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REVIEW

Green agriculture enabled by versatile metal-organic frameworks: A review

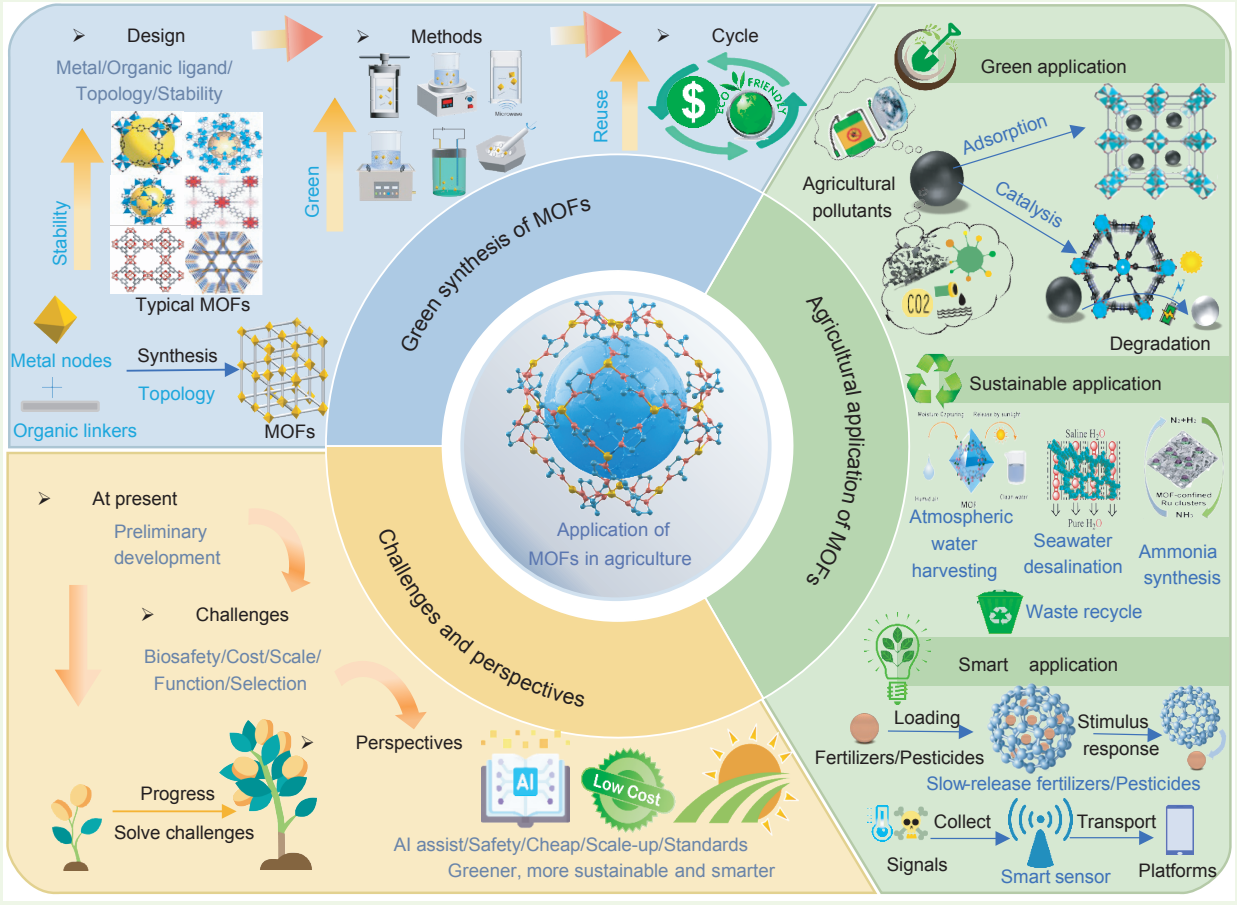
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Highlights

- Strategies for green synthesis and production of target metal-organic frameworks (MOFs).
- Removal of agricultural pollutants using functional MOFs.
- Water capture and nutrient management through designed MOFs.
- Challenges and perspectives of novel MOFs in smart agriculture.

Graphical abstract



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Abstract

Modern agriculture faces unprecedented challenges: A growing global population, limited arable land, freshwater scarcity, and inefficient agrochemical use have triggered severe environmental degradation. Pollutants including pesticides, heavy metals, microplastics, antibiotics, nutrient runoff, and greenhouse gases threaten ecosystem stability, food security, and human health. Metal-organic frameworks (MOFs), with their tunable structures, high porosity, and versatile functionality, emerge as promising materials to address these issues. This review comprehensively summarizes recent advances in MOFs-based solutions for agriculture. It covers green synthesis strategies to enhance structural stability and promote circular economy principles. Applications span three primary domains: pollutant remediation, sustainable technologies (e.g., atmospheric water harvesting, seawater desalination, and green ammonia synthesis), and smart agricultural systems. The latter enables controlled agrochemical release and real-time sensing and monitoring. Finally, challenges — such as high costs, biosafety concerns, and scalability limitations — are discussed, alongside forward-looking perspectives including AI-assisted design, improved recyclability, scalable production, and multifunctional integration toward green and smart agriculture.

Keywords: MOFs, pollutant remediation, green synthesis, sustainable technologies, smart agriculture

1. Introduction

The global population is projected to reach 10.2 billion by the end of this century, intensifying demand for secure, high-quality food production (Menozzi *et al.* 2024). With arable land comprising only 38% of terrestrial area, modern agriculture relies heavily on synthetic agrochemicals (e.g., pesticides and fertilizers) to sustain nearly 7 billion people (Rojas *et al.* 2022). However, conventional pesticides (~0.1% utilization) and fertilizers (~35% utilization) remain highly inefficient, prompting excessive application and resulting in pesticide residues, toxin accumulation, eutrophication, and greenhouse gas emissions (Lin *et al.* 2021; Wang *et al.* 2023; Bhomick *et al.* 2025). Beyond these inputs, current agriculture increasingly faces compound pollution from antibiotics, microplastics, and heavy metals. Antibiotics used in livestock farming and mismanaged composting threaten soil and ecosystem health (Wei *et al.* 2022; Akhter *et al.* 2024), while mulching films and herbicides exacerbate microplastic contamination (Guan *et al.* 2025). Additionally, heavy metal pollution affects 14–17% of global farmland, further jeopardizing agricultural productivity and food security (Hou *et al.* 2025). Water resource challenges, including coastal salinization and arid-region shortages, remain unresolved. Meanwhile, smart agriculture is still in its infancy, lacking cost-effective and highly sensitive monitoring systems for environmental and crop quality control (Ahmed *et al.* 2024). Green agriculture, which emphasizes environmentally protective practices to improve crop quality, economic returns, and sustainability (Zheng *et al.* 2024), is urgently needed. Nanotechnology could offer promising solutions (Rojas *et al.* 2022; Karimi-Maleh *et al.* 2024; Zain *et al.* 2024), though many nanomaterials (e.g., carbon nanotubes, nanometals) face barriers such as high cost and limited recyclability. Identifying suitable, sustainable alternatives is therefore critical.

Metal-organic frameworks (MOFs) are porous crystalline nanomaterials composed of metal ions or clusters linked by organic ligands into extended frameworks (Yaghi *et al.* 1995; Pang *et al.* 2025). Compared to traditional porous materials (e.g., zeolites, activated carbon), MOFs exhibit superior porosity, high surface area, tunable pore sizes, structural flexibility, and functional diversity, enabling broad applications in adsorption, separation, sensing, catalysis, and delivery systems (Modak *et al.* 2023; Jiang *et al.* 2024; Wu *et al.* 2024; Zhang M *et al.* 2024; Prada *et al.* 2025). Since the term “metal-organic frameworks” were introduced by Yaghi *et al.* (1995), significant advances have been made in their agricultural applications (Fig. 1). Classic MOFs — including the MOFs-5, IRMOFs, MIL, ZIF, PCN, and UiO series — are notable for their large surface areas, abundant active sites, and modifiable ligands (Furukawa *et al.* 2013; Li Y *et al.* 2024). These properties make them effective in adsorbing CO_2 and removing agricultural pollutants (e.g., pesticides, antibiotics, heavy metals, microplastics) (Millward *et al.* 2005; Chen *et al.* 2020; Yu *et al.* 2025). MOFs have demonstrated broad potential in atmospheric water harvesting, seawater desalination, ammonia synthesis, agrochemical delivery, and smart detection (Chen *et al.* 2014; Kim *et al.* 2017; Li *et al.* 2018; Cui *et al.* 2024). Their multifunctionality supports green and smart agriculture by addressing water scarcity, enabling sustainable fertilizer production, improving agrochemical utilization through controlled release, and enhancing precision monitoring. Importantly, the green synthesis and recyclability of MOFs embody the core principles of sustainable agricultural development.

Although several reviews have discussed MOFs in agriculture, most focus narrowly on topics like plant disease management, pesticide removal, or agrochemical delivery, overlooking broader issues such as other pollutants (e.g., microplastics, greenhouse gases), sustainable and smart agricultural practices, and green recycling synthesis (Rojas *et al.* 2022; Wang *et al.* 2023; Cui *et al.* 2024; Li Y *et al.* 2024; Yu *et al.* 2025). This review provides a comprehensive overview of recent advances in MOFs-based agriculture, emphasizing: (1) green design and synthesis, focusing on stability and circular production; (2) eco-friendly pollutant removal, targeting contaminants such as pesticides, heavy metals, microplastics, antibiotics, greenhouse gases, and eutrophication-related pollutants; (3) sustainable agricultural technologies, including atmospheric water harvesting,

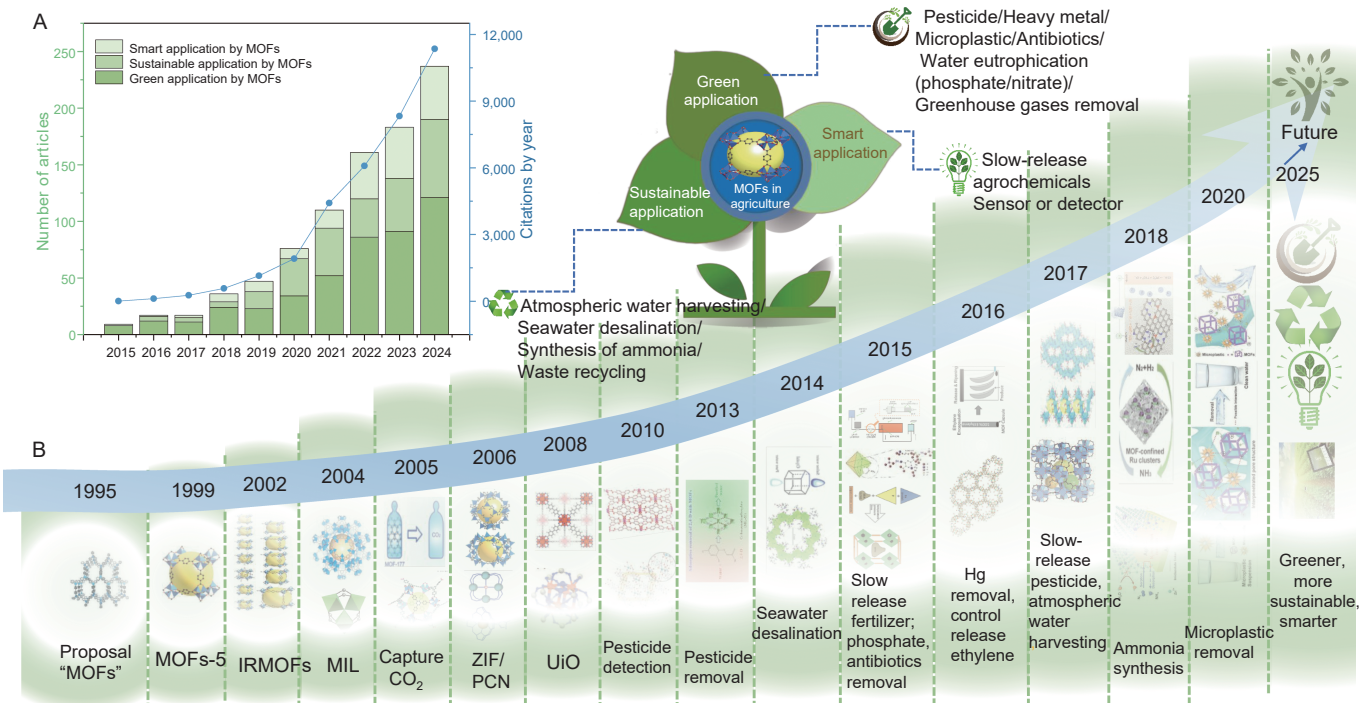


Fig. 1 The development of metal-organic frameworks (MOFs) in agriculture. A, research topics about MOFs in agriculture (references considered based on Web of Science from 2015–2024). B, progress and application of MOFs in agriculture.

seawater desalination, and ammonia synthesis; and (4) smart agricultural applications, such as controlled release and sensing systems. Current challenges and future perspectives are also discussed to guide innovative strategies toward greener, more sustainable, and smarter agriculture.

2. Green design and synthesis

2.1. Green design

MOFs are crystalline, porous materials formed through coordination-driven self-assembly of metal ions or clusters (secondary building units, SBUs) with organic linkers. The ligand arrangement and structural features of MOFs determine their catalytic, sensing, and adsorption functions, which in turn influence their potential agricultural applications. By applying green design principles (e.g., eco-friendly, cost-efficient) to MOFs construction, their advancement in agriculture could be effectively enhanced (Chakraborty *et al.* 2025). Metal nodes act as coordination centers, while ligands bridge them into extended networks. Despite diverse coordination geometries, MOFs can be rationally designed by topology (Han *et al.* 2025; Pang *et al.* 2025). Their tunable porosity, chemical versatility, and structural designability provide rich adsorption sites, where guest molecules interact *via* hydrogen bonding, electrostatics, or π–π stacking (Cui *et al.* 2024). By tuning open metal sites, linker functionality, or pore microenvironments, the types and strengths of these interactions can be precisely controlled (Rojas *et al.* 2022; Pang *et al.* 2025). Additionally, MOFs facilitate electron/energy transfer and redox reactions due to their abundant catalytic sites (Zeng *et al.* 2025; Zhao *et al.* 2025). Their coordination architectures also enable facile surface functionalization, enhancing catalytic activity (Fig. 2-A) (Zhu *et al.* 2018). Thus, the outstanding performance of MOFs arises from these structural features, making rational design coupled with long-term stability critical for sustained functionality in agriculture (e.g., pollutants removal, real-time sensing and monitoring).

Metal nodes Metal ions or clusters are fundamental building blocks of MOFs structures. Their coordination number and geometry directly determine the framework's structural units. Transition metals (e.g., Ti, Co, Mn, Fe, Zn, Zr and Ni) and rare-earth elements (e.g., La, Nd, Eu and Ce) are commonly employed as metal nodes (Feng *et al.* 2020; Li Y *et al.* 2024), owing to their multiple oxidation states, flexible coordination numbers, and rich electronic configurations. For instance, Co^{2+} and Zn^{2+} adopt tetrahedral or octahedral geometries (Fig. 2-B). Beyond single metal ions, multinuclear metal clusters serving as SBUs are widely used. These clusters provide more coordination sites, enabling the construction of multidimensional frameworks. Moreover, SBUs of a given type exhibit fixed geometry and coordination points, allowing predictable topologies through organic ligand selection (Fig. 2-B) (Kalmutzki *et al.* 2018).

