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Editorial: Integration of legume intercropping into sustainable farming systems for nitrogen fixation, soil health, and climate resilience

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Editorial on the Research Topic
Integration of legume intercropping into sustainable farming systems for nitrogen fixation, soil health, and climate resilience

1 Introduction

Soil health describes a soil's capacity to function within its ecological boundaries—supporting plant growth, sustaining water and air quality, and maintaining robust microbial and animal life. It's critical to ecosystem's ability to deliver services such as food production, nutrient cycling, carbon storage, and biodiversity support (Pinto et al., 2017). Unfortunately, converting native landscapes into monocultures and relying heavily on synthetic fertilizers depletes soil organic matter, damages microbial communities, and lowers water retention, weakening these essential services.

The incorporation of legumes in various cropping systems holds immense potential for addressing numerous challenges in modern agriculture, from improving soil health to enhancing crop yields and combating climate change. As biologically nitrogen-fixing crops, legumes naturally enrich the soil and reduce dependence on chemical fertilizers. They also enhance soil structure, promote microbial life, suppress insect pests and weeds, improve water use efficiency (Kokkini et al.; Akchaya et al.; Rajpoot et al., 2016), improve crop nutritional quality and production sustainability (Nuemsi et al., 2018). These "service crops" align with the economic, social, and environmental goals of sustainable agriculture. Despite its potential, the adoption of legume intercropping remains limited by the lack of suitable adaptation strategies across various climates and socio-economic contexts (Akchaya et al.). Practical agronomic recommendations, such as optimal spacing, sowing methods, and management based on local conditions, are still emerging as research advances.

This Research Topic aimed to address these needs by compiling high-quality contributions provided by individual studies and reviews on the subject of legume intercropping and its role in sustainable agricultural practices. These works focus on: (i) Nutrient cycling and nitrogen fixation, human-centered ecosystem services, (ii) Soil quality and physico-chemical properties, (iii) Crop productivity and resilience, (iv) Microbial and pest interactions, and (v) Resource use efficiency and climate adaptation.

2 This Research Topic

This collection brings together nine insightful contributions that explore the ecological and agronomic roles of legume intercropping across diverse farming systems, from rice-fallows in India to maize–peanut fields and high-altitude grasslands.

Greening rice–fallow systems: Kumar et al. reviewed the potential of integrating pulses (e.g., chickpea, lentil) and oilseeds (mustard, safflower) into post-rainy fallow lands in eastern India. They emphasize that deploying short-duration, low-water-demand crops on the 11–12 million hectares of rice-fallow lands can significantly boost land-use efficiency, enhance system productivity, and support smallholder livelihoods with clear policy implications for sustainable intensification**.** Legume Intercropping and Ecosystem Services: Kokkini et al. presented a compelling mini-review on how legumes improve ecosystem services. The authors highlighted that intercropping legumes contributes to improved soil structure, enhanced microbial biodiversity, superior water retention, natural pest suppression, pollination, and biodiversity support, along with various human-centered services such as disease prevention, reduced risk of malnutrition, and food security, showcasing the deep ecological benefits these crops support.

Akchaya et al. systematically evaluated the role of legume-based intercropping in enhancing soil fertility, resource use efficiency (land, water, and nutrients), and climate resilience. Their study reported nitrogen fixation rates ranging from 50 to 300 kg N ha^{-1} $year^{-1}$, alongside improvements in nutrient and water efficiency and overall yield advantages. These benefits were attributed to ecological mechanisms such as bio-littering, bio-plowing, bio-irrigation, and bio-pumping, which contribute to better nutrient cycling, soil conservation, and agroecosystem stability. However, the authors also noted challenges related to the complexity of managing multiple crops simultaneously.

Soybean rhizosphere microbiome: Han et al. explored how different soybean genotypes shaped the assembly of rhizosphere microbes and their subsequent influence on yield traits. They reported that the M579 genotype exhibited the highest bacterial alpha diversity. Their findings underscore the importance of cultivar selection in maximizing beneficial microbiome interactions correlating with yield. Maize–Peanut Strip Width Optimization: Sun et al. analyzed strip spacing in maize–peanut systems, demonstrating that four rows of peanut and four rows of maize (row spacing of 50 cm) maintained the highest water use efficiency significantly, influencing the edge effects of rainfall-redistribution, improving crop and land productivity. Summer legume residual effects: Sunil Kumar et al. investigated the residual impacts of summer legumes on kharif rice. They found that such rotations enhance nutrient availability and efficiency for the following rice crop, underscoring the value of thoughtful cropping sequence design. Rice Fallow Sowing Strategies: Jaya Singh et al. examined seed rates and timing in machine-harvested rice fallows, finding that a 20% increase in seed rate resulted in higher grain yield and straw yield among the blackgram treatments, showing tailored sowing approaches improve crop establishment and yield potential in these challenging environments.

High-altitude legume–grass nitrogen fixation: Luo et al. demonstrated that mixtures of legumes and grasses enhance nodulation and nitrogen transfer, root system configuration bolstering system productivity under low-temperature stress. Soil legacy effects on maize: Jalloh et al. revealed that previous edible legume intercropping can reduce *Spodoptera frugiperda* damage in subsequent maize crops, highlighting how soil history influences pest dynamics and crop resilience.

3 Concluding remarks/future directions

The studies compiled in this Research Topic underscore the diverse and essential ecosystem services offered by legumes when integrated into intercropping systems. From enhancing nutrient cycling and biological nitrogen fixation to improving soil structure, microbial activity, and crop resilience, legumes consistently demonstrate their potential as cornerstone crops in sustainable agriculture. The success of legume intercropping depends on many factors like local climate, soil conditions, crop combinations, and how farmers manage their fields. To make it truly effective, region-specific practices, farmer involvement, and practical recommendations are essential. Future efforts should focus on long-term studies, develop suitable agronomic packages, and explore how legumes interact with soil life, especially under changing climates. Understanding the economic trade-offs and offering market support will also help farmers adopt these systems more widely.

In conclusion, legumes offer a practical and ecologically grounded solution to many of the pressing challenges in agriculture. Their role in building resilient, efficient, and sustainable agroecosystems continues to grow, and this Research Topic contributes meaningfully to the scientific and practical understanding of their multifaceted value.

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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.

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The author(s) declare that no Gen AI was used in the creation of this manuscript.

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