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Editorial: Sustainable nutrient management under climate change

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Editorial on the Research Topic:
Sustainable nutrient management under climate change

1 Introduction

As the sector most intimately tied to climate, the agricultural sector is likely to face unprecedented challenges with regard to productivity in the wake of climate change. Ensuring sustainable nutrient management (SNM) in the face of climate variability is crucial. Fertile soils and balanced nutrient cycles are fundamental for productive farming; however, climate change threatens to destabilize such states, putting food security, farmer livelihoods, and ecosystem services at risk (Paustian et al., 2016; Geyik et al., 2023; Scherzinger et al., 2024). Additionally, climate change could alter the availability and cycling of nutrients in soil, making it challenging for farmers to predict and manage nutrient requirements, with reduced crop yields and increased production costs.

SNM is essential for global food security and environmental sustainability, especially in the context of climate change. Climate change could alter soil and water conditions, which in turn would affect nutrient availability and uptake by plants (Amelung et al., 2020). Furthermore, shifts in temperature and rainfall patterns could increase nutrient leaching, runoff, and soil erosion, and negatively impact soil health and water quality. To sustainably manage nutrients in the wake of climate change, farmers must adopt a range of practices that promote soil health, conserve water, and reduce nutrient losses (Koch et al., 2012).

One of the major SNM challenges is overuse and misuse of synthetic fertilizers. Whereas synthetic fertilizers enhance crop yield in the short term, they could case nutrient imbalance, soil degradation, and water pollution in the long term. In addition, excessive synthetic fertilizer use contributes to greenhouse gas (GHG) emissions and affects climate change. SNM practices should be explored and farmers encouraged to adopt them in crop production activities.

Economic and policy incentives for SNM practices are often weak or non-existent. Without appropriate incentives, many farmers may not adopt SNM practices. Overall, addressing such challenges requires concerted effort from farmers, researchers, policymakers, and other stakeholders, in the forms of SNM practice promotion, technical support and training, and formulation of appropriate policies and incentives.

SNM improves crop productivity, reduces production costs, and minimizes the adverse environmental impacts of agriculture, such as GHG emissions and water pollution. In addition, by adopting SNM practices such as crop rotation, cover cropping, and precision nutrient management, farmers could improve soil health, conserve water, and reduce nutrient loss.

2 Climate-nutrient nexus

Climate change alters the availability, efficiency, and demand for nutrients in agricultural systems. Increases in temperature, altered precipitation patterns, and increased frequency of extreme events such as floods and droughts influence soil nutrient dynamics, microbial activity, and plant nutrient uptake (Gu et al., 2024). For instance, higher temperatures accelerate organic matter decomposition, potentially increasing nutrient mineralization, while also increasing nutrient leaching and volatilization. Drought conditions can limit the microbial processes essential for nitrogen (N) fixation, whereas excessive rainfall can wash away valuable nutrients, especially N and P, leading to eutrophication (Zhang et al., 2015).

SNM practices influence GHG emissions, establishing a two-way interaction. For example, nitrogenous fertilizers are a major source of nitrous oxide (N_2O), a GHG with a global warming potential nearly 300 times that of carbon dioxide. Thus, improper nutrient input not only compromises productivity but also exacerbates climate change, creating a vicious feedback loop (Xu et al., 2025).

3 Shortcomings of conventional nutrient management strategies

Conventional nutrient management strategies depend primarily on chemical fertilizers and generalized basic recommendations, and they have currently reached their ecological and economic limits. Globally, irrational fertilization, whether through overuse or underuse, has led to a primary decline in soil health, increased input costs, and diminished returns. In India, China, and many African nations, excessive N use in some areas leads to pollution, whereas in others, nutrient deficiencies cause chronic yield gaps (Snapp et al., 2025).

The narrow focus on macronutrients N, P, and K, while neglecting secondary nutrients and micronutrients, has skewed further soil fertility status. Combined with the continued decline in organic matter levels and increased soil degradation, the narrow focus undermines the foundation of sustainable agriculture (Woolf et al., 2010).

Climate change compounds the issues above by increasing uncertainty and variability in nutrient requirements. What worked in the past may no longer be valid under new agroclimatic conditions. Therefore, a paradigm shift is required to integrate adaptive, science-based, and locally tailored nutrient management solutions into climate-resilient agricultural strategies (Schneider et al., 2023; Herrick et al., 2024).

4 Principles of sustainable nutrient management

SNM under climate change rests on a few key principles illustrated in Figure 1, as follows:

- **Site-specific and crop-specific nutrient planning:** Instead of blanket recommendations, nutrient strategies should be tailored based on soil testing, cropping systems, climate zones, and projected weather patterns. The “5R” principle rather than the “4R” principle should be adopted, i.e., Right source, Right rate, Right time, Right place, and Right combination.
- **Integrated nutrient management:** Combining chemical fertilizers with organic fertilizers, such as compost, farmyard manure, green manure, and biochar, can improve nutrient use efficiency (NUE) and soil resilience. Integrated Nutrient Management (INM) enhances soil carbon sequestration, improves microbial diversity, and buffers crops against climate-induced stress.
- **Recycling and circularity:** Encouraging the reuse of agricultural and urban organic wastes (*e.g.*, crop residue and animal waste) could reduce dependence on synthetic inputs, while promoting sustainability.
- **Precision agriculture and digital tools:** Leveraging remote sensing, GIS, soil sensors, and mobile-based decision-support systems can enable real-time nutrient diagnostics and recommendations that can directly help smallholder farmers.
- **Climate smart fertilizer products:** Use of enhanced efficiency fertilizers, such as slow-release and stabilized formulations (*e.g.*, neem-coated urea and urease/nitrification inhibitors), can reduce N losses and GHG emissions, while maintaining crop yields.
- **Capacity building and extension:** Empowering farmers with knowledge, training, and institutional support is vital for adoption SNM practices.