A classic case is MOFs-5 (Fig. 2-D), constructed from $[Zn_4O]^{6+}$ clusters and terephthalic acid (H_2BDC), forming a cubic $Zn_4O(BDC)_3$ frameworks (six carboxylate groups connect to -(C_6H_4)- linkers), with high surface area (~2,900 m^2 g^{-1}) and thermal stability, making it ideal for gas storage (Eddaoudi *et al.* 2002). The incorporation of different metal nodes significantly enhances MOFs structural and functional diversity. For example, mixed-metal systems could expand functionality; Fe/Co bimetallic MOFs exhibit 8–10 times higher catalytic activity in degrading

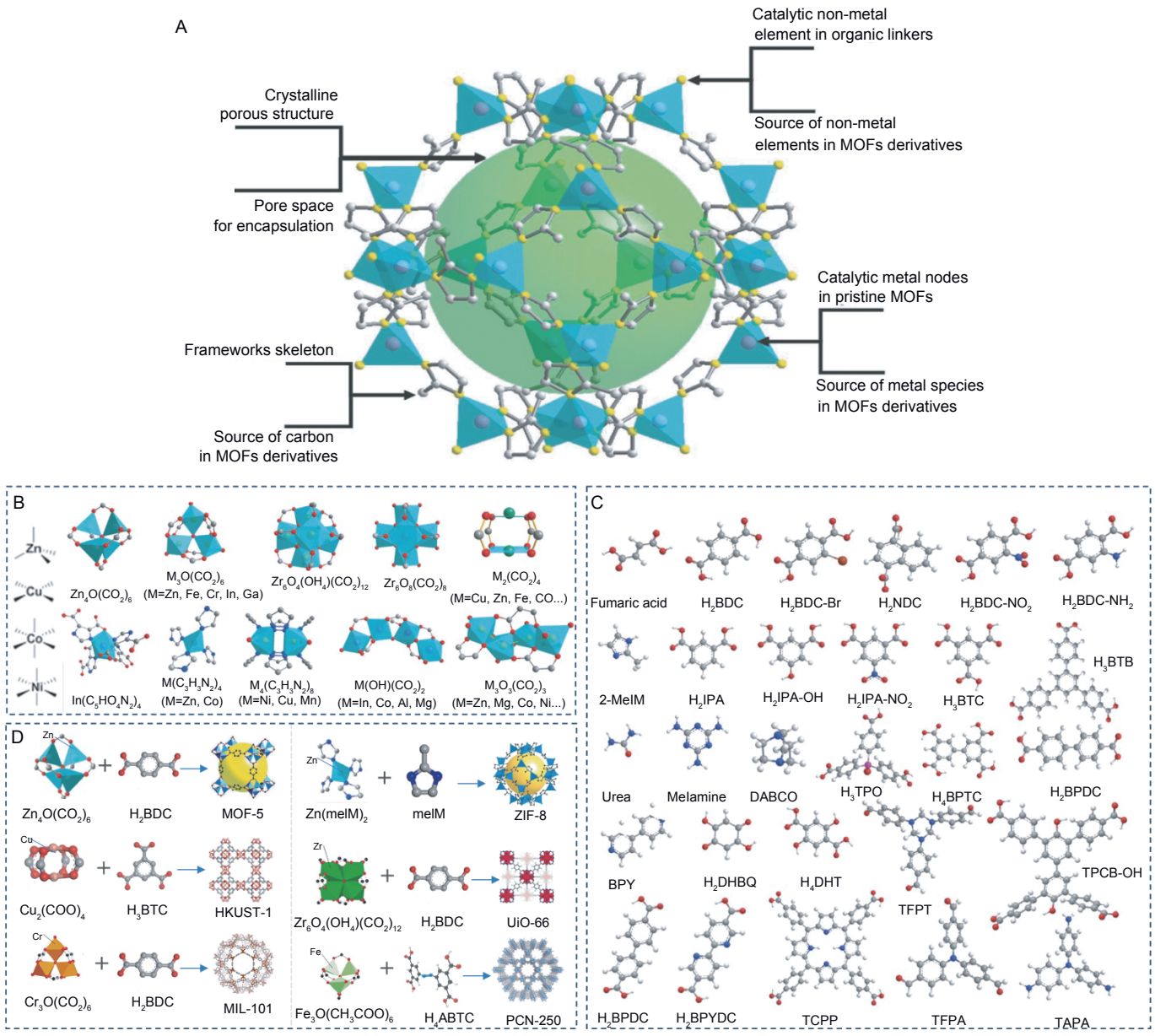


Fig. 2 The structural characteristics and composition of metal-organic frameworks (MOFs). A, structural characteristics of MOFs as catalyst (Zhu *et al.* 2018). B, representative secondary building unit (SBU). C, typical organic linkers (Chai *et al.* 2021). D, self-assembly process of typical MOFs.

2,4-dichlorophenoxyacetic acid (2,4-D) than single-metal counterparts (Pattappan *et al.* 2023). This MOFs-based catalyst demonstrates stable, recyclable performance, and the resulting 2,4-D degradation products are non-toxic, with no adverse effects on cellular metabolism. High-level exposure to copper-based MOFs-199 (100–1,000 mg L^{-1}) induces oxidative stress and growth inhibition in peas and damages photosystem II receptors, though germination remains unaffected (Guan *et al.* 2021). In contrast, HKUST-1 shows no toxicity to the germination or growth of sweet corn, tomato, lettuce, or black bean across 10–1,000 mg L^{-1} (Loera-Serna *et al.* 2024). These discrepancies likely arise from species-specific heavy-metal tolerance. Nevertheless, heavy metal ions (e.g., Cu, Ni, Cr) released from MOFs pose potential risks in agricultural applications and warrant long-term assessment. Enhancing MOFs stability through surface modification or incorporation of protective matrices (e.g., cellulose, silica) could mitigate harmful metal release.

Organic ligands Organic linkers connect metal ions or clusters in MOFs, critically determining their structures and properties. Their broad chemical diversity and tunability provide a versatile platform for designing functional frameworks (Fig. 2-B and C). Based on chemical functionality, linkers are commonly divided into four groups: carboxylates (e.g., fumaric acid, H_2BDC, H_3BTC), azolates (e.g., 2-MeIm, BPY, DABCO), phosphonate/phosphate (e.g., 1,4-benzenediphosphonic acid, benzene-1,3,5-triphosphonic acid, 1-phosphomethylproline), and hydroxyl/thiol ligands (e.g., 2,5-dioxido-1,4-benzenedicarboxylic acid, dithioglycol) (Ramesha *et al.* 2020; Lee *et al.* 2023; Li *Y*

et al. 2024; Pang *et al.* 2025). Compared to metal nodes, linkers provide greater chemical flexibility, with their charge, length, and rigidity significantly influencing coordination modes, frameworks topology, and stability (Furukawa *et al.* 2013; Kalmutzki *et al.* 2018). Deprotonation controls crystal nucleation and morphology, while linker length dictates pore size, architecture, and mechanical robustness (Eddaoudi *et al.* 2002). Rigid ligands (e.g., H_2BDC) favor predictable topologies and stable porous frameworks like IRMOFs (Eddaoudi *et al.* 2002; Hyun *et al.* 2024).

In contrast, flexible linkers (e.g., linear carboxylates, heteroaromatic acids) could adopt multiple conformations, generating novel topologies and functionalities, such as stimuli-responsive behavior (Zhang *et al.* 2019). Ferdinando's group constructed MOFs with rhombic 1D channels using flexible H_8L_2 and etbipy ligands, exhibiting a reversible breathing behavior through pore contraction and expansion upon dehydration/rehydration (Taddei *et al.* 2013). This dynamic response was attributed to the conformational flexibility of both H_8L_2 and the ethylene linker in etbipy; replacing H_8L_2 with the rigid analogue H_8L_1 suppressed this behavior. Semi-rigid ligands combine flexibility and rigidity, enabling MOFs with large pores and dynamic properties. For instance, the combination of rigid oxalate and flexible 1,1′-ferrocene dicarboxylic acid enhanced the optical and redox performance of In-MOFs (Zhang *et al.* 2022). Multifunctional linkers could further enhance structural and functional diversity (Huang *et al.* 2024). Thus, strategically combining rigid, flexible, and multifunctional linkers enables the precise design of MOFs structures and properties. The biological toxicity of hydrophobic ZIF-8 and UiO-66 synthesized from 2-methylimidazole and terephthalic acid, and hydrophilic HKUST-1 and MIL-100 synthesized from benzophenic acid, was evaluated (Salehipour *et al.* 2023). The study revealed that cytotoxicity increased markedly when the application concentration exceeded 50 μg mL^{-1}. Among them, UiO-66 exhibited the lowest toxicity, attributed to the interplay between the hydrophilic and hydrophobic properties of its organic ligands and cellular membranes. Furthermore, UiO-64(Zr) and UiO-66(Zr), synthesized from Zr(IV) with fumaric acid or terephthalic acid, showed no cytotoxicity, consistent with the inherent biocompatibility of Zr (Sifaoui *et al.* 2021). The overall toxicity of MOFs is jointly determined by metal and organic ligands, with the former often exerting a stronger influence. However, the toxicological mechanisms in agricultural systems remain to be fully elucidated. Developing green MOFs could involve using natural, non-toxic organic ligands (e.g., oxalic acid, gallic acid, cyclodextrin) or by introducing biocompatible functional groups (e.g., $–NH_2$, –SH).

Topological structures The self-assembly of MOFs is dictated by interactions between metal ions and organic linkers, with their spatial arrangement defining network topology. Diverse crystal structures are often simplified using polyhedral representations, where metal nodes and linkers define morphology and properties (Pang *et al.* 2025). Rational topology design requires specification of connectivity (coordination number), local symmetry, and the geometry of building units (Kalmutzki *et al.* 2018). Generally, two-connected units are considered linkers, while those with three or more connections are nodes. Tailoring coordination features enables construction of targeted frameworks. Databases such as the reticular chemistry structure resource (RCSR) provided valuable guidance (O'Keeffe *et al.* 2008), encompassing a wide range of 2D (e.g., sql, hcb) and 3D (e.g., dia, pcu, tbo, fsc) networks. Structural diversity largely arises from SBU geometries (Fig. 3-A). For instance, HKUST-1 (Fig. 2-D) arises from triangular H_3BTC ligands and square paddle-wheel SBUs, forming a tbo topology (Fig. 3-A). Recently, a topology-guided *in situ* assembly approach (Fig. 3-B) produced novel jcq topologies, where a hexapyridyl ligand served as a six-connected node, partially coordinated Cu^{2+} as five-connected nodes, and halides (F^-, Cl^-, Br^-) as two-connected blockers, yielding MOFs such as LNU-H1 with outstanding $C_2H_2/CO_2/C_2H_4$ separation efficiency at room temperature (Han *et al.* 2025).

With over 100,000 MOFs reported, experimental screening is increasingly inefficient (Gropp *et al.* 2020). Advanced artificial intelligence (AI) and computational methods, including machine learning, Monte Carlo simulations, molecular dynamics, and density functional theory (DFT), are accelerating property prediction and structure–function analysis (Demir *et al.* 2023). For example, configurational-bias Monte Carlo helped screen 550,357 MOFs spanning over 18 topologies, identifying five with record-breaking CH_4/N_2 separation (Lan *et al.* 2019). Similarly, controlled growth through AI improved MOFs electrochemical performance by 90% (Li *Q et al.* 2025). Overall, topology acts as a structural blueprint, and emerging computational tools and AI are accelerating the design of MOFs with tailored properties.

MOFs stability The emergence of MOFs has enriched the field of porous materials, offering promising agricultural applications such as pollutant removal, sensing, and controlled agrochemical release (Rojas *et al.* 2022). Their practical application, however, depends critically on stability, which is governed by thermodynamic and kinetic factors alongside environmental influences (Yuan *et al.* 2018). For instance, MOFs-5 degrades upon prolonged exposure to humid air (Li *et al.* 1999). Thermodynamically, stability reflects metal-ligand bond strength, as predicted by HSAB theory (Li Y *et al.* 2024; He *et al.* 2025), with robust frameworks resulting from hard–hard or soft–soft combinations. Stable examples include carboxylate-based MIL/UiO frameworks with high-valent metals (e.g., Zr^{4+}, Fe^{3+}, Cr^{3+}) and ZIFs with azolate-based ligands and low-valent metals (e.g., Zn^{2+}, Co^{2+}, Ni^{2+}). Yet, identical clusters and topologies do not ensure stability, as ligand elongation or pore enlargement may lower kinetic barriers and promote degradation (He *et al.* 2025). Kinetic stability is shaped by ligand rigidity, coordination environment, bond geometry, hydrophobicity, and interpenetration (Yao *et al.* 2015; Yuan *et al.* 2018). Environmental stresses such as water, acids, bases, competing ligands, microbes, or UV radiation can also drive partial or complete degradation (He *et al.* 2025).

Crucially, intrinsic structural characteristics (e.g., metal ion charge density, coordination number, bond strength, ligand hydrophobicity) play decisive roles. Reinforcement strategies include high-connectivity metals, rigid ligands, interpenetrated

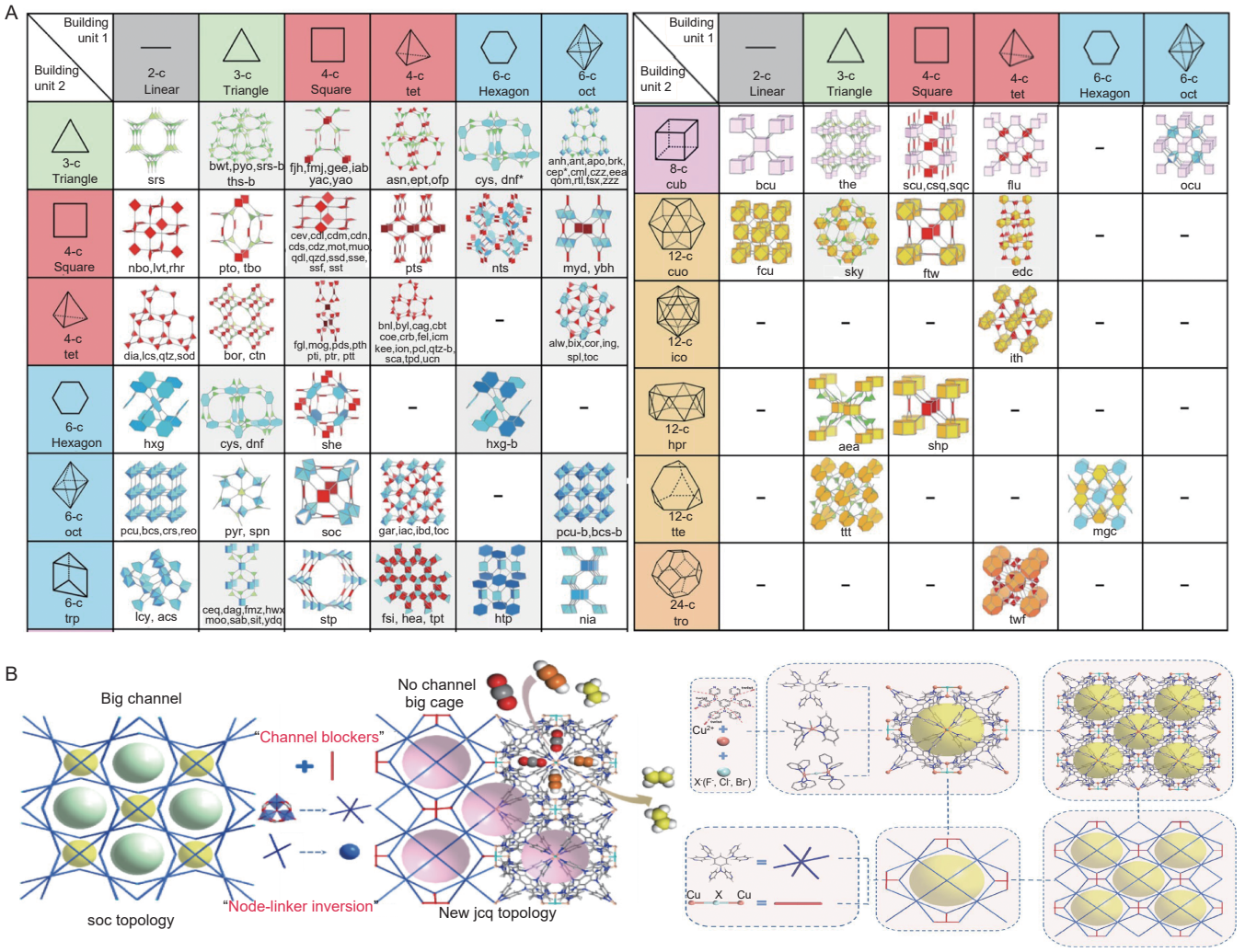


Fig. 3 Typical metal-organic frameworks (MOFs) topologies. A, diverse MOFs topologies (Kalmutzki *et al.* 2018). B, jcq topology-directed cage engineering in MOFs (Han *et al.* 2025).

