang, X. Li, M. Jiang, L. Zhang, *J. Environ. Chem. Eng.* **2023**, *11*, 110125.
[135] O. Guselnikova, P. Postnikov, R. Elashnikov, E. Miliutina, V. Svorcik, O. Lyutakov, *Anal. Chim. Acta* **2019**, *1068*, 70.

Brij Briz Mohan is a research member at the Centro de Química Estrutural, Instituto Superior Técnico, Universidade de Lisboa (ULisboa) in Portugal. He completed Ph.D. under the supervision of Professor Harish Kumar Sharma at Kurukshetra University in Kurukshetra, India. Then, he joined as a postdoctoral research associate at Harbin Institute of Technology in Shenzhen, China, from November 2019 to December 2021. He has been listed among Stanford's Top 2% highly cited researchers (Year 2024). His research interests include designing new coordination materials, metal-organic frameworks (MOFs), and nanomaterials for energy, catalysis, sensing, optics, the environment, agriculture, food, and medicine applications.

Harish Kumar Sharma is a distinguished Indian researcher and serves as a professor and former head of the Department of Chemistry at Kurukshetra University in Kurukshetra, India. He completed his Ph.D. at the University of Delhi in 1989. He has been recognized for his expertise in the design, development, and innovative ideas in the inorganic and analytical chemistry fields. He has supervised several M.Phil. amd Ph.D. studies, and all his students are well-placed and work at leading scientific institutes globally. He taught inorganic chemistry for over 30 years. His research area covers designing inorganic materials for sensing, energy, and environmental applications.

Stefan Ručman was born in Serbia and is a lecturer at Maejo University, Chiang Mai, Thailand, the leading agricultural university in Thailand. He specializes in environmentally friendly nanomaterials and sustainable production. Dr. Ručman earned his Ph.D. in Environmental Science from Chiang Mai University. Before joining Maejo University, he worked as an expert and lecturer at Mahidol University for 2 years. His current research focuses on adapting agriculture and epidemiology to climate change.

Pisith Singjai is an Associate Professor with a Ph.D. in materials science and engineering from the University of Surrey, UK. He has made significant contributions to nanotechnology, particularly in developing sparking methods for nano-coating. Dr. Singjai founded Nano Generation Co., Ltd., a spin-off company dedicated to commercializing research equipment products. With over 130 articles published in peer-reviewed journals indexed by SCOPUS, Dr. Singjai is a prolific researcher. In 2019, the Institute of Materials, Minerals, and Mining, UK, recognized his outstanding contributions to materials science with the prestigious Alan Glanvill Award.

Armando J. L. Pombeiro is a Full Professor Emeritus at the Instituto Superior Técnico, Universidade de Lisboa (ULisboa). He is a Full Member of the Academy of Sciences of Lisbon and President of its Scientific Council. Additionally, he is a member of the European Academy of Sciences (EURASC) and the Academia Europaea. He is the founding President of the College of Chemistry at ULisboa and has previously coordinated the Centro de Química Estrutural. He leads the "Coordination Chemistry and Catalysis" research group and co-founded the Portuguese Electrochemical Society, where he served as former President and the Ibero-American Society of Electrochemistry (SIBAE). His research concentrates on activating small molecules crucial for industry, the environment, and biology through methods such as metal-mediated synthesis, catalysis, crystal engineering, non-covalent interactions, molecular electrochemistry, and theoretical analyses involving catalytic, anti-tumor, and anti-bacterial coordination compounds, as well as multinuclear complexes and MOFs.

