frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 16 October 2025
DOI 10.3389/fsufs.2025.1711141



OPEN ACCESS

EDITED AND REVIEWED BY
Maryke T. Labuschagne,
University of the Free State, South Africa

*CORRESPONDENCE
Mohamed Ait-El-Mokhtar
✉ mohamed.aitelmokhtar@univh2c.ma
Raffaella Balestrini
✉ raffaellamaria.balestrini@cnr.it
Marouane Baslam
✉ mmm.baslam@gmail.com

RECEIVED 23 September 2025
ACCEPTED 03 October 2025
PUBLISHED 16 October 2025

CITATION
Ait-El-Mokhtar M, Balestrini R and Baslam M (2025) Editorial: Innovative solutions for next-generation fertilizers.
*Front. Sustain. Food Syst.* 9:1711141.
doi: 10.3389/fsufs.2025.1711141



# Editorial: Innovative solutions for next-generation fertilizers

Mohamed Ait-El-Mokhtar[1]*, Raffaella Balestrini[2,3]* and Marouane Baslam[4,5]*

[1]Laboratory of Biotechnology, Agri-Food, Materials, and Environment (LBAME), Department of Biology, Faculty of Science and Techniques—Mohammedia, Hassan II University of Casablanca, Mohammedia, Morocco, [2]Institute for Sustainable Plant Protection, National Research Council (CNR-IPSP), Torino, Italy, [3]Institute of Biosciences and Bioresources, National Research Council (CNR-IBBR), Bari, Italy, [4]Center of Agrobiotechnology and Bioengineering, Research Unit labelled CNRST (Centre AgroBiotech-URL-7 CNRST-05), Cadi Ayyad University, Marrakesh, Morocco, [5]GrowSmart, Paul van Vlissingenstraat 10 F, Amsterdam, Netherlands

KEYWORDS

**next-generation fertilizers, nutrient use efficiency, microbial biofertilizers, biostimulants, controlled/slow release fertilizers, nano-fertilizers, nanotechnology in agriculture, sustainable crop production**

Editorial on the Research Topic
Innovative solutions for next-generation fertilizers

Feeding a global population approaching 10 billion by 2050 requires not only more food but smarter ways of producing it. Fertilizers remain at the heart of agricultural intensification, yet their current forms contribute heavily to nutrient losses, greenhouse gas emissions, and soil degradation. The challenge is clear: to develop next-generation fertilizers that are efficient, affordable, and environmentally responsible, thereby aligning productivity with sustainability.

The Research Topic "*Innovative Solutions for Next-Generation Fertilizers*" assembled 14 contributions-—13 original research articles and one review—reflecting the breadth of strategies being developed worldwide. Collectively, these studies span microbial biotechnology, nanotechnology, soil amendments, and bioactive inputs for stress tolerance. Together, they form a broad, interdisciplinary picture of how fertilizer research is evolving toward resilient, climate-smart agriculture.

One of the strongest themes in this collection is the role of microbial and bio-based fertilizers. The review by Alori et al. set the stage by discussing the potential of cell-free supernatants (CFS) derived from plant growth-promoting microbes. Unlike live inoculants, which often fail due to survival and formulation challenges, CFS retain bioactive metabolites capable of enhancing plant growth, conferring stress tolerance, and suppressing pathogens. This positions CFS as an underexplored yet promising avenue for sustainable agriculture. Building on this microbial focus, Khattak et al. reported the isolation of *Bacillus velezensis* strain ARF4, which proved highly effective against *Verticillium* wilt in eggplants. The strain produced a suite of antifungal metabolites and hydrolytic enzymes, visibly deforming fungal hyphae, and ultimately reduced disease severity by nearly 70% in greenhouse trials. Such results highlight how biological alternatives can displace fungicides in disease management. Bitire et al. evaluated the inoculation of *Bradyrhizobium japonicum* in Bambara groundnut across two Nigerian regions and cropping seasons. Their findings showed that rhizobial inoculation not only improved plant height and biomass but also significantly increased yields compared with urea fertilization, demonstrating that biofertilizers can provide affordable, environmentally friendly options for smallholder farmers. Similarly, de Andrade da Silva et al. tested soybean co-inoculation with several plant growth-promoting bacteria, including *Bacillus subtilis* and Streptomyces species. While the yield differences were modest compared with mineral fertilization, the inoculated plants displayed profound shifts in root microbiome composition, particularly enhanced colonization by *Bradyrhizobium*. This suggests that microbial consortia may exert their benefits by reshaping rhizosphere communities rather than direct yield gains. Finally, Barua et al. pioneered a high-throughput microwell recovery array (MRA) platform to identify beneficial microbial consortia within the maize rhizobiome. Using this approach, they uncovered combinations of bacteria—mainly from *Acinetobacter*, *Enterobacter*, and *Serratia* genera—that improved *Azospirillum brasilense* colonization and accelerated maize seedling growth. This study demonstrates a scalable route for assembling robust microbial consortia as next-generation biofertilizers. Together, these works illustrate how the frontier of microbial fertilization lies not in single strains but in engineered communities and metabolite-based solutions designed to deliver consistent results in the field.