or multi-walled frameworks, self-reinforced networks, and surface modification (Li N *et al.* 2016). Substituent effects also enhance resilience: UiO-67-*ortho*-2CF_3, for example, exhibits superior acid/base resistance relative to unsubstituted analogues (Wang *et al.* 2019). Importantly, stability demands differ by function in agriculture practices: adsorption and sensing demand long-term robustness, whereas controlled agrochemical release often requires designed degradation in response to stimuli (e.g., pH shifts, enzymes) (Lin *et al.* 2021; Wu *et al.* 2024). Beyond structural design guided by the HSAB principle and ligand characteristics, MOFs stability can be further improved through modification with composite materials such as sodium alginate, chitosan, and SiO_2. For instance, a hydrogel-like composite of MIL-100(Fe) cross-linked with cellulose and sodium alginate not only exhibited enhanced stability and excellent water-holding and urea slow-release capacities but also promoted wheat germination and growth (Guo *et al.* 2021; Wang Y *et al.* 2021). Likewise, SiO_2-modified MIL-100(Fe) formed a robust core-shell structure that efficiently adsorbed urea, provided sustained release in soil for 42 d, and improved rice nitrogen utilization efficiency and yield by 45.5 and 34.7%, respectively (Wu *et al.* 2024). Additionally, incorporating Fe_3O_4 or tannic acid further improved both function and recyclability of MOFs (Zhou *et al.* 2022, 2025; Salehi *et al.* 2024).

2.2. Green synthesis of MOFs

MOFs synthesis has advanced considerably, with diverse methods developed to enhance environmental compatibility, economic feasibility, and agricultural potential. Eco-friendly methods mainly include hydrothermal synthesis, solution precipitation, microwave-assisted synthesis, sonochemistry, electrochemistry, and mechanochemistry (Fig. 4). Green synthesis aims to avoid toxic reagents and byproducts while enabling cost-effective, scalable production through benign solvents, renewable ligands, recyclable precursors, and energy-efficient processes. Conventional MOFs metal precursors (e.g., chlorides, nitrates) are effective but can emit toxic byproducts (e.g., HCl, NO_x). Greener alternatives, such as metal carbonates and oxides, are increasingly favored. Similarly, many organic linkers originate from non-renewable petrochemicals, whereas naturally derived ligands (e.g., oxalic acid and biomolecules) are gaining attention for MOFs

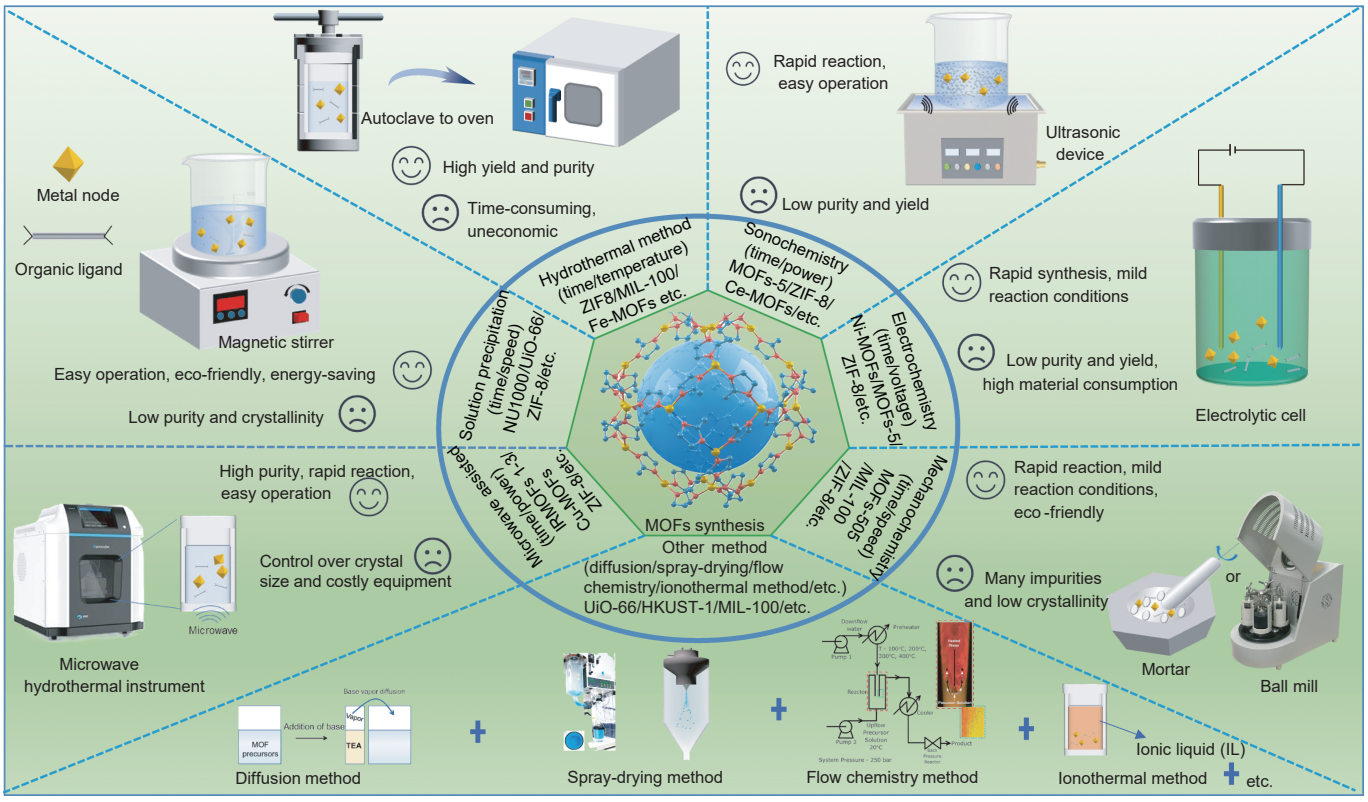


Fig. 4 Green synthesis methods of metal-organic frameworks (MOFs).

synthesis (Sun *et al.* 2019; Wu *et al.* 2022; Zeng *et al.* 2025).

Solvent choice is another key factor. Common high-boiling-point solvents (e.g., DMF, DEF, DMSO) ensure solubility but pose toxicity and carcinogenicity risks. Safer alternatives include water, ionic liquids, and bio-derived solvents such as dihydrolevoglucosenone (Zhang *et al.* 2016; Duan *et al.* 2023). Water is particularly attractive for its safety and abundance, although solubility challenges may arise; these can be mitigated by modulators that also help tune crystal morphology. For instance, MIL-100(Fe) hydrothermally synthesized achieved a higher BET surface area (1,781 m^2 g^{-1}) and larger crystal size (1.3 μm) than DMF-synthesized counterparts (1,607 m^2 g^{-1}, 141 nm) (Du *et al.* 2022). Similarly, Na_2CO_3 as a green modulator produced MIL-100(Fe) with higher surface area (1,327 m^2 g^{-1}), improved Cr(VI) adsorption (45 mg g^{-1}), and lower environmental impact relative to HF or TMAOH (Fang *et al.* 2018). Thus, selecting sustainable ligands, metal sources, and solvents supports high-performance MOFs and advances green chemistry and sustainable agriculture.

Hydrothermal synthesis Hydrothermal or solvothermal synthesis is among the most common methods for MOFs preparation, involving high-temperature, high-pressure conditions that facilitate the self-assembly of metal salts and ligands, thereby promoting nucleation and crystal growth (Karimi-Maleh *et al.* 2024; Wang D Y *et al.* 2024). Key parameters such as temperature, reaction time, solvent, modulator type, and ligand ratio influence product morphology and crystal size (Pang *et al.* 2025). This method enhances solubility and mass transfer, enabling reactions that are difficult under ambient conditions. Typical MOFs, such as UiO, ZIF, and MIL series, were initially synthesized *via* solvothermal methods (Lin *et al.* 2023). MIL-101(Fe), prepared *via* solvothermal synthesis in DMF (120°C, 12 h), exhibits a high loading rate (23%) toward chlorantraniliprole and forms a UV-resistant SiO_2-coated core-shell structure (Gao *et al.* 2021). Under alkaline conditions, cleavage of Si-O and Fe-carboxylate bonds trigger rapid pH-responsive pesticide release, effectively targeting *Plutella xylostella* larvae. It showed excellent biocompatibility with cabbage, promoting seed germination and a 17.7% increase in dry weight without observable toxicity during the entire growth period. However, reliance on high-boiling-point solvents (DMF, DEF, DMSO) and extended reaction times raises environmental and economic concern (Wang *et al.* 2014). Greener strategies address these issues by replacing solvents and modulators. For instance, hydrothermal MIL-100(Fe) (160°C, 24 h) achieved high crystallinity and surface area (Du *et al.* 2022), while low-temperature (65°C, 4 h) synthesis of MIL-88A-Fe in water yielded superior Fenton-like activity compared with DMF analogues (Liao *et al.* 2019). Incorporation of only 1.3 wt% zeolite as a regulator reduced the crystallization time of MIL-101(Fe) by 75% (Liu *et al.* 2013). Additionally, MIL-156 prepared hydrothermally at 120°C for 24 h with sodium acetate as a modulator exhibited higher surface area and mesoporosity (Zhang R *et al.* 2025), achieving outstanding adsorption capacities for urea (427.6 g $g^{-1)}$ and phosphate (397.6 g g^{-1}). Its pH-responsive nutrient release significantly enhanced potted rice growth, increasing nitrogen and phosphorus fertilizer utilization efficiencies by

35.6 and 13.3%, respectively. Similarly, Na_2CO_3, a low-cost, environmentally friendly modulator, enabled Fe-MOFs with improved Cr(VI) adsorption compared to those prepared using HF or TMAOH (Fang *et al.* 2018). Our group has further demonstrated kilogram-scale hydrothermal synthesis of Fe-MOFs (100°C, 24 h) for controlled-release fertilizer applications (Wu *et al.* 2022). Despite these advantages, hydrothermal synthesis still suffers from high energy consumption and long reaction times, necessitating further optimization.

Solution precipitation Solution precipitation (or co-precipitation) provides a simple, mild, and eco-friendly approach for synthesizing MOFs (Zhao *et al.* 2024). Typically performed at room temperature, it involves mixing metal salt and ligand solutions, often with acid/base modulators, under stirring. Reaction conditions such as metal/ligand ratio, solvent volume, and time determine the resulting MOFs morphology and porosity. The method's mildness makes it especially attractive for scalable, green production. For example, research has demonstrated that MOFs including NU-1000, UiO-66/67, PCN-94, Rod-8, and MFM-300 within minutes at room temperature, contrasting with days-long solvothermal methods (Zhang *et al.* 2023). Similarly, other studies reported hierarchically porous MIL-100(Fe) with a surface area near 2,000 m^2 g^{-1} and high 2,4-D adsorption capacity (858.11 mg g^{-1}) (Tan *et al.* 2021). Additionally, a report described the rapid synthesis of ZIF-8 and ZIF-67 within 10 min using ammonia and triethanolamine modulators, yielding materials effective in dye adsorption (Li Y *et al.* 2016). Bimetallic ZnM-ZIFs with excellent imidacloprid loading efficiency were synthesized by mixing zinc nitrate and copper or nickel nitrate with 2-methylimidazole at room temperature for 4 h (Zhou *et al.* 2025). Protonation of 2-methylimidazole under acidic conditions induces partial carrier degradation, enabling rapid pesticide release — a mechanism well-suited for weakly acidic plant leaf environments that trigger pH-responsive release upon pest feeding. Toxicological evaluations confirmed biosafety, showing no significant effect on lettuce germination and safe Zn, Cu, and Ni residues.

Likewise, dinotefuran-loaded ZIF-8 (Ma *et al.* 2022) obtained *via* a 10 min precipitation method exhibited selective targeting and no observable toxicity to corn or organisms (e.g., grass carps, earthworms, zebrafish). Ber@ZnO-Z decomposes in tomato, releasing bioavailable Zn^{2+} without harmful effects (Liang *et al.* 2022), while PD@ZIF-8 demonstrates similar safety (Ren *et al.* 2022). Furthermore, non-toxic ZIF-8 precursors can encapsulate individual bacteria *via* a rapid 30 s room-temperature synthesis, providing environmental protection and assisting in soil remediation from pesticide residues (Li M *et al.* 2025). Despite its simplicity, this method can sometimes yield products with lower crystallinity. Optimizing stirring speed, reaction time, and modulator choice can mitigate this issue.

Microwave-assisted synthesis Microwave-assisted synthesis is a rapid, energy-efficient alternative that directly transfers microwave energy (0.2–300 GHz) into the reaction medium, generating localized heating and accelerating nucleation (Lin *et al.* 2023). Compared to solvothermal methods, it drastically shortens reaction times from days to minutes while often producing higher yields. Pioneering work by Ni *et al.* (2006) achieved IRMOF-1–3 in 30 s to 2 min with superior yields to solvothermal methods. Similarly, ZIF-7/8 membranes was synthesized in just 90 s (Hillman *et al.* 2018). And even modified household microwave household microwaves have proven effective. For instance, TN@Ti-MOFs/PT synthesized in a microwave oven (400 W, 2 min) demonstrated efficient recognition of imidacloprid (Tari *et al.* 2016). Importantly, a microwave-assisted synthesis of MIL-53(Al) reduced production costs by 42.2% compared with solvothermal methods (Pan *et al.* 2024). The microwave-assisted synthesis of HKUST-1 (200 W, 30 min) achieved a yield of 96%, with a specific surface area of 1,206 m^2 g^{-1} and a pore volume of 0.75 cm^3 g^{-1}, outperforming the 94% yield from the traditional solvothermal method (120°C, 24 h), which resulted in a surface area of 1,143 m^2 g^{-1} and a pore volume of 0.60 cm^3 g^{-1} (Schlesinger *et al.* 2010). Likewise, NH_2-MIL-101(Fe) synthesized by microwave at 110°C for 45 min exhibited a higher specific surface area (258 *vs.* 239 m^2 g^{-1}) and significantly greater tetracycline adsorption (378.2 *vs.* 221.2 mg g^{-1}) than its solvothermal counterpart (Dong *et al.* 2020). While this method offers high crystallinity and rapid results, it often involves non-eco-friendly solvents, requires specialized equipment, and can struggle with crystal size control. Employing water and suitable modulators could address these challenges.