5 Research and policy gaps

SNM focuses on optimizing NUE, minimizing environmental impacts and improving soil health along with enhancing crop productivity. The key study under this Research Topic on the sugar alcohol-chelated calcium fertilizer in tobacco demonstrates improved nutrient uptake and crop quality aligning with SNM’s efficiency goals (Sun et al.). The present research on wheat cultivars under the graded nitrogen levels (Gawdiya et al.) and the combined use of nitrogen fertilizer and biochar highlights nutrient efficiency and reduced greenhouse gas emissions, supporting both productivity and environmental stewardship which is well presented in this Research Topic (Yang et al.). The two Costa Rican studies on urease inhibitors address nitrogen losses and emissions, keenly reinforcing principles of emission reduction and nitrogen management (Pérez-

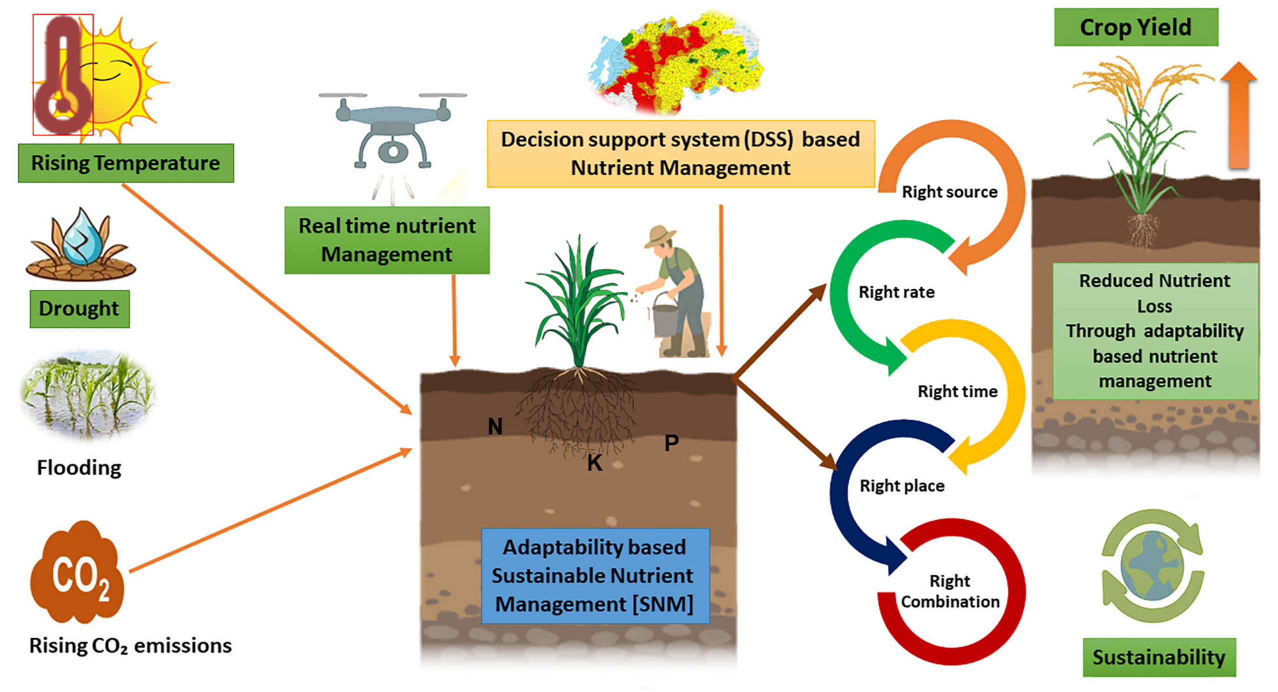

FIGURE 1
Systematic sustainable nutrient management approach under climate change.

Castillo et al.; Giraldo-Sanclemente et al.). The papers presented in the Research Topic on phosphorus and potassium use in Ghana and integrated nutrient strategies in lowland paddy systems (using Azolla, rice straw and NPKS) focus on nutrient recycling and adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet have been well discussed which is core relevant with soil health elements of SNM (Akinseye et al.; Awuni et al.; Marzouk et al.). While the need for SNM is clear to globally, several research and policy gaps remain (Vermeulen et al., 2019). First, long-term field studies on nutrient-climate interactions are limited, especially in tropical and semiarid regions. More transdisciplinary research is required to understand how climate variability affects nutrient cycles across different soil types, cropping systems, and socio-economic contexts. Second, national fertilizer subsidy policies often distort nutrient use patterns by favouring certain fertilizers (notably urea). This encourages irrational application and reduces the incentive to adopt INM or organic sources. Reforming subsidies to promote balanced fertilization and environmental sustainability is essential.

Third, the institutional mechanisms for monitoring soil fertility and NUE at scale are weak. Reinforcing national soil health initiatives, integrating climate-resilient nutrient indicators into monitoring frameworks, and making soil data openly accessible could improve policy planning and field-level decision-making considerably.

Fourth, gender and equity dimensions are often overlooked in nutrient management programs. Female farmers, who play a crucial role in soil and crop management, require targeted support, access to extension services, and decision-making power to implement sustainable practices.

6 Conclusion

The climate crisis has forced us to rethink every facet of agriculture. Nutrient management, which is often taken for granted in policy and practice, should be examined from a climate perspective. By embracing sustainable, inclusive, and knowledge-driven nutrient strategies, resilient food systems that serve both people and the planet can be established. The time to act is now before the invisible threats posed by unsustainable nutrient management unravel under the weight of a changing climate.

Author contributions

HJ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. VR: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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