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Metal–Organic Frameworks for Conserving Soil Health

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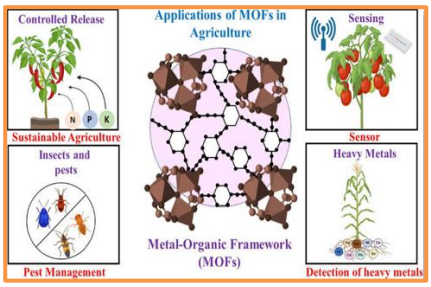

Soil is the principal medium through which water, nutrients and energy enter terrestrial food chains, and its productive and regulatory functions depend on the combined condition of its chemical, physical and biological attributes. Sustained intensification of crop production has placed these functions under considerable stress. A large proportion of nitrogen applied as urea or ammonium fertilizers is lost through nitrate leaching, ammonia volatilization and denitrification, water-soluble phosphorus is rapidly converted into sparingly soluble calcium, iron and aluminium phosphates and repeated application of synthetic pesticides leads to residue accumulation that affects non-target soil fauna and microbial communities. In peri-urban and industrial catchments, irrigation with untreated wastewater and the land application of sewage sludge have additionally introduced potentially toxic elements such as lead (Pb), cadmium (Cd), copper (Cu) and nickel (Ni), which are transferred to edible plant tissues and, ultimately, to the human diet.

Nanotechnology-based inputs have been proposed as a means of improving input-use efficiency while reducing the environmental burden of agrochemicals. Within this group, metal–organic frameworks (MOFs) have attracted particular interest because their composition and pore architecture can be tailored to distinct functions. Large-scale synthesis, cost reduction and field validation were identified as the main constraints. This article examines MOFs for nutrient delivery, crop protection and immobilization of potentially toxic elements, together with the evidence on their effects on soil biota.

Structure and Properties of Metal–Organic Frameworks

Metal–organic frameworks are crystalline coordination polymers in which metal ions or metal–oxo clusters, termed secondary building units, are connected by multidentate organic ligands to form three-dimensional networks with permanent porosity. Pore apertures typically range from sub-nanometre to several nanometres, and the high void fraction results in specific surface areas commonly between several hundred and several thousand square metres per gram.

The pore network can accommodate guest molecules, including urea, pesticide active ingredients and plant growth regulators. The framework itself can function as a nutrient reservoir when the metal centre (e.g., Fe, Zn, Mg or Cu) or the ligand contains elements essential for plant growth, which are released progressively as the coordination bonds undergo hydrolysis. Hydrolytic and chemical stability can be modulated through the choice of metal–ligand combination, ranging from highly robust zirconium carboxylates to pH-labile zinc imidazolates.

Table 1. MOFs used for soil applications

MOFs	Metal node	Organic ligand	Soil applications
ZIF-8	Zn(II)	2-Methylimidazole	pH-labile, degrading under acidic conditions; investigated as a pH-responsive pesticide carrier; source of Zn
UiO-66	Zr(IV)	Terephthalic acid	High hydrolytic and chemical stability; adsorbent for metal ions and organic pollutants
MIL-100(Fe)	Fe(III)	Trimesic acid	Mesoporous cages with coordinatively unsaturated Fe sites; used to functionalize biochar for Cu and Pb retention
MIL-101(Fe)	Fe(III)	Terephthalic acid	Large mesoporous cages; carrier for controlled-release nanopesticides
HKUST-1	Cu(II)	Trimesic acid	Also designated Cu-BTC; high specific surface area; immobilizes Pb in contaminated soil but contributes Cu
OPA-MOF	Fe(III)	Oxalate, with phosphate and amine	Composed of plant nutrient elements (Fe, P, N); nutrient release driven by microbial degradation of oxalate
GR-MOF-27	Mg(II)	Phosphonate ligand derived from fosfomycin	Two-dimensional framework; gradual Mg release through framework dissolution

MOFs as Controlled-Release Nutrient

Conventional water-soluble fertilizers dissolve rapidly after application, and a considerable fraction of the dissolved nutrients may be transported below the rhizosphere following heavy rainfall or irrigation. Polymer-coated and other controlled-release formulations reduce these losses by retarding dissolution. MOFs provide an alternative mechanism in which the nutrient forms an integral part of the framework and becomes available only as the structure degrades. The earliest example was an iron-based oxalate–phosphate–amine framework (OPA-MOF), designed as a microbially triggered slow-release source of nitrogen and phosphorus. Despite this early demonstration, the field has developed slowly; a Web of Science search conducted in November 2024 retrieved only 23 studies reporting the use of MOFs as fertilizers (Morales-Cámara *et al.*, 2025).