Sonochemistry Sonochemistry, also known as ultrasound-assisted synthesis, uses ultrasound (20 kHz-1 MHz) to efficiently synthesize MOFs by facilitating metal-ligand interactions through cavitation (Zhao *et al.* 2024). Collapsing cavitation bubbles generate transient high-temperature and high-pressure microenvironments that promote chemical transformations while improving reactant dispersion and mitigating aggregation (Wang D Y *et al.* 2024). Volatile solvents (e.g., ethanol, trichloroethylene) should be avoided as they inhibit cavitation (Lin *et al.* 2023). This method reduced MOFs-5 synthesis time from 24 h to 30 min compared to solvothermal methods (Son *et al.* 2008). Additionally, it has also enabled rapid fabrication of MOFs films with tunable crystallinity, where extended ultrasonication improved growth and yielded ZIF-8 films with enhanced methane sensing (Abuzalat *et al.* 2018). Furthermore, Ce-MOFs prepared under ultrasound (50% amplitude, 60 min) removed 82.5% tetracycline (TC), outperforming hydrothermal and precipitation methods (Shahabinejad *et al.* 2024). Zn-MOFs was rapidly synthesized using an ultrasonic method (50 W, 1 h), which proved more efficient than the traditional solvothermal approach (100°C, 48 h) (Moradi *et al.* 2019). The material's fluorescence quenching behavior enabled highly sensitive detection of Fe^{3+}, achieving a fast response and detection limit of 17 ppb. Despite its simplicity and speed, sonochemistry still requires optimization to improve reaction control and reduce impurities.

Electrochemistry Electrochemical synthesis uses an external electric field to drive coordination between metal ions and ligands, fitting well within green chemistry principles. For instance, a simple electrochemical synthesis (4 V, 1 h) yielded UiO-66-NH_2 with a high specific surface area (844.3 m^2 g^{-1}) and yield (62.2%), outperforming the solvothermal method

(120°C, 24 h; 730.2 m^2 g^{-1}) (Wei *et al.* 2019). The reaction residues were recyclable at least five times, and the material demonstrated exceptional Fe^{3+} sensing capability (LOD= 10^{-8} mol L^{-1}), markedly superior to that of the solvothermally synthesized counterpart (LOD=5×10^{-6} mol L^{-1}). Depending on the mechanism, the approach is classified as anodic or cathodic. In the anodic route, the metal electrode itself dissolves under applied voltage to supply ions, enabling MOFs growth (Lin *et al.* 2023). Previous research optimized solvent composition, reaction time, and voltage (~10 V) for Ni-MOFs synthesis, achieving excellent catalytic performance in hydrogen evolution (Jabarian *et al.* 2019). While anodic methods offer rapid synthesis and avoid extraneous anions, they face limitations related to electrode compatibility and structural complexity. In the cathodic approach, soluble metal salts enable MOFs formation near the cathode. For instance, ZIF-8 films with tunable thickness were electrochemically deposited by adjusting potential (Ito *et al.* 2023). However, both methods struggle with controlling MOFs morphology and yield on electrodes. Reduction reactions may also cause metal deposition, impair performance and introduce impurities, requiring further improvement.

Mechanochemistry Mechanochemistry utilizes mechanical forces (e.g., grinding, milling) to induce reactions without bulk solvents, making it an inherently green approach. It bypasses solubility limitations, reduces reaction times, and accommodates a wide range of precursors (Wahan *et al.* 2025). Liquid-assisted grinding enhances efficiency by facilitating reactant mobility with minimal solvent. Chen *et al.* (2018) synthesized MOFs-505 from copper acetate and biphenyl-3,3′,5,5′-tetracarboxylic acid with minimal DMF/ethanol, yielding high CO_2 adsorption. Remarkably, high-crystallinity MIL-100(Fe) with high drug-loading capacity was prepared *via* 10-min manual grinding (Souza *et al.* 2020). Similarly, MOFss (MIL-100(Fe), ZIF-8, Cu-BTC) can be even synthesized in just 5 min using a domestic blender (Samal *et al.* 2018). Among these, the MIL-100(Fe) achieved 98% methylene blue removal. Our group fabricated slow-release Fe-MOFs fertilizers *via* 10 min mechanical grinding, achieving 46% nutrient content and 37% cumulative nitrogen release over 21 d (Du *et al.* 2021). Recently, a solvent-free resonant acoustic mixing method recently achieved rapid synthesis of 10.5 g of MIL-88A(Fe) (209 m^2 g^{-1}) within 20 min at room temperature and ambient pressure, outperforming the hydrothermal process (60°C, 4 h) that yields only 480 mg with a surface area of 149 m^2 g^{-1} (FitzGerald *et al.* 2025). Recycling polyethylene terephthalate (PET) as an organic ligand and coordinating it with metal salts *via* solvent-free ball milling enables rapid MOFs synthesis (~2 h), presenting a green and scalable strategy for sustainable production (He *et al.* 2023). Nonetheless, this method often yields impure MOFs, introducing additional purification steps could increase production costs.

Other methods Beyond the six common strategies (Fig. 4), other green MOFs synthesis include diffusion, spray drying, flow chemistry, and ionothermal techniques. Diffusion synthesis enables gradual mixing of reactants across phases, producing morphologies unattainable by solvothermal routes. For instance, MOFs grown in porous graphene hydrogels exhibited enhanced oxygen evolution reaction performance due to precise structural control (Sikdar *et al.* 2021), while alkaline vapor diffusion yielded core–shell MOFs with tunable shell thickness (Zhang W *et al.* 2024). Spray drying atomizes precursor solutions into heated airflow, enabling large-scale MOFs nanoparticle production and composite fabrication (Troyano *et al.* 2020). Carné-Sánchez *et al.* (2013) prepared hollow (<5 μm) MOFs by this method, which were ultrasonically dispersed for multifunctional applications. Flow chemistry continuously pumps reactants through reactors, synthesizing MOFs such as $MgFe_2O_4$@UiO-66-NH_2 with strong CO_2 adsorption (He *et al.* 2019). Ionothermal synthesis replaces volatile organics with recyclable ionic liquids (e.g., [EMIM]OAc), enabling cleaner media and superior crystal; UiO-66 prepared *via* this method exhibited superior RB adsorption over DMF-derived analogues (Duan *et al.* 2023). Hybrid approaches, such as microwave-assisted mechanochemistry, further enhance efficiency and functionality (Wei *et al.* 2024). Together, these diverse strategies expand the design space for MOFs, with method choice requiring balance between environmental impact, process economics, and agricultural applicability.

2.3. Green circular production

A green lifecycle framework is essential for advancing MOFs applications in agriculture (Fig. 5-A), encompassing eco-friendly raw material sourcing, cost-effective and green synthesis, efficient utilization, and pollution-free recycling. Raw material sourcing is shifting toward waste-derived alternatives. For example, terephthalic acid (TPA) recovered from PET waste (Fig. 5-B) can synthesize MIL-53(Al) *via* microwave-hydrothermal methods. This MOFs effectively adsorbed organic carbon (129 mg g^{-1}) from swine wastewater while demonstrating sustainability in lifecycle assessments (Pan *et al.* 2024), a finding confirmed in similar studies (Chinglenthoiba *et al.* 2024). Similarly, MIL-100(Fe) derived from stainless steel pickling wastewater through microwave synthesis reduced energy consumption by 94%, cost by 89%, and maintaining high atrazine degradation (Chang *et al.* 2025). Notably, MIL-88B was synthesized *via* a one-step hydrothermal process using waste PET and steel pickling wastewater, eliminating additional chemicals and reducing costs by 99.8% compared to traditional methods (Zhao *et al.* 2023). Green synthesis routes are also important for scale-up. Room-temperature precipitation from ZIF-L intermediates replaces energy-intensive ZIF-8 synthesis (Deacon *et al.* 2022), spray drying facilitates large-scale HKUST-1 and ZIF-8 production (Fig. 5-C) (Troyano *et al.* 2020), and hydrothermal methods enable Fe-MOFs pilot-scale fabrication (Wu *et al.* 2022). Recycling synthesis solutions by replenishing consumed ligands/regulators, as demonstrated for ZIF-8 and HKUST-1 (Chu *et al.* 2024), further minimizes waste.

Post-synthesis, MOFs require activation to remove residual ligands and expose catalytic sites. Traditional methods involving hazardous solvents (e.g., DMF, acetone) can be replaced by water or ionic liquids, enabling ligand recovery (Wu *et al.* 2019; Duan *et al.* 2023). Energy-intensive activation (e.g., vacuum/freeze-drying) or solvent

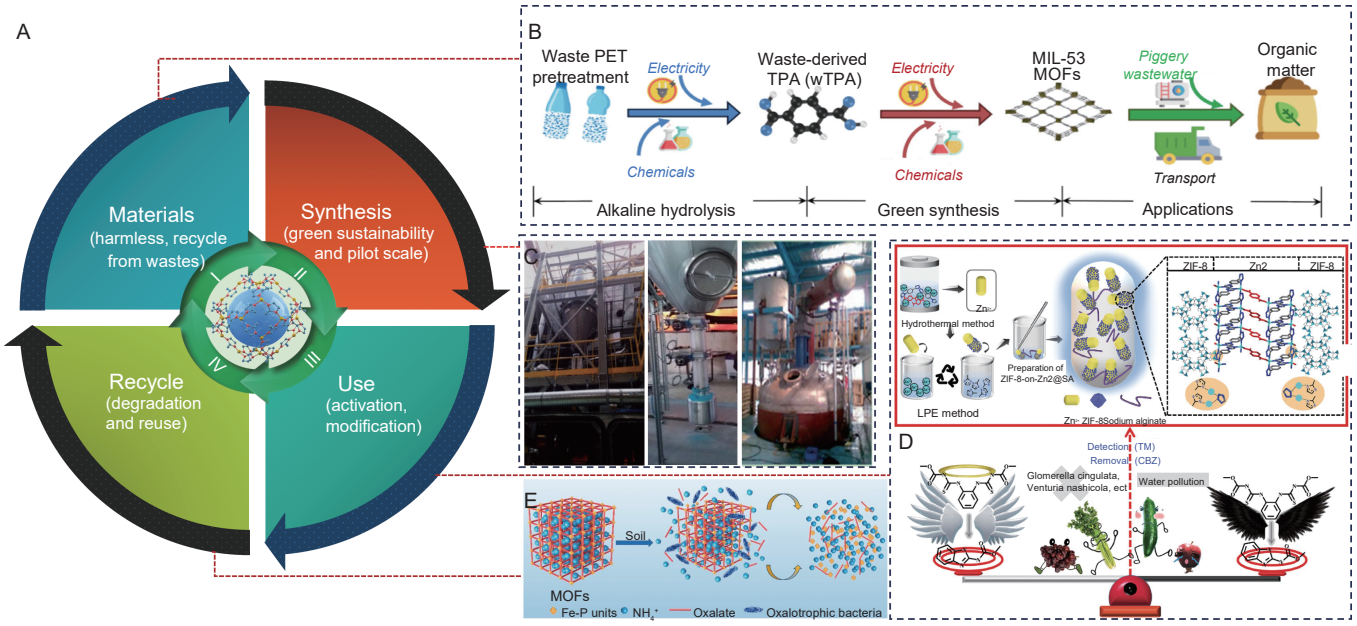


Fig. 5 Green circular production. A, green cycle stage. B, recycle raw materials from waste plastics to synthesis MOFs (Pan *et al.* 2024). C, pilot production equipment for spray drying and hydrothermal methods (Troyano *et al.* 2020; Wu *et al.* 2022). D, modified MOFs detected pesticides (Jia *et al.* 2022). E, diagram of MOFs decomposition in soils (Wu *et al.* 2022).

exchange with toxic chemicals poses environmental risks (Kumar *et al.* 2019). Supercritical CO_2, in contrast, offers a non-toxic and structure-preserving alternative (Dapaah *et al.* 2020). Stability in agricultural settings can be improved by functionalization (e.g., -NH_2, -COOH, THP) or hybridization with carbonaceous/metallic phases (Lin *et al.* 2023; Pang *et al.* 2025). For instance, the ZIF-8-on-Zn2@SA composite (Fig. 5-D) detected thiabendazole residues (LOD=0.14 μmol L^{-1}) and adsorbed carbendazim (q_{max}=161.8 mg g^{-1}) (Jia *et al.* 2022). End-of-life strategies include recycling or benign degradation (Kumar *et al.* 2019). Fe-MOFs naturally decompose in soil, releasing nutrients (N, P, Fe) (Fig. 5-E) (Wu *et al.* 2022), while pollutant-saturated MOFs can be converted into catalytic graphene/Fe@N-doped carbon hybrids for advanced oxidation (Yang *et al.* 2022). Together, such measures establish a circular, low-impact lifecycle that accelerates sustainable agricultural integration of MOFs.

3. Green, sustainable and smart agricultural applications of MOFs

Green agriculture prioritizes environmental safety and long-term sustainability (Zheng *et al.* 2024). However, overreliance on agrochemicals (pesticides, fertilizers, antibiotics) and agricultural films has caused extensive soil and water contamination, including microplastic accumulation and harmful residues. These practices disrupt agroecosystems and pose risks to human health. Improper fertilization further contributes to greenhouse gas emissions and eutrophication. Consequently, removing agricultural pollutants is essential for ecological restoration. MOFs have emerged as promising candidates due to their high porosity, structural tunability, and abundant active centers. Beyond pollutant remediation, MOFs support sustainable resource utilization, such as atmospheric water harvesting, seawater desalination, and ammonia synthesis, while their tunable architectures enable applications in smart agriculture, including controlled-release agrochemicals and intelligent sensing. Overall, MOFs demonstrate significant potential in three key areas: green pollutant removal, sustainable resource utilization, and smart agricultural technologies.

3.1. Green removal of agricultural pollutants

The excessive and improper use of agrochemicals has led to the accumulation of hazardous residues — pesticides, heavy metals, antibiotics, and microplastics — in soils and waters. These contaminants diminish agricultural productivity, infiltrate the food chain, and endanger both ecosystems and human health. Additionally, agricultural-source eutrophication and greenhouse gas emissions are of increasing concern. MOFs, with their ultrahigh surface area, hierarchical porosity, and abundant active sites, offer efficient adsorption, catalytic degradation, and gas capture/separation, making them highly promising for pollutant mitigation.