Another prominent theme is the development of advanced delivery systems and nanotechnology-enabled fertilizers. Baral et al. investigated nano-ZnO–coated urea combined with green manuring in Basmati rice. Their field trials showed yield increases of over 30% compared to conventional practices, along with improvements in grain quality and nutrient uptake, revealing how nanomaterials can work synergistically with organic soil amendments to optimize nutrient use efficiency. Elshayb et al. took a different approach by formulating chitosan-based NPK nanostructures as foliar applications. Remarkably, they demonstrated that applying chitosan-NPK at 300 ppm allowed for a 30% reduction in synthetic fertilizer use without compromising rice yield or nutrient content. Hu et al., meanwhile, focused on fertilizer application methods by testing localized nitrogen supply (LNS) with controlled-release urea in rice paddies. They showed that root-zone fertilization dramatically increased nitrogen uptake and chlorophyll content while reducing nitrogen leaching by half compared to farmer practices. These findings collectively demonstrate how nanotechnology, controlled-release coatings, and spatially optimized application methods are redefining fertilizer efficiency, moving away from bulk nutrient application toward precision nutrient management.

Soil amendments and nutrient cycling also featured prominently in this Research Topic, reflecting the growing recognition that sustainable fertilization must be rooted in long-term soil health. Zhang et al. investigated the integration of soybean green manure with moderate reductions in synthetic N and P inputs. Their two-season pot study revealed that wheat yields were maintained while soil organic C increased by more than 12%, alongside significant gains in microbial biomass and labile C fractions. Adhikari et al. evaluated the impact of reduced rates of mustard meal and dried molasses in strawberry systems in North Carolina. Even at half the conventional application rates, these organic amendments improved soil bacterial diversity and produced marketable yields comparable to chemical fumigation, demonstrating both economic and ecological benefits. In sugarcane, Bhatt et al. tested polyhalite, a multi-nutrient mineral fertilizer rich in potassium, calcium, magnesium, and sulfur. Their trials showed improved cane yield, better juice quality, and reduced pest incidence compared with muriate of potash, particularly under nutrient-deficient semiarid soils. These contributions underscore the importance of reintroducing organic matter, diversifying nutrient sources, and balancing multi-nutrient deficiencies as part of next-generation fertilizer strategies.

A fourth cluster of studies focused on how innovative fertilizers can confer stress resilience and improve crop quality. Xiao et al. examined silicon foliar sprays during strawberry propagation under high-temperature stress. Their results showed that continuous silicon application improved photosynthesis, enhanced antioxidant enzyme activity, and increased sugar accumulation, with sprayed daughter plants performing best under 43 °C heat stress. In greenhouse sweet pepper, Tahmasebi et al. compared microbial-based fertilizers with conventional chemical programs and found that biological treatments significantly enriched the fruits' nutritional and nutraceutical qualities, including higher antioxidant activity and mineral content. Oddi et al. tested the combined use of arbuscular mycorrhizal fungi inoculation and chito-oligosaccharides in meadow restoration. They observed not only higher root colonization and improved early plant establishment but also greater species evenness and long-term productivity, demonstrating the ecological potential of bioactive fertilizers in biodiversity-based systems. These studies highlight how fertilizers can be designed not only as nutrient suppliers but also as enhancers of resilience, quality, and ecosystem function.

Taken together, the 14 contributions in this Research Topic make clear that next-generation fertilizers are not defined by a single innovation but by the convergence of multiple approaches: microbial inoculants and metabolites, nanostructured carriers, controlled-release formulations, organic and mineral amendments, and bioactives that confer stress tolerance and quality benefits. A unifying message is that the fertilizers of the future must not only feed crops but also regenerate soils, strengthen resilience, and reduce environmental impacts.

Looking ahead, the central challenge lies in scaling these solutions. Laboratory and greenhouse successes must be validated under real-world conditions, adapted to diverse agro-ecological zones, and made affordable for smallholder farmers. Policy frameworks, farmer-centered innovation, and interdisciplinary collaboration will be critical to ensure that these technologies are not only developed but also deployed at scale.

We thank all contributing authors and reviewers for their invaluable efforts. This Research Topic demonstrates that fertilizers can no longer be regarded as simple yield enhancers but must be seen as tools for sustainability, resilience, and food security in the decades ahead.

## Author contributions

MA-E-M: Writing – original draft. RB: Writing – review & editing. MB: Writing – review & editing.

## Conflict of interest

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