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REVIEW PAPER

Applauding Soil Quality Improvement through Legume-based Intercropping System: A Review

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ABSTRACT

Intercropping is one of the ancient cropping systems that involves growing two or more crops together in the same field. Effective intercropping system management warrants to prevent crops from competing for space, moisture, nutrients, sunlight, and other resources. Combining legumes and non-legumes in an intercropping system offers significant benefits, such as reducing moisture scarcity and nutrient stress, while boosting overall productivity and soil health. Legumes play a key role in enhancing the soil's chemical, biological, and physical properties, which helps counteract the declining productivity often seen in cereal-based cropping systems. The critical factors are choosing the right intercrops, determining the optimal nitrogen doses for non-legumes, and considering the benefits of biological nitrogen fixation (BNF) from legumes. Assessing the benefits of intercropping compared to sole cropping is vital for determining agricultural productivity. Intercropping systems should be evaluated for increased crop productivity and resource-use efficiency and their impact on soil health. This review highlights the potential of legume-based intercropping systems in improving soil quality.

HIGHLIGHTS

- The combination of legumes and non-legumes can ensure multi-faceted benefits towards agricultural sustainability.
- The legume-based intercropping system can ensure the improvement of the soil health.

Keywords: Intercropping system, soil physical properties, soil chemical properties, soil biological properties, agricultural sustainability, smallholders

The global human population is projected to exceed 9.8 billion by 2050 as projected by the United Nations (UN, 2023). This significant increase poses a daunting challenge: how to feed a rapidly growing population sustainably. To address this issue, agriculture must harness scientific advancements and technological innovations developed over the years. Such progressions include precision farming, adoption of crops and cropping systems with higher productivity, and advanced irrigation techniques with soil moisture conservation, which have shown promise in enhancing agricultural productivity and sustainability (FAO, 2017; Nduwimana *et al.* 2020; Ravi Sankar *et al.* 2020; Mwakidoshi *et al.* 2021; Ray *et al.* 2024).). However, the agricultural

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sector must minimize its reliance on fossil fuels. Fossil fuel dependency is a major contributor to greenhouse gas emissions, leading to global warming, biodiversity loss, and environmental pollution. The Intergovernmental Panel on Climate Change (IPCC, 2023) and various other studies have highlighted the urgent need to reduce fossil fuel usage in agriculture to mitigate these harmful effects (Roy *et al*. 2002; Shivanna, 2022; Santosh *et al*. 2023). Transitioning to renewable energy sources and adopting more sustainable farming practices are crucial steps in this direction.

Climate change and global warming present significant threats to agriculture. Rising temperatures, unpredictable weather patterns, and increased frequency of extreme weather events can adversely affect crop yields. These changes impose abiotic stresses on crops, such as drought, heat stress, and flooding, which can severely impact food production (Baidya *et al*. 2023; Maitra *et al*. 2023a). Therefore, developing resilient crop varieties and improving farming practices to withstand these stresses are essential for ensuring food security. In addition to climate challenges, essential resources for crop production, particularly soil and water, are increasingly polluted and degraded due to improper usage and management (Tomar *et al*. 2021). Overuse of chemical fertilizers and pesticides, along with inadequate waste management, leads to soil degradation and water contamination (Mondal *et al*. 2023; Pramanick *et al*. 2021; Maitra *et al*. 2023b). This pollution reduces soil fertility and adversely affects the health of agricultural ecosystems, further complicating the challenge of sustainable agriculture.

Furthermore, there is a noticeable reduction in arable land and a scarcity of water resources for agricultural purposes. Urbanization, industrialization, and climate change contribute to the shrinkage of available agricultural land and the depletion of water resources (Samadder *et al*. 1997; Tomar *et al*. 2021). Efficient land use planning and water management strategies are essential to optimize the use of these limited resources. Balancing the need for increased food production with the preservation of soil health and environmental integrity is a critical challenge. It requires a holistic approach that integrates sustainable farming practices, soil conservation techniques, and ecosystem management (Maitra *et al*. 2001a; Lal *et al*. 2003; FAO, IFAD, UNICEF, WFP, and WHO, 2023). The goal is to enhance crop productivity without compromising soil fertility, environmental health, and food quality (Lal *et al*. 2003; Pozza and Field, 2020). Therefore, it is imperious to explore and implement ways to boost crop yields while ensuring the sustainability of soil and environmental factors. This includes adopting conservation agriculture, agroforestry, organic farming, and integrated pest management practices. These strategies not only improve productivity but also maintain ecosystem services and promote biodiversity (Maitra *et al*. 2020; Maitra and Gitari, 2020). By focusing on sustainable agricultural practices, we can address the food security challenges of the future while preserving the planet for future generations.