Pesticides removal Pesticides are essential for sustaining agricultural productivity, with global crop losses projected at 30% without their use (Karimi-Maleh *et al.* 2024). Yet their extensive use poses greater environmental risks than fertilizers or growth regulators (Li Y *et al.* 2024). Pesticides classified as herbicides, fungicides, and insecticides (e.g., dimethoate) remain widely used for their low cost and efficacy but persist in the environment, raising bioaccumulation concerns (Mohan *et al.* 2023). Annual global pesticide consumption reaches 4.1 million tons; alarmingly, only about 0.1% reaches target pests, with the remainder lost through volatilization and degradation (Liang *et al.* 2017; Karimi-Maleh *et al.* 2024). Current mitigation strategies focus on adsorption

and catalytic degradation (Saleh *et al.* 2020), where MOFs provide distinct advantages due to its high porosity, tunable structures, and chemical versatility.

MIL-53(Cr), the first MOFs applied to 2,4-D adsorption, achieved a capacity (556 mg g^{-1}) almost twice that of activated carbon or zeolite, with an adsorption rate 10-fold higher than activated carbon even at low concentrations (Jung *et al.* 2013). This performance arises from its large surface area (1,438 m^2 g^{-1}) and strong π–π and electrostatic interactions, with recyclability ensured by simple water/ethanol desorption. More recently, MOFs-808 reached 797 mg g^{-1} for 2,4-D and 775 mg g^{-1} for MCPA, retaining 96% capacity after five cycles (Huang *et al.* 2025). Composite MOFs extend performance: Fe_3O_4@ZIF-90@MIL-68(Al) removed 352 mg g^{-1} prochloraz, far exceeding Fe_3O_4@MIL-68(Al) (24 mg g^{-1}), through pore filling, complexation, and π–π stacking (Zhou *et al.* 2022). Similarly, pAAm-g-XG/HKUST-1@Fe_3O_4 achieved ultrafast adsorption, capturing>4,500 mg g^{-1} chlorpyrifos and 1,700 mg g^{-1} diazinon within 15 min (Salehi *et al.* 2024). In parallel, MOFs catalytically degrade pesticides through high porosity, coordinatively unsaturated metal sites, and functional ligands. Nano-sized nMOFs-808 (~65 nm) degraded 95% of glyphosate within 2 h, outperforming conventional MOFs-808 (~600 nm, 72%) due to abundant reactive ligands (Prada *et al.* 2025). A Cu-MOFs–PAN fiber membrane (Fig. 6-A) with hierarchical porosity degraded 208 mg g^{-1} for chlorpyrifos and removed >70% of six organophosphates within 10 min (Zhao *et al.* 2025). Overall, pesticide removal by MOFs relies primarily on pore filling, π–π and electrostatic interactions, with future advances expected through group modification, composite engineering, and mixed-ligand systems to enhance field performance.

Heavy metals removal Heavy metal contamination impacts 14–17% of global cropland, threatening the health of 0.9–1.4 billion people (Hou *et al.* 2025). Toxic, persistent contaminants such as Cd, Hg, Pb, Cr, As, Cu, and Ni accumulate in the food chain, posing severe health risks. Among remediation strategies, adsorption is highly efficient and cost-effective, outperforming electrochemical reduction, chemical precipitation, membrane separation, and ion exchange (Lin *et al.* 2023). MOFs are superior to traditional adsorbents (e.g., activated carbon, zeolites, carbon nanotubes, and clays) owing to their tunable pore structures, large surface area, selectivity, and multifunctionality (Abdollahi *et al.* 2022). Surfactant-modified nano-sized ZIF-8 particles (~168 nm) exhibited a Pb^{2+} adsorption capacity of 629 mg g^{-1} (Tanihara *et al.* 2021), with smaller particles enhancing diffusion and performance. Fig. 6-B illustrates that ZIF-8

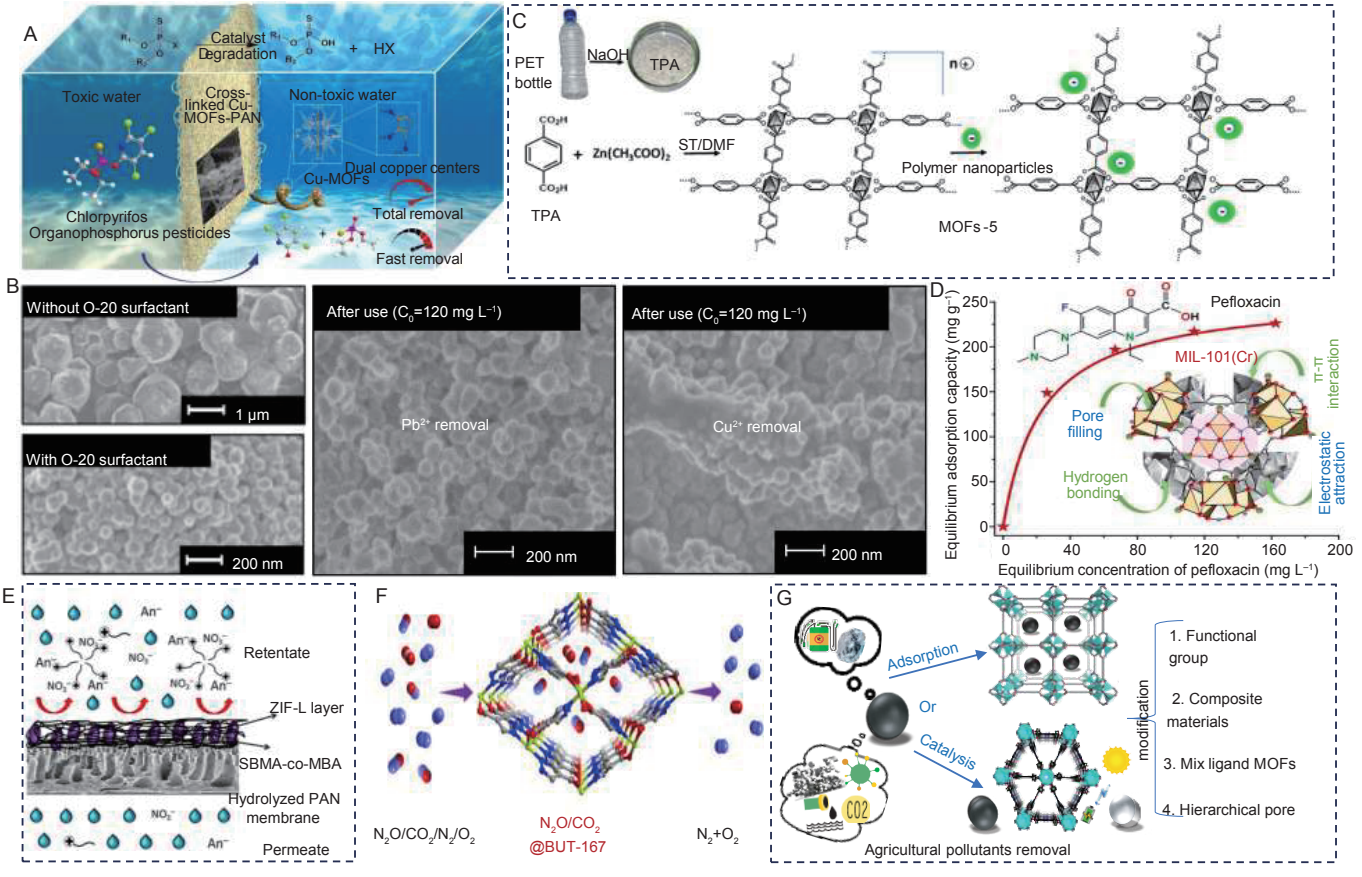


Fig. 6 Typical agricultural pollutants removal. A, adsorption mechanisms of Cu-MOFs-PAN FM (Zhao *et al.* 2025). B, FE-SEM micrographs of ZIF-8 with/without O-20 surfactant and after Pb^{2+} and Cu^{2+} removal (Tanihara *et al.* 2021). C, recycle TPA to prepare MOFs-5 for the removal of microplastics (Chinglenthoiba *et al.* 2024). D, adsorption mechanism of pefloxacin antibiotics by MIL-101(Cr) (Nguyen *et al.* 2024). E, mechanism of nitrate removal by HyZifLG membrane (Modi *et al.* 2024). F, N_2O/CO_2 removal by BUT-167 (Zhang *et al.* 2025c). G, summary of agricultural pollutants removal by MOFs.

maintains its structure after Pb^{2+} adsorption, whereas Cu^{2+} uptake caused morphological transformation *via* ion exchange (q_{max}=726 mg g^{-1}).

Nevertheless, pristine MOFs often aggregate and are difficult to recover. Composite design and functional modification provide effective solutions. For composites, Mg-MOFs-74 grown *in situ* on cellulose aerogel (CA) produced a 3D porous Mg-MOFs-74@CA composite that adsorbed Pb(II), Cr(VI), and Cu(II) through ion exchange and complexation, reaching equilibrium about 5 h (Guo *et al.* 2023). This process follows pseudo-second-order kinetics and Langmuir isotherms, indicating monolayer chemisorption, while the composite exhibited recyclable and eco-friendly. For functionalization, thiol-functionalized Zr-MOFs (Zr-MSA-DMSA) rapidly remove Pb(II), Hg(II), and Cr(VI) with over 97% efficiency, facilitated by abundant oxygen vacancies and unsaturated metal sites (Zhou Y *et al.* 2024). Hybrid strategies offer further promise. N-CQD@MIL-53(Fe) couples adsorption with photocatalytic oxidation for As(III) removal, achieving sixfold higher efficiency than MIL-53(Fe) and maintaining multi-cycle stability (Chen H *et al.* 2022). Thus, optimizing MOFs for heavy-metal removal through composite integration, functionalization, and hybridization can deliver high-capacity, selective, and reusable systems suitable for agricultural remediation.

Microplastics removal Microplastics, defined as plastic particles smaller than 5 mm, are emerging contaminants of global concern due to their chemical stability and environmental persistence (Guan *et al.* 2025). Their widespread presence poses significant threats to agricultural ecosystems and human health, making effective removal a critical challenge. MOFs are promising candidates for microplastic adsorption and degradation owing to their tunable structures and multifunctional properties. For instance, hydrothermally synthesized MIL-101(Cr) achieved ~800 mg g^{-1} adsorption capacity for 65 nm polystyrene nanoplastics (PSNPs), with 96% removal efficiency, dominated by electrostatic interactions, though performance declined slightly after regeneration (Modak *et al.* 2023). Similarly, MOFs-5, synthesized *via* a green route using terephthalic acid recycled from waste plastic bottles (Fig. 6-C), removed polymethyl methacrylate and polyvinyl chloride with efficiencies of 97 and 95% within 40 min, demonstrating both efficacy and sustainability (Chinglenthoiba *et al.* 2024).

Functionalization also enhances performance. UiO-66-EDTMP (ethylenediamine tetramethylene phosphonic acid–modified UiO-66) removed 97% of 100 nm PSNPs in 120 min, retaining 89% efficiency after 10 cycles (Xu *et al.* 2025), while hierarchical mesoporous UiO-66-NH_2/P123 reached ~99% adsorption of 26 nm PSNPs *via* electrostatic interactions (Pedrero *et al.* 2024). Beyond powder adsorbents, membrane-based MOFs are emerging. A flower-like Ni-MOFs/nylon membrane demonstrated 97% removal of Congo red and 99% filtration of 220 nm PSNPs, with excellent reusability (Han L *et al.* 2023). For photocatalytic degradation, the TiO_2 (12.5 wt%)/MIL-100(Fe) composite (179 m^2 g^{-1} surface area, 7 nm pores) exhibited visible-light activity, efficiently degrading microplastics by generating hydroxyl radicals and photogenerated holes (Rojas-Guerrero *et al.* 2023). Thus, by integrating tailored functional groups, hierarchical porosity, photocatalytic activity, and even microplastic-derived feedstocks, MOFs offer promising solutions to mitigate microplastic pollution.

Antibiotic removal Antibiotics are extensively used in livestock and aquaculture, with more than 250 types spanning sulfonamides, tetracyclines, fluoroquinolones, macrolides, and chloramphenicols (Akhter *et al.* 2024; Cui *et al.* 2024). Because 30–90% of administered antibiotics are excreted unmetabolized, large quantities enter soils and waters, driving environmental contamination (Wei *et al.* 2022). MOFs have recently gained attention for antibiotic removal. MIL-101(Cr) exhibited an ultrahigh surface area (3,166 m^2 g^{-1}) and achieved a 254 mg g^{-1} adsorption capacity for pefloxacin at 308 K and neutral pH (Nguyen *et al.* 2024). Adsorption follows pseudo-second-order kinetics and the Langmuir isotherm, involving electrostatic attraction, pore filling, hydrogen bonding, and π–π interactions (Fig. 6-D). A bimetallic Fe/Zr-MOFs demonstrated spontaneous, endothermic adsorption of doxycycline hydrochloride (DC) with 88% removal efficiency, showing practical potential (Wei *et al.* 2022). Hierarchical porous Zr-MOFs, synthesized with propionic acid modulators, achieve complete sulfonamide removal within 10 min, primarily through mechanisms such as van der Waals forces, π–π interactions, and hydrogen bonding (Han L Z *et al.* 2023). Additionally, hierarchical HP-ZIF-67, fabricated from PVP-modified γ-cyclodextrin-MOFs, exhibited 3.7-fold higher catalytic degradation of TC compared to unmodified ZIF-67, attributed to hierarchical porosity and abundant active sites (Zeng *et al.* 2025). Furthermore, a novel Co-MOFs topology functions as an efficient and multifunction photocatalyst, degrading metronidazole, tinidazole, and nitrofurantoin (Wang J J *et al.* 2024), corroborating earlier studies (Shahabinejad *et al.* 2024). Despite these advances, pristine MOFs show limited antibiotic adsorption/degradation capacity. Enhancing efficiency and selectivity requires strategies such as ligand functionalization, composite derivatization, and hierarchical structural tuning.

Other pollutants removal Excessive nitrogen and phosphorus fertilizers application has led to nutrient runoff, driving water pollution and eutrophication. Removing nitrate and phosphate from contaminated water is critical for ecosystem recovery. MOFs offer versatile solutions for both contaminant removal and resource recovery. Quaternary ammonium–functionalized UiO-66-NH_2 achieved 96% nitrate removal within 60 min at neutral pH (Mohajer *et al.* 2023), while a hybrid membrane (HyZifLG) combining *in situ* ZIF-L growth and monomer grafting (Fig. 6-E) showed durable, multi-cycle performance (Modi *et al.* 2024). Green electrocatalysis using a 2D Cu/Fe-MOFs cathode, synthesized *via* room-temperature precipitation, achieved 88% nitrate reduction with high ammonia yield (907.2 μg h^{-1} mg^{-1}) and excellent recyclability (Ma *et al.* 2025). Phosphate pollution can be mitigated through adsorption strategies. Our group developed a size-tunable hierarchical porous HUiO-66-NH_2-HTC templated by MOFs-5, which contained both micropores and mesopores and achieved phosphate adsorption capacity of 227 mg g^{-1} (Wu *et al.* 2025).