In the same study, a two-dimensional magnesium phosphonate framework, GR-MOF-27, was evaluated as a magnesium source. In aqueous medium at pH 6.5, representative of many agricultural soils, Mg^{2+} release followed a biphasic pattern, with 26% released within 4 h, 63% within 7 d and complete dissolution by 21 d. At an equivalent magnesium supply (10 ppm), Italian ryegrass (*Lolium multiflorum*) seedlings treated with GR-MOF-27 showed increases of 10.5%, 11.0% and 13.1% in shoot length, root length and dry weight, respectively, relative to magnesium sulphate, while Mg and P uptake exceeded those of untreated controls by 64.9% and 57.4%. These results warrant cautious interpretation: growth inhibition occurred at higher doses, the assays were short-term laboratory experiments conducted without soil, and the organic ligand was derived from the antibiotic fosfomycin, whose fate in biologically active soil has yet to be established.

MOF-Based Carriers for Crop Protection

A substantial proportion of foliar-applied pesticide fails to reach the target organism and is lost through spray drift, wash-off and deposition on the soil surface, where persistent active ingredients may accumulate. Encapsulation of the active ingredient within MOF pores protects it against photodegradation and permits sustained release, or release triggered by environmental stimuli such as pH shifts, pest- or pathogen-derived enzymes and temperature. Yang *et al.* (2026) classified MOF-based nanoformulations into insecticidal, fungicidal,

herbicidal and plant growth-regulating systems, highlighted the dual role of the frameworks as carriers and as sources of macro- and micronutrients, and identified environmental fate, biosafety, economic feasibility and regulatory acceptance as unresolved issues. The contribution of such formulations to soil health is therefore largely indirect, arising from a reduction in the total quantity of active ingredient that reaches the soil during a cropping season.

Immobilization of Heavy Metals in Contaminated Soils

Because extractive remediation is costly, *in situ* immobilization is generally preferred for contaminated agricultural soils, with amendments such as lime, phosphate, biochar and clay minerals reducing the mobile and phytoavailable fractions of metals through sorption, complexation and precipitation. The large specific surface area and abundant coordination sites of MOFs make them promising candidates for increasing the metal-binding capacity per unit mass of amendment.

Zarrabi *et al.* (2024) evaluated three trimesic acid-based frameworks (Zn-BTC, Cu-BTC and Fe-BTC) applied at 0.5% and 1% (w/w) to a soil spiked with 100 mg kg^{-1} each of Zn, Ni, Pb and Cd, with quinoa (*Chenopodium quinoa*) as the test crop. Cu-BTC exhibited the highest specific surface area (768 m^2 g^{-1}, compared with 503 and 92 m^2 g^{-1} for Zn-BTC and Fe-BTC, respectively), and its application at 1% resulted in the lowest plant uptake of all four metals. Ethylenediaminetetraacetic acid (EDTA)-extractable Pb in the post-harvest soil declined to 11.86 mg kg^{-1} in this treatment, the lowest value recorded.

The integration of MOFs with biochar offers a complementary strategy that combines the low cost and agronomic familiarity of biochar with the high sorption capacity of MOFs. In a comparative evaluation of ZIF-8, UiO-66 and MIL-100(Fe) for Cu^{2+} and Pb^{2+} adsorption, MIL-100(Fe) proved most effective and was subsequently used to functionalize wheat-straw biochar. The resulting nanocomposite showed an approximately six-fold increase in surface area (to 419 m^2 g^{-1}) and a two-fold increase in sorption capacity for heavy metals in soil (142 mmol kg^{-1} for Cu^{2+} and 156 mmol kg^{-1} for Pb^{2+}), with complexation and cation exchange identified as the dominant retention mechanisms (Polyakov *et al.*, 2025). Iron-based composites are particularly suited to agricultural use, since iron is a ubiquitous and major constituent of soils.

