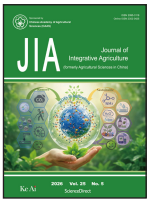
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COMMENTARY

Commentary: Roles of metal-organic frameworks in sustainable agriculture — A critical overview

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The recent review article "Green agriculture enabled by versatile metal-organic frameworks: A review" by Wan *et al.* (*Journal of Integrative Agriculture* 2026) provides a timely and comprehensive synthesis of the rapidly evolving role of metal-organic frameworks (MOFs) in addressing the pressing challenges of modern agriculture. As the global population grows and environmental degradation intensifies, the quest for sustainable agricultural practices has never been more urgent. This review not only catalogues the impressive versatility of MOFs but also frames their application within the broader paradigms of green chemistry, circular economy, and smart farming.

Holistic integration of MOFs into agricultural systems

One of the standout strengths of this review is its holistic approach. Unlike previous works that often focused on specific applications — such as nutrient utilization, pesticide delivery or pollutant adsorption — Wan *et al.* systematically explore MOFs across three interconnected domains: green pollutant remediation, sustainable resource utilization, and smart agricultural technologies. This tripartite framework effectively mirrors the core objectives of sustainable agriculture: reducing environmental harm, optimizing resource use, and enhancing precision and efficiency.

The sections on green synthesis and circular production are particularly noteworthy. By emphasizing solvent-free methods, waste-derived precursors, and energy-efficient processes (e.g., mechanochemistry, microwave-assisted synthesis), the authors align MOFs production with the principles of green chemistry. The concept of a "green lifecycle" for MOFs — from sustainable sourcing to end-of-life recycling — offers a pragmatic blueprint for reducing the environmental footprint of these materials.

Bridging the gap between laboratory and field

The review excels in translating fundamental MOFs properties — such as tunable porosity, high surface area, and stimuli-responsive behavior — into tangible agricultural applications. For instance, the discussion on MOFs-based slow-release fertilizers and pesticides highlights how structural design can be leveraged to improve nutrient use efficiency and reduce chemical runoff. Similarly, the exploration of MOFs in atmospheric water harvesting and seawater desalination addresses critical water scarcity issues, especially in arid and coastal regions.

However, the authors rightly caution that many of these applications remain at the proof-of-concept stage. The scalability of MOFs synthesis, long-term stability under field conditions, and cost-effectiveness are significant hurdles. The review's candid discussion of these challenges — including high production costs, potential biosafety risks, and the lack of regulatory standards — provides a necessary reality check for researchers and policymakers.

Critical challenges and unresolved questions

While the review thoroughly outlines the potential of MOFs, several critical issues warrant further emphasis:

Biosafety and environmental impact Although some toxicity studies are cited, the long-term effects of MOFs on soil health, microbial communities, and food chains remain poorly understood. The release of metal ions or organic ligands during MOFs degradation could pose unintended risks. Future research must integrate ecotoxicological assessments into the design phase, ensuring that MOFs are not only effective but also environmentally benign.

Economic viability and scale-up The high cost of MOFs,

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often cited as a barrier, must be contextualized within their lifecycle benefits. For example, MOFs-based slow-release fertilizers may reduce the frequency of application and mitigate environmental cleanup costs. However, without large-scale, low-cost production methods — such as continuous flow synthesis or the use of industrial waste streams — MOFs may remain confined to niche applications.

Multifunctionality and system integration The review touches on the potential for multifunctional MOFs (e.g., materials that combine pollutant adsorption with nutrient delivery). Yet, the integration of MOFs into existing agricultural infrastructures — such as irrigation systems, soil amendments, or precision farming platforms — requires interdisciplinary collaboration. Engineers, agronomists, and data scientists must work together to design MOFs-based solutions that are compatible with real-world farming practices.

Future directions: beyond the laboratory

The perspectives section of the review thoughtfully outlines a roadmap for future research, including AI-assisted design, improved recyclability, and the development of multifunctional MOFs. To this, we might add:

Digital agriculture integration MOFs-based sensors could be linked to internet of thing (IoT) platforms for real-time monitoring of soil health, crop stress, and pollutant levels. This would enable dynamic, data-driven decision-making in precision agriculture.

Policy and regulation As MOFs move toward commercialization, clear regulatory guidelines for their use in agriculture must be established. This includes standards for safety, efficacy, and environmental impact.

Circular economy models Future work should explore closed-loop systems where MOFs are regenerated, repurposed, or safely degraded after use. For example, spent MOFs could be converted into soil conditioners or carbon capture materials.

Conclusion

Wan *et al.* have delivered a masterful review that consolidates the state-of-the-art in MOFs-enabled agriculture while thoughtfully addressing the field's challenges and opportunities. This work serves not only as a valuable reference for researchers but also as a call to action for interdisciplinary innovation. By bridging materials science with agronomy, environmental engineering, and digital technology, MOFs hold the promise of transforming agriculture into a more sustainable, efficient, and resilient system. The path forward will require not only scientific ingenuity but also collaborative efforts across academia, industry, and policy to ensure that these advanced materials realize their full potential in feeding the world without harming the planet.

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

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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