Adsorption followed Langmuir and pseudo-second-order kinetics, with DFT simulations revealing inner-sphere Zr-O-P complexation as the dominant mechanism, complemented by hydrogen bonding and electrostatic interactions. Beyond nutrient pollution, MOFs show promise for addressing agricultural greenhouse gases (e.g., CO_2, CH_4, N_2O). MEA-functionalized MIL-101(Cr) captured 2.15 mmol g^{-1} CO_2 directly from air (Jiang *et al.* 2024), while BUT-167 selectively removed both N_2O and CO_2 from humid gas mixtures through hydrogen bonding within confined pores (Fig. 6-F) (Zhang X *et al.* 2025). Moreover, ZIF/Q-CsNF$^+$ catalytically to convert CO_2 into carbonate species, providing a sustainable utilization pathway (Jung *et al.* 2025).

In summary, MOFs present multifaceted solutions for agricultural pollutions, ranging from pesticides, heavy metals, antibiotics, and microplastics to eutrophication and greenhouse gases (Fig. 6-G). Their performance could be further enhanced through group functionalization, hybrid composites design, hierarchical pore optimization, and mixed-ligand strategies. Continued advances are expected to establish MOFs as critical materials in agricultural pollutant remediation.

3.2. Sustainable agricultural applications of MOFs

Water and fertilizers form the backbone of crop cultivation, yet their overuse and scarcity often cause ecological burden. MOFs and their hybrid materials stand out for their ability to bridge both needs — offering cutting-edge solutions for harvesting water from the air, seawater desalination, and enabling green pathways for ammonia synthesis. As summarized in Table 1, these innovations represent a promising step toward more sustainable agricultural practices.

Atmospheric water harvesting Water scarcity in arid regions severely restricts agricultural productivity. Atmospheric water, a reservoir nearly six times larger than all global rivers combined, represents an alternative resource, yet its capture is particularly challenging under low-humidity conditions (Luo *et al.* 2022). MOFs are promising candidates for atmospheric water harvesting (AWH) due to their structural tunability, high porosity, and chemical resilience.

A hybrid aerogel-MIL-101(Cr) composite (PC-MOFs) enabled solar-driven water release, achieving ~6 g d^{-1} at 90% relative humidity (RH) without external evaporators (Fig. 7-A) (Yilmaz *et al.* 2020). Moreover, MIL-160 demonstrated strong potential under desert conditions, with a water uptake of 0.34 g g^{-1} and energy demand of 3.5–6.8 kJ g^{-1} per cycle (Solovyeva *et al.* 2021). Solar-driven desorption offers a promising strategy for reducing energy consumption. Through functionalization of MIL-160 and modification with mixed ligands, CGF-mixed-MOFs were developed, exhibiting enhanced cycling stability and improved adaptability to varying humidity conditions (Luo *et al.* 2022). Low-humidity performance has been advanced with fluorophenyl oligomer (FO)-modified HKUST-1 (FO@HK), which exhibited excellent and rapid uptake rates (8.0/11.8 L kg^{-1} h^{-1} at 20/30% RH) with an optimized outdoor yield of 264.8 mL d^{-1} (Kang *et al.* 2024). Additional composites, such as $CaCl_2$-modified PCC-42 (Fig. 7-B) and core–shell UiO-66@MIL-101(Cr), also demonstrated efficient low-humidity performance and robust cycling stability (Hu *et al.* 2023; Su *et al.* 2024). Overall, these advances highlight MOFs' potential for sustainable AWH in agriculture. Future research should optimize pore structures and surface functionalization to enhance water uptake while ensuring environmental durability and eco-compatibility.

Seawater desalination With 97% of Earth's water being saline and less than 1% suitable for agriculture, desalination is critical for freshwater security and sustainable coastal farming (Lai *et al.* 2024). MOFs show strong potential in this field through three main approaches, i.e., membrane-based separation, solar-driven evaporation and photothermal membrane distillation. Fluorinated MOFs membrane (FMOFs-1) demonstrated exceptional water permeability (16.18 L cm^{-2} d^{-1} MPa^{-1}), outperforming conventional reverse osmosis and nanofiltration membranes while maintaining 100% ion rejection at 50 MPa and 90% at 250 MPa due to hydrogen bonding and electrostatic modulation (Chen *et al.* 2021). Similarly, tannic acid-modified ZIF-8 improved hydrophilicity, yielding a reverse osmosis membrane with 64.56 L m^{-2} h^{-1} water flux (1.74×unmodified) and 99.5% rejection against high-salinity NaCl (32,000 mg L^{-1}) (Lai *et al.* 2024). In solar thermal desalination, Fe-MOFs-74/Cu composites achieved 81.5% solar-to-vapor efficiency and 1.35 kg m^{-2} h^{-1} evaporation, supporting recyclable freshwater production (Wang J L *et al.* 2021). Furthermore, electron-donating ligands (-F, -H, -OH, $-NH_2$, $-(NH_2)_2$) boosted UiO-66 photothermal performance, with UiO-66-$(NH_2)_2$ reaching 97.4% efficiency and 2.34 kg m^{-2} h^{-1} evaporation by narrowing the band gap and improving light absorption (Fig. 7-C) (Shao *et al.* 2025). More recently, a dual-layer P-Janus TLNMs membrane of Cu-MOFs and nanofibers attained a stable 88°C within 200 s under 1 kW m^{-2} illumination, maintaining >99.9% salt rejection even in seawater containing oils and surfactants (Li Z J *et al.* 2024). Notably, multifunctional CuS@MIL-100(Fe)–cellulose hydrogel membrane combined high evaporation performance (2.37 kg m^{-2} h^{-1}, 94.4% efficiency) with excellent photocatalytic degradation of pollutants such as methylene blue (97.3%) and tetracycline (93.3%) (Shu *et al.* 2024). As MOFs continue to demonstrate multifunctional desalination, future efforts should prioritize stability enhancement, cost reduction, and scalability for real-world implementation.

Ammonia synthesis The conventional Haber-Bosch process for ammonia synthesis requires extreme conditions (400–500°C, 10–30 MPa), incurring high energy costs. Given its central role in fertilizer supply, alternative sustainable synthesis methods are critical for agriculture. MOFs offer promising electrocatalytic and photocatalytic platforms owing to their tunable porosity and accessible active sites. In electrocatalysis, Cu_1Co_1HHTP bimetallic MOFs utilized Cu/Co synergy to lower reaction ΔG by 32%, achieving 96.4% Faradaic efficiency and 299.9 μmol h^{-1} cm^{-2} NH_3 yield (Liu P *et al.* 2023). CoP/Zn-ZIF leveraged Zn-ZIF's positive charge to adsorb NO_3^- and desorb NH_4^+, yielding 0.89 mmol h^{-1} cm^{-2} NH_3 and 97% Faradaic efficiency at neutral pH (Zhang C Q *et al.* 2024). However, most nitrate-rich wastewater is acidic, whereas conventional electrocatalysis functions

Table 1 Current researches on the agricultural sustainability by metal-organic frameworks (MOFs)

MOFs	Capability	Descriptions	Reference
Atmospheric water harvesting			
PCA-MOFs	6.04 g g^{-1} (90% RH)	Harvest content (6 g g^{-1} d^{-1} without active condensation), continuous water delivery (1,440 h), total liquid delivery efficiency (95%)	Yilmaz *et al.* (2020)
MIL-160 (Al)	0.34 g g^{-1} (10% RH)	Regeneration(80°C), water extracted (δex=0.90–0.98), water collected (δcol=0.48–0.97), energy consumption (3.5–6.8 kJ g^{-1})	Solovyeva *et al.* (2021)
CGF-mixed-MOFs (Al)	0.25/0.31/0.37 g g^{-1} (20%/25%/30% RH)	Cycling stability (50 cycles), high temperature (56°C), AWH efficiency (87.5%), exposing more active absorption sites for harvesting water	Luo *et al.* (2022)
FO@HK	8.0/11.8 L kg^{-1} MOFs h^{-1} (20%/30% RH)	Daily water production (264.8 mL d^{-1} outdoor), energy- and time-efficient sorbents for AWH	Kang *et al.* (2024)
UiO-66@MIL-101(Cr)	0.408 g g^{-1} (25°C/30% RH)	Daily water production (1.336 kg m^{-2} d^{-1} outdoor), good water-harvesting cycle stability, adaptable and portable	Su *et al.* (2024)
PCC-42	0.45/0.59/0.76 /0.9 g g^{-1} (20%/30%/40%/50% RH)	Harvest content (1.13 L kg^{-1} MOFs at 30–60% RH), release 80% of the captured water within 50 min under 1-sun, wide adaptability, excellent photothermal performance	Hu *et al.* (2023)
Seawater desalination			
FMOFs	16.18 L cm^{-2} d^{-1} MPa^{-1}	Ion rejection (>95%), transport mechanism (fast transport and oscillatory jump), excellent water permeability	Chen *et al.* (2021)
TA-ZIF-8	64.56 L m^{-2} h^{-1}	Salt rejection (99.5%) at 5.5 MPa, good hydrophilicity, high membrane stability	Lai *et al.* (2024)
Fe-MOFs-74/Cu	1.35 kg m^{-2} h^{-1}	Light absorption (83.8%), low thermal conductivity (0.1730 W m^{-1} K^{-1}), conversion efficiency (81.5%), salt resistance, stable evaporation performance	Wang *et al.* (2021a)
UiO–66-$(NH_2)_2$	2.34 kg m^{-2} h^{-1}	Conversion efficiency (86.5%), evaporation efficiency (97.4%), good evaporation performance and applicability	Shao *et al.* (2025)
Cu-CAT	1.71 kg m^{-2} h^{-1}	Salt rejection (99.9%), energy utilization (81%), achieve 88°C under solar illumination (1 kW m^{-2}), excellent stability and durability	Li *et al.* (2024d)
CuS@MIL-100	2.37 kg m^{-2} h^{-1}	Evaporation efficiency (94.4%), superior photocatalytic degradation (97.3% MB, 93.3% TC), decontamination and energy-efficient freshwater	Shu *et al.* (2024)
Ammonia synthesis			
Cu_1Co_1HHTP	299.9 μmol h^{-1} cm^{-2}	Electrochemical nitrogen reduction reaction, NO_3^- concentration (0.1 mol L^{-1}) at –0.6 V, $FE_{(NH3)}$ (96.4%), efficient and catalytic stability	Liu *et al.* (2023b)
CoP/Zn-ZIF	0.89 mmol cm^{-1} h^{-1}	Electrochemical nitrogen reduction reaction, NO_3^- concentration (0.1 mol L^{-1}) at –1V, $FE_{(NH3)}$ (97%) in neutral condition, high catalytic performance	Zhang *et al.* (2024a)
Fe_2Co-MOFs	2,0653.5 μg h^{-1} mg^{-1}	Electrochemical nitrogen reduction reaction, NO_3^- concentration (50 g L^{-1}, pH 1) at –1.1 V, $FE_{(NH3)}$ (90.6%), NH_3-selectivity (98.5%), good catalytic stability (75 h)	Lv *et al.* (2023)
GSCe	3.06 mmol L^{-1} (24 h)	Photocatalytic ammonia synthesis (LED light source 365 nm, 3.5 mW cm^{-2}), apparent quantum efficiency (9.25%), high stability, eco-friendly solar nitrogen fertilizers	Liu *et al.* (2022)
Ca^{2+}-doped UiO-66	759.3 μmol h^{-1} g^{-1}	Photocatalytic ammonia synthesis (300 W Xenon lamp), promote the efficiency of charge transfer, high photocatalytic activity	Tan *et al.* (2023)
Ni-Co MOFs	88.2 μmol g^{-1} min^{-1}	Plasma-assisted ammonia synthesis (DBD reactor, N_2 and H_2 flow 66 mL min^{-1}, 15 W), outstanding stability and cycling performance (36 h, 24 cycles)	Jing *et al.* (2024)

optimally near neutral pH, restricting their applicability. To overcome these challenges, trinuclear Fe-cluster-based MOFs (Fe_2M-MOFs, M=Fe, Co, Ni, Zn) were developed for acidic conditions (pH=1) (Lv *et al.* 2023). Among them, Fe_2Co-MOFs achieved 20,653.5 μg h^{-1} mg^{-1} NH_3 yield, 90.6% Faradaic efficiency, and >75 h stability, and the resulting ammonia was convertible into ammonium sulfate fertilizer. For photocatalytic nitrogen fixation, graphene-embedded Ce-UiO-66 (GSCe) utilized UV-induced bond cleavage and enhanced N_2 adsorption, yielding 3.06 mmol L^{-1} NH_3 over 24 h, with pot experiments confirming improved rice growth (Fig. 7-D) (Liu *et al.* 2022). Ca^{2+}-modified UiO-66 increased Zr electron density and charge separation, boosting NH_3 yield to 759.3 μmol h^{-1} g^{-1} (7×pristine MOFs) (Tan *et al.* 2023). Furthermore, plasma-assisted Ni–Co MOFs further offered scalable, durable production routes (Jing *et al.* 2024). Despite such progress, MOFs-based ammonia synthesis requires structural stabilization for recyclability, composite and derivative optimization for enhanced activity, and cost-effective, eco-friendly designs for agricultural implementation.

In addition to atmospheric water harvesting, seawater desalination, and ammonia synthesis, MOFs offer promising solutions for the sustainable reuse of agricultural waste (Fig. 7-E). Adsorbed metals (e.g., Zn, Fe, Ni) from wastewater could be reused as micronutrient fertilizers. Recovered nitrates/phosphates from eutrophic water serve