Ecotoxicological study for Soil Biota

Any amendment intended to improve soil health must itself be compatible with soil biota; however, the ecotoxicological implications of MOFs have received considerably less attention than their functional performance. Degradation of MOFs in soil releases both metal ions and organic ligands. A copper-based framework applied at 1% (w/w) therefore constitutes a substantial copper input, and elevated copper concentrations are known to inhibit many soil microorganisms. Zirconium, chromium and several synthetic ligands have no nutritional function, and their long-term behaviour in soil remains poorly characterized.

Chen *et al.* (2024) examined the long-term effects of an iron-based MOF (MIL-101) loaded with the insecticide chlorfenapyr on earthworm–microorganism interactions in maize-field soil. In filter-paper contact tests, the MOF formulation was more toxic to earthworms than a conventional suspension concentrate, whereas in soil it was less toxic, inducing lower oxidative stress, weaker inhibition of detoxification enzymes and less tissue damage. Prolonged exposure og MOFs altered the composition of microbial communities in both the earthworm gut and the surrounding soil, including nitrifying and denitrifying bacteria, thereby affecting soil nitrogen cycling. Short-term laboratory bioassays are thus poor predictors of behaviour in soil, and microbial functional groups may shift even when acute toxicity to soil fauna is reduced.

Conclusion

Metal–organic frameworks offer a versatile platform for addressing several constraints on soil health, including nutrient losses, pesticide residue accumulation and contamination by

potentially toxic elements. Recent studies have reported measurable benefits: improved seedling growth with a magnesium-based framework relative to magnesium sulphate, reduced metal accumulation in quinoa grown in MOF-amended soil and a two-fold increase in the metal sorption capacity of biochar following MOF functionalization. The same body of evidence also reveals important limitations. Most investigations have been short-term and small in scale, some frameworks introduce metals of their own, and prolonged exposure to a MOF-based insecticide altered nitrogen-cycling microbial communities in soil. MOFs should therefore be regarded as a promising but not yet field-ready technology for soil conservation. Adoption will depend on cost-effective green synthesis, soil-compatible metals and ligands, and field evidence that productivity gains do not compromise soil biological function. Balanced fertilization, organic matter management and judicious pesticide use will remain the foundation of soil health management, with MOF-based products serving to complement rather than replace these practices.

References

1. Alves, R.C., Luna, V.C., Baco, C.J., Terezo, A.J., Castilho, M. and Siqueira, A.B. (2025). Emerging applications of nano-metal-organic frameworks for sustainable agriculture: A critical review. *Plant Nano Biology*, 12: 100159.
2. Chen, H., Yang, L., Zhao, S., Xu, H. and Zhang, Z. (2024). Long-term toxic effects of iron-based metal-organic framework nanopesticides on earthworm-soil microorganism interactions in the soil environment. *Science of the Total Environment*, 917: 170146.
3. Morales-Cámara, S., Cardona-Carrascosa, L., Salcedo-Abraira, P., Rodríguez-Diéguez, A. and Rojas, S. (2025). Controlled magnesium release and nutritional effect of a novel metal–organic framework on plants. *Crystal Growth & Design*, 25(13): 4685-4689.
4. Polyakov, V.A., Bauer, T.V., Kirichkov, M.V., Butova, V.V., Gritsai, M.A., Minkina, T., Soldatov, A.V. and Kravchenko, E. (2025). MOF-biochar nanocomposite for sustainable remediation of contaminated soil. *Environmental Science and Pollution Research*, 32(9): 5533-5550.
5. Yang, F., Han, L., Liang, Y. and Huo, Z. (2026). Recent advances in metal–organic framework as nanocarriers for pesticide delivery. *Frontiers in Plant Science*, 17: 1776360.
6. Zarrabi, A., Ghasemi-Fasaei, R., Ronaghi, A., Zeinali, S. and Safarzadeh, S. (2024). Application of synthesized metal-trimesic acid frameworks for the remediation of a multi-metal polluted soil and investigation of quinoa responses. *PLoS ONE*, 19(9): e0310054.