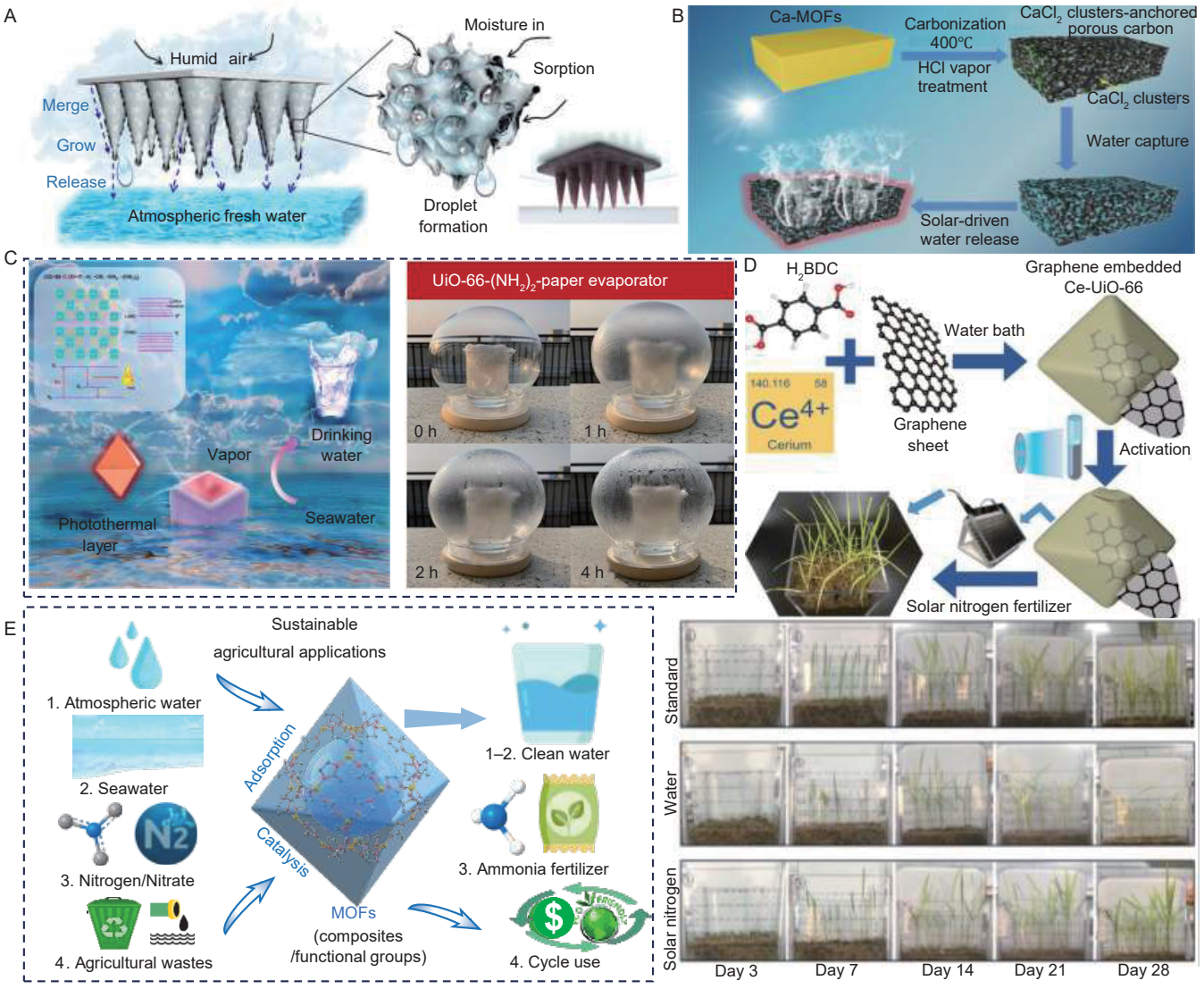


Fig. 7 Sustainable agricultural applications of metal-organic frameworks (MOFs). A, schematic illustration of capture water by PCA-MOFs cone array (Yilmaz *et al.* 2020). B, synthesis of PCC-42 sorbents (Hu *et al.* 2023). C, photothermal desalination process and outdoor evaporation experiments based on Shao *et al.* (2025). D, synthesis of GSCe photocatalyst and pot experiments at nitrogen fertilizer/pure water/solar nitrogen fertilizer (Liu *et al.* 2022). E, summary of sustainable agricultural applications by MOFs.

as fertilizer inputs. Captured contaminants (e.g., pesticides, antibiotics) could be converted into controlled-release agrochemicals. Collectively, these approaches promote circularity, optimizing both water and input utilization. Future advances in MOFs-based AWH, seawater desalination, and ammonia synthesis should prioritize long-term stability, composites engineering, functional groups optimization and eco-friendly scalability.

3.3. Smart agricultural applications of MOFs

Smart agriculture demands precise pesticide and fertilizer control and intelligent monitoring of products and environments. MOFs, with its porous structure, abundant active sites, designability and ease of assembly, makes it possible to achieve these smart applications. Current advances in fertilizer/pesticide slow-release and sensing systems (Table 2) demonstrate their pivotal role in advancing the process of smart agriculture.

Slow-release fertilizers Nutrient use efficiency in conventional fertilizers remains below 35%, resulting in resource waste, environmental pollution, and elevated costs (Lin *et al.* 2021; Yang *et al.* 2025). MOFs, with tunable porosity and stimuli-responsive design, offer promising slow-release systems for urea, phosphate, and micronutrients (Table 2). For nitrogen fertilizers, MIL-100(Fe)@CNFs-NVCL incorporated pH-sensitive cellulose nanofibers (CNFs) with a thermos-responsive N-Vinylcaprolactam (NVCL), retaining 22.8% soil moisture for 30 d with a cumulative urea release of 40.8%; MIL-100(Fe)@CNF-SA achieved 1.47 g g^{-1} urea loading, 60% cumulative release, and 17.36% moisture retention, following non-Fickian kinetics (Guo *et al.* 2021; Lin *et al.* 2021). Our team further developed a core–shell carrier MIL-100(Fe)/silica (Fig. 8-A) (Wu *et al.* 2024), which delivered

Table 2 Current researches on the smart agriculture by metal-organic frameworks (MOFs)

MOFs	Agrochemicals	Descriptions	Application	Reference
Slow-release fertilizer				
MIL-100 (Fe)@ CNFs	Urea	Retained 22.8% moisture on the 30th d, 40.8% of urea was released within a month, sensitivity to temperature and pH, promote crops growth	Wheat	Lin *et al.* (2021)
MIL-100 (Fe)@ CNF-SA	Urea	Loading capacity (1.47 g g^{-1}), retained 17.36% moisture on the 30th d, 60% of urea was released within a month	Wheat	Guo *et al.* (2021)
Urea/MIL-100 (Fe)/silica	Urea	Loading capacity (25.5%), release of accumulated nutrients (N 80% within 56 d in an aqueous solution), NUE (46%), increase production by 13%	Rice	Wu *et al.* (2024)
MOFs-303 (MBCF3)	Urea	N release periods extend to 105 d, increase production by 37.5%	Spinach	Yang *et al.* (2025)
MBCF-3	Urea	N release periods extend to 112 d, hydrophobic angle (138.2°)	–	Zhang *et al.* (2025a)
CMC/PVA-ZIF-8 TSP	Triple superphosphate	Coating (0.5% ZIF-8 NP), release of accumulated nutrients (P 12% within 5 d in soil), 16% increase in plant height	Tomato	Channab *et al.* (2024)
Fe-MOFs	N, P, and Fe	Nutrient loading (N 6.2%, P 14.6%, Fe 13.9%), release of accumulated nutrients (N 85%, P 75%, Fe 34% within 98 d in soil) for pilot scale	Rice	Wu *et al.* (2022)
ZIF-8@HA	Zn, P and Ca	Loading capacity (Zn 59.7%, P 3.4%, Ca 5.4%), release of accumulated nutrients (Zn 68% within 24 h in KB media)	Wheat	Morales-Cámara *et al.* (2024)
Slow-release pesticides				
ZIF-8	Dazomet	Loading capacity (4.4%), release situation (60/54/37% within 60 h at pH 4.8/7.2/8.5), pH responsive release	*Botrytis cinerea*	Ren *et al.* (2022)
ZnMOFs @CMC	Tbuconazole	Loading capacity (18.3%), release situation (96% within 120 h at pH 5; 75% within 120 h under cellulase), pH/cellulase responsive release	Wheat scab/ sheath blight	Sun *et al.* (2023)
PCN-777@SL/ CS	Avermectin	Loading capacity (25%), release situation (9/19/53% within 96 h at pH 7/5/9), pH/laccase/phosphate/phytic acid responsive release, photostability, high biosafety	*Spodoptera litura* Fabricius	Liu *et al.* (2023a)
DNF@ZIF8 @PMMA/Zein	Dinotefuran	Loading (16%), release situation (77/55/51% within 120 h at pH 5/7/9, release over 32 d in soil), pH/protease responsive release, UV resistance, eco-friendly	Herbivorous mole cricket	Ma *et al.* (2022)
CS-MOFs	Cycloxaprid, dsRNA	Loading capacity (27%, cycloxaprid), release situation (over 80% mortality in *Diaphorina citri* within 2 d)	Citrus greening disease	Wang *et al.* (2025)
NH_2-MIL-101 (Fe)@PCL	2,4-D, MCPA	Loading capacity (26.6 wt% for 2,4-D, 23.3 wt% for MCPA), release situation (0.09 mg kg^{-1} at 5 d; 0.07 mg kg^{-1} at 9 d in water; their PCL composites release more slowly)	Herbicides	Bhomick *et al.* (2025)
Smart sensing and detection				
NH_2-MIL-88B (Fe)	Glyphosate	Detection limit (198 nmol L^{-1}), detection ranges (1 μmol L^{-1}–1 mmol L^{-1}), high selectivity	Pesticide residues in water	Adusumalli *et al.* (2023)
UiO-66/AuNPs	Paraquat and diquat	Detection limit (6 and 3 μg L^{-1}), recovery (92.7–118.3%), good producibility and stability	Pesticide residues in cabbage	Pu *et al.* (2023)
AChE@Zn-MOFs-74	Chlorpyrifos	Detection limit (1.0 ng mL^{-1}), recovery (93.3–107.7%), activity of AChE (90%), excellent stability, superior sensitivity	Pesticide residues in river/juice	Li *et al.* (2024b)
MIL-53-Al-DHBDC	Temperature	Detection ranges (80–480 K), sensing sensitivity (0.32% K^{-1})	Temperature sensing	Li *et al.* (2024a)
PAA/TPE-EP/ UiO-66	Humidity	Detection limit (<7% RH), detection ranges (7–98% RH), rapid (<100 ms), excellent stability and sensitivity (over 10 cycles)	Humidity sensors	Zhou *et al.* (2024a)
MOFs-SEIRA	CO_2, CH_4	Response (<60 s), detection ranges (0–2.5×10^4 mg kg^{-1}), accuracy (1.1 and 0.4%), sensitivity (0.0358 and 0.0121 mg L^{-1}), all-in-one and real-time detection	Greenhouse gas sensing	Zhou *et al.* (2020)
ABTS/HRP/ ZIF-8	H_2O_2	Detection limit (510 nmol L^{-1}), detection ranges (1–100 μmol L^{-1}), rapid construction (5 min), fast detection (30 s), highly biocompatible	Reactive oxygen species sensing	Yan *et al.* (2022)
CAU-1	Ethephon	Detection limit (1 mg L^{-1}), detection ranges (2–400 mg L^{-1}), high specificity	Plant growth regulator	Zhang *et al.* (2024d)
Cu-MOF-COOH-GO	Methyl jasmonate	Detection limit (0.35 pmol L^{-1}), detection ranges (10 pmol L^{-1}–100 μmol L^{-1}), simple and low cost	Phytohormone	Xing *et al.* (2022)
flexible MOFs	Volatile organic compounds	Olfactory sensor detects VOC fingerprinting owing to it unique colorimetric mechanism; accurately identify late blight in the tomato	Late blight detection	Chen *et al.* (2022b)

(Continued on next page)

Table 2 (Continued from preceding page)

MOFs	Agrochemicals	Descriptions	Application	Reference
Eu-DMB	Tetracycline	Detection limit (0.23 μmol L^{-1}), 3 cycles, sensitive sensing towards tetracycline, good stability and adaptability	Antibiotics residues in water	Wei *et al.* (2025)
AuNCs@ZIF-8	Cu^{2+}	Detection limit (4.57 μmol L^{-1}), recovery (96.5–121.6%), easy preparation and operation, good scalability	Visual sensing Cu^{2+}	Zhang *et al.* (2024b)
Ce-bpy	Phosphate	Detection ranges (0–75 μmol L^{-1}), rapid (4–5 min) and sensitive detection	Phosphate detection	Dong *et al.* (2023)

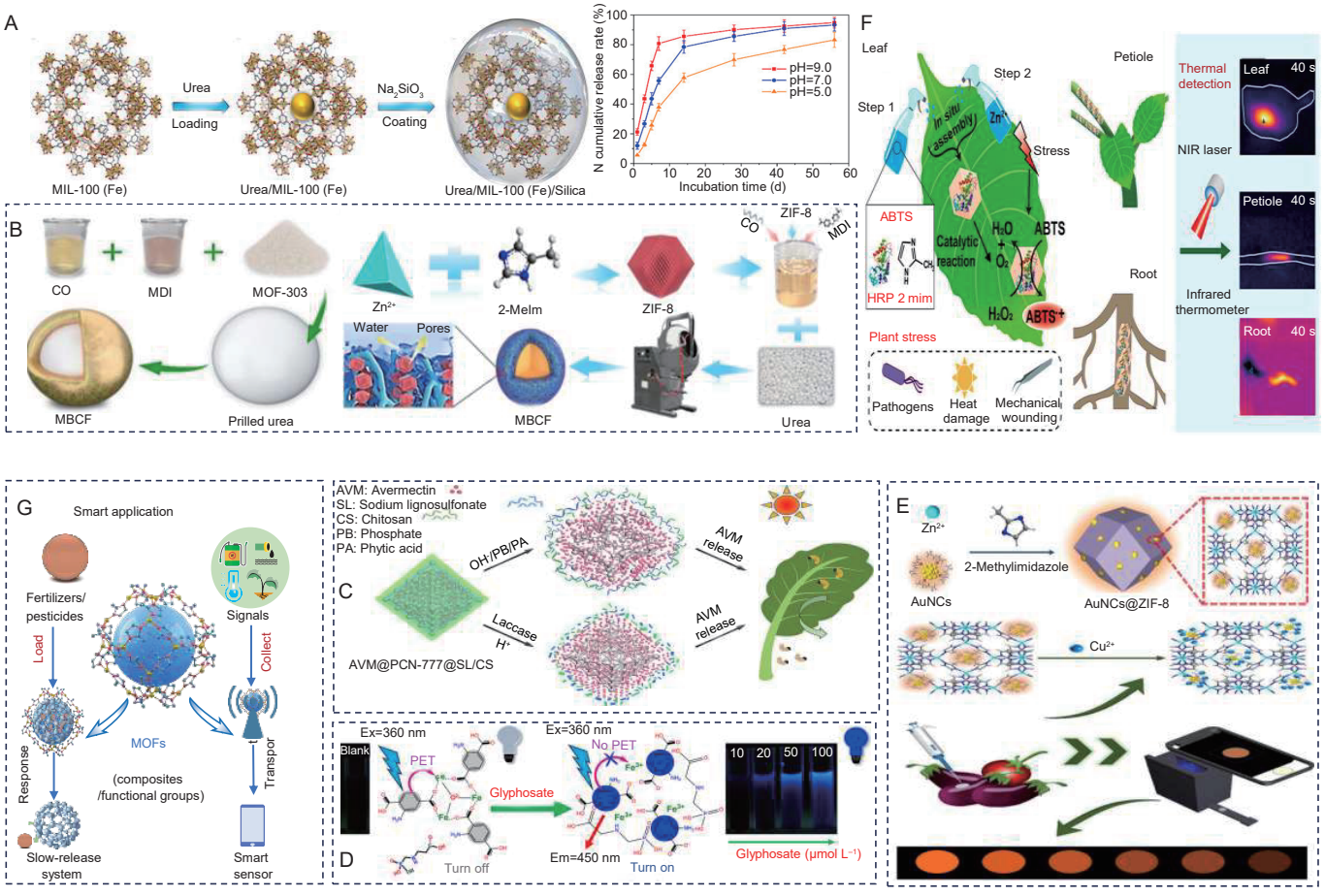


Fig. 8 Smart agricultural applications of metal-organic frameworks (MOFs). A, synthesis of urea/MIL-100(Fe)/silica and nutrient release (Wu *et al.* 2024). B, preparation of MBCF based on MOFs-303 and ZIF-8 (Yang *et al.* 2025; Zhang *et al.* 2025a). C, multi-stimulus response of AVM@PCN-777@SL/CS (Liu *et al.* 2023a). D, mechanisms of NH_2-MIL-88B (Fe) for glyphosate detection (Adusumalli *et al.* 2023). E, synthesis of AuNCs@ZIF-8 and principle and process of Cu^{2+} detection (Zhang *et al.* 2024b). F, mechanisms of ABTS/HRP/ZIF-8 for H_2O_2 detection in plants (Yan *et al.* 2022). G, summary of smart application by MOFs.

pH-responsive nitrogen release over 56 d in aqueous and >90% release within 42 d in soil, significantly boosting crop biomass. Traditional coated urea fertilizers often suffer from limited release control. Recently, MOFs-modified bio-based coatings (e.g., MOFs-303, ZIF-8; Fig. 8-B) extended controlled-release duration by optimizing pore structure and hydrophobicity (Yang *et al.* 2025; Zhang Q *et al.* 2025).

Phosphorus release has similarly been improved: a CMC/PVA-ZIF-8 coating on triple superphosphate provided controlled release for 9 d in aqueous solution and 50 d in soil at 0.5% ZIF NP, promoting tomato growth (Channab *et al.* 2024). Furthermore, MOFs have been explored for trace element delivery. An Fe-MOFs (13.9% Fe content) showed 34% cumulative iron release over 98 d, serving as a direct iron fertilizer (Wu *et al.* 2022); while ZIF-8@hydroxyapatite delivered zinc gradually while inhibiting pathogens (Morales-Cámara *et al.* 2024). Together, MOFs can not only function as carriers for nutrients such as urea and phosphate fertilizers, but also act as novel fertilizers themselves, directly supplying essential nutrients to crops. Future research should focus on precisely regulating nutrient release rates to align with crop demands and validate their effects through field experiments ensuring economic viability.

Slow-release pesticides With utilization efficiency as

low as 0.1%, pesticides are often overapplied, resulting in environmental contamination and ecological damage (Hou *et al.* 2024; Bhomick *et al.* 2025). MOFs provide advanced solutions through stimuli-responsive controlled-release systems enabled by their porosity and tunable surface chemistry (Table 2). For example, DZ@ZIF-8 achieved pH-dependent dazomet release (60% at pH 4.8 *vs*. 37% at pH 8.5 over 60 h), improving antifungal efficacy by 42.7% while reducing phytotoxicity and aquatic toxicity (Ren *et al.* 2022). Through functional modification or material compounding, MOFs can respond to multiple environmental stimuli such as pH, temperature, and enzymes. Tebu@ZnMOFs@CMC responded to cellulase and acidic pH, releasing 96% tebuconazole within 120 h, with enhanced leaf adhesion and safety compared to commercial formulations (Sun *et al.* 2023), while AVM@PCN-777@SL/CS (Fig. 8-C) combined responsiveness to pH (9% at pH 7, 19% at pH 5, and 53% at pH 9), laccase, and phosphate, yielding strong insecticidal activity and biosafety (Liu J C *et al.* 2023).

Moreover, dinotefuran (DNF) was loaded into ZIF-8 and coated with poly (methyl methacrylate) and zein protein to create DNF@ZIF-8@PMMA/Zein (Ma *et al.* 2022). This formulation had a DNF loading of 16%, exhibited dual responsiveness to protease and pH, enabled the co-release of zinc ions, and provided excellent UV protection, making it an environmentally friendly. Beyond single-agent systems, MOFs have also been applied to co-deliver dual pesticides. A notable example is a chitosan-modified MOFs loaded with both ds*ABCH6* RNA and cycloxaprid, forming a high-efficiency RNA nanopesticides (Wang *et al.* 2025). This system demonstrated potent insecticidal activity against citrus pests while overcoming the instability and poor targeting of conventional RNA agents. Similarly, NH_2-MIL-101(Fe) has also been used to load two different pesticides simultaneously (Bhomick *et al.* 2025). Therefore, MOFs significantly enhance pesticide efficiency through controlled release minimizing environmental impact, multi-stimuli responsiveness and co-delivery of synergistic agents, and future efforts should emphasize biosafety evaluation, scalable and economical manufacturing for sustainable agriculture.

Smart sensing or detection Real-time monitoring of crops and environmental conditions is essential for smart agriculture. MOFs, with tunable structures, abundant active sites, and fluorescence properties, provide versatile sensing platforms (Rojas *et al.* 2022; Yu *et al.* 2025). As summarized in Table 2, MOFs have been applied to detect signals of agrochemicals, environmental factors, and plants growth. For pesticide, NH_2-MIL-88B(Fe) achieved 198 nmol L^{-1} glyphosate detection *via* phosphate-Fe^{3+} coordination-enhanced fluorescence (Fig. 8-D) (Adusumalli *et al.* 2023), while a UiO-66/TGA–AuNP composite enabled dual sensing of paraquat and diquat (Pu *et al.* 2023). A noteworthy biosensor, AChE@Zn-MOFs-74, prepared *via in situ* acetylcholinesterase encapsulation, detected chlorpyrifos at 1.0 ng mL^{-1} with 93.3–107.7% recovery and retained 90% enzyme activity (Li H Y *et al.* 2024). Beyond pesticides, MOFs have been used to monitor antibiotics, heavy metals, and phosphates (Dong *et al.* 2023; Zhang M *et al.* 2024; Wei *et al.* 2025). For example, AuNCs@ZIF-8-based sensors can wirelessly transmit Cu^{2+} detection results to smartphones for real-time visualization, showing strong potential for use (Fig. 8-E).

Environmental monitoring has also advanced. MIL-53-Al-DHBDC and PAA/TPE-EP/UiO-66 exhibited rapid, stable responses to temperature (80–480 K) and humidity (7–98% RH) (Li D *et al.* 2024; Zhou X *et al.* 2024). Notably, a MOFs–SEIRA platform enabled rapid (<60 s) CO_2 and CH_4 field detection in the field with 1.1 and 0.4% accuracy, respectively (Zhou *et al.* 2020). Plants under abiotic or biotic stress (e.g., wounding, salinity, pathogen invasion) release signaling molecules such as H_2O_2. Monitoring these signals is critical for assessing stress responses and ensuring health growth. A biosensor based on ABTS/HRP/ZIF-8 (Fig. 8-F) detected H_2O_2 *in situ* with a 510 nmol L^{-1} LOD, 1–100 μmol L^{-1} linear range, and sub-micromolar detection within 30 s (Yan *et al.* 2022). Additionally, CAU-1 and Cu-MOFs-COOH-GO sensitively detected growth regulators (ethephon, methyl jasmonate) (Xing *et al.* 2022; Zhang Z *et al.* 2024), while flexible MOFs identified pathogen-specific volatile organic compounds (VOCs) for tomato blight diagnosis (Chen H Y *et al.* 2022). Although MOFs-based sensors have improved agricultural monitoring capabilities, they require further optimization in terms of applicability and multifunctional use.

MOFs have already demonstrated their potential in advancing smart agriculture, with applications in slow-release fertilizers/pesticides, and intelligent sensing (Fig. 8-G). Moving forward, emphasis should be placed on multifunctional MOFs composites modifications and integrated functions, green biosafety and cost optimization to advance smart agriculture.

4. Perspectives and conclusions

MOFs exhibit exceptional structural diversity and functional adaptability, making them powerful tools for advancing agricultural innovation. Their tunable metal-ligand bonding and customizable topologies, which can be engineered using AI-assisted design and HSAB principles, ensure both applicability and stability. While adsorption and catalytic processes demand robust structures, controlled-release systems require responsiveness to environmental conditions. Green synthesis techniques, including solution precipitation, sonochemistry, electrochemistry, mechanochemistry, hydrothermal and microwave-assisted methods, ensure that raw materials and solvents are biosafe, economical, and recyclable. Incorporating these processes within a circular economy framework — from resource recovery to reuse — further promotes sustainability. Beyond pollutants removal (e.g., pesticides, heavy metals, antibiotics, microplastics, greenhouse gases), MOFs contribute to sustainability through atmospheric water harvesting, seawater desalination, ammonia synthesis, and resource recovery. In smart agriculture, they function as precision carriers for fertilizers and pesticides and as sensors for pollutants, environmental conditions, and plant signals, facilitating data-driven decision-making in precision agriculture.

4.1. Perspectives

Although MOFs have made initial progress in promoting green, sustainable, and smart agriculture, several challenges remain for their widespread application (Fig. 9). Large-scale production remains limited, with high costs hindering practical use. Biosafety concerns are unresolved, as systematic toxicological studies across crops and ecosystems are scarce. Furthermore, multifunctional and context-specific applications are insufficiently explored, and the stability and recyclability of MOFs require further enhancement. The absence of regulatory guidelines and oversight also limits agricultural integration. To overcome these limitations, future studies should focus on several key directions:

Cheap, scale-up and standards The agricultural application of MOFs is constrained by high costs (e.g., UiO-66, \$89.16 g^{-1}; ZIF-67, \$155.03 g^{-1}) and inadequate large-scale synthesis technologies (Gao *et al.* 2023). Achieving low-cost, reproducible production is therefore critical. Recycling metal precursors and organic ligands from electronic waste, industrial effluents, and plastics offers a sustainable route to reduce expenses, while mother liquor recovery further improves efficiency. Conventional solvothermal remains unsuitable for scale-up due to high energy demands and long reaction times. Alternatively, solution precipitation, mechanochemical routes, and spray drying are more practical. Tuning ligand ratios and reaction parameters is critical to ensure MOFs stability at scale. To facilitate the practical agricultural application of MOFs, it is essential to establish appropriate production standards and regulatory guidelines tailored to their real-world use in agriculture.

Biosafety and eco-friendly requirements While MOFs offer promising agricultural applications, their biosafety must be comprehensively evaluated. Green precursors and sustainable synthesis methods are crucial, with unreacted ligands recovered to minimize environmental risks. MOFs may degrade under light, pH variations, or in the presence of competitive ions, releasing harmful metal or ligands that could affect plants, soil, and human health. Early studies on biosafety exist (Liu J C *et al.* 2023; Hou *et al.* 2024), but more extensive toxicological and life-cycle assessments are required. MOFs design must prioritize biocompatibility and environmental safety. Moreover, the collapse of MOFs upon cycling requires effective regeneration strategies, particularly for heavy metal-containing MOFs to prevent secondary contamination.

Multifunction application Although MOFs exhibit strong potential in pollutant removal, sustainability, and smart agriculture, most reported researches remain single-functional. With high porosity and abundant active sites, MOFs have the potential to combine multiple roles, such as catalysis, adsorption, and controlled release. Recent advances highlight this potential: dual-function MOFs capable of co-delivering pesticide and fertilizer *via* controlled release; novel MOFs with integrated sensing and removal capabilities for pesticides (Jia *et al.* 2022; Ma *et al.* 2022). Additionally, MOFs can also recover valuable nutrients such as phosphate and nitrate from eutrophic waters, subsequently reusing them as slow-release fertilizers, promoting resource recycle. Advancing multifunctional MOFs is essential for enhancing agricultural sustainability and resource efficiency.

AI-assisted design and selection As MOFs advance, conventional experimental screening is insufficient for efficient development. AI offers new solutions by integrating

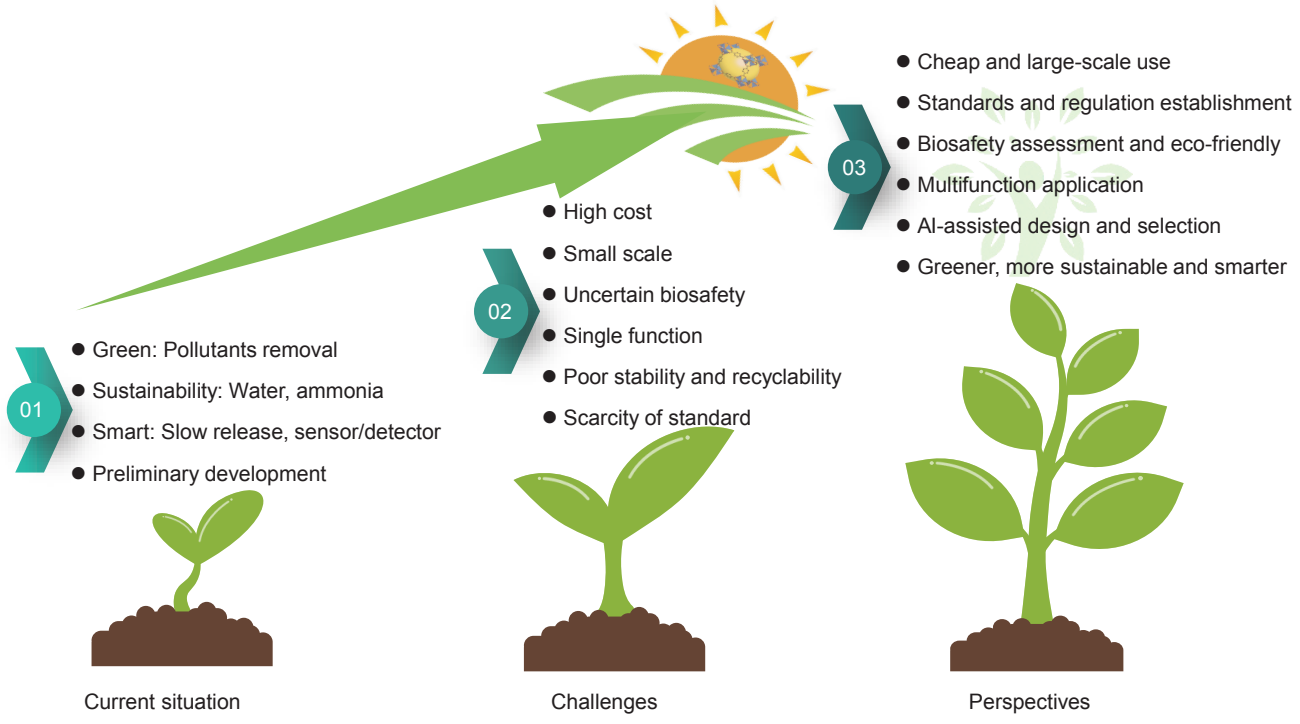


Fig. 9 Current situation, challenges and perspectives of metal-organic frameworks (MOFs) in agricultural application.

material informatics with datasets to predict MOFs performance, evaluate application outcomes, and facilitate smart agricultural decision-making. For instance, analyzing crop growth and soil nutrient dynamics enables AI to optimize the release profiles of MOFs-based pesticides and fertilizers, improving precision and sustainability. Previous studies have applied AI to improve MOFs synthesis and performance (Lan *et al.* 2019; Li Q *et al.* 2025). Extending this, AI could guide the rational design, improvement, and screening of MOFs, accelerating innovation and efficiency even in complex agricultural environments, thereby advancing their practical applications.

4.2. Conclusions

This review systematically summarizes the potential of MOFs in green agriculture. Green design and synthesis strategies of MOFs provide environmentally friendly and cost-effective approaches for agricultural use, particularly through green circular production models. For agricultural pollutants, MOFs exhibit excellent removal capabilities for pesticide, heavy metals, microplastics, greenhouse gases, and other harmful substances, ensuring both food safety and ecological health. From a sustainability perspective, MOFs also show promise in atmospheric water harvesting, seawater desalination, and ammonia synthesis. Moreover, their applications in smart agriculture such as controlled release of agrochemicals and sensing system, enhance agricultural precision and efficiency. Despite these advantages, challenges persist in large-scale production, high cost, single function and uncertain biosafety. Future research should focus on tailoring MOFs performance to specific agricultural needs through AI-assisted design, improving structural stability and biocompatibility, reducing production costs, and enabling effective regeneration and reuse. Fully realizing the potential of MOFs will accelerate the progress toward greener, more sustainable, and smart agricultural practices.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT-4o to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

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