Enhancing plant diversity in agricultural systems is essential for sustainable farming (Cheptoek *et al*. 2021; Heydarzadeh *et al*. 2021; Cappelli *et al*. 2022; Mwadalu *et al*. 2022). Farmers frequently use synthetic nitrogen (N) fertilizers to achieve immediate crop yield enhancement (Jena *et al*. 2020; Sairam *et al*. 2023a, b). Nevertheless, the overuse and imbalance of these fertilizers can cause long-term deterioration of soil health (Maitra *et al*. 2021; Panda *et al*. 2021). Sustainable crop production in the future will likely heavily rely on legumes' ability to fix nitrogen through symbiosis (Maitra *et al*. 2023b; Jena *et al*. 2022; Pramanick *et al*. 2023; Sairam *et al*. 2023c,d). Incorporating legumes in crop rotations or intercropping them with other plants contributes to carbon sequestration, nitrogen storage, and increased biodiversity (Praharaj and Maitra, 2020). Thus, leveraging the biological nitrogen fixation (BNF) capabilities of legumes is crucial for reducing dependence on synthetic nitrogen fertilizers, as highlighted by Nieder and Benbi (2008). Additionally, this approach can help decrease the carbon footprint of agricultural production (Gan *et al*. 2011).

The goal of legume-based intercropping is to boost yields from a given area by efficiently utilizing resources that a single crop might not fully exploit (Palai *et al*. 2019; Hossain *et al*. 2022; Islam *et al*. 2023). Effective intercropping management is essential to avoid crop competition for space, sunlight, and nutrients (Maitra *et al*. 2023c). An ideal intercropping system maximizes natural resource use, increases productivity per unit area within a set timeframe, and reduces the risk of crop failure (Manasa *et al*. 2018, 2020). Intercropping typically demonstrates higher biological efficiency than sole cropping by accessing a larger volume of soil (Chamkhi *et al*. 2022). This extensive soil resource utilization enhances the overall effectiveness of intercropping systems.

Intercropping has ancient origins and plays a significant role in achieving Sustainable Development Goals (SDGs), as Maitra *et al*. (2023c) mentioned. Growing compatible crops together offers various socioeconomic, biological, and ecological benefits compared to monocropping (Maitra, 2018; Maitra, 2020; Maitra *et al*. 2019; Santosh *et al*. 2022). It enhances ecosystem biodiversity by providing habitats for insects and soil organisms absent in monoculture systems (Maitra and Ray, 2019). Natural predators like spiders and parasitic wasps help control crop pests by managing their populations (Veres *et al*. 2013). Given legumes' well-documented biological nitrogen fixation (BNF) capabilities, incorporating them into cropping systems as intercrops or sequential crops is beneficial (Mirriam *et al*. 2022; Bedoussac *et al*. 2015). Legumes improve soil fertility through BNF, reducing nitrogen competition, especially with more competitive cereals (Praharaj and Maitra, 2020; Ray and Sairam, 2024). This integration ensures complementary and efficient use of nitrogen resources (Sarkar *et al*. 2000; Panda *et al*. 2020; Sain *et al*. 2023; Priya *et al*. 2023).

Sustainable Intensification of Crops through Intercropping Systems

Intercropping applies fundamental ecological principles—diversity, competition, and facilitation—to boost crop production (Maitra *et al*. 2001a, b; Bedoussac *et al*. 2015; Mandal *et al*. 2018). Typically, intercropping systems yield higher productivity than sole cropping systems (Maitra *et al*. 2000; Panda *et al*. 2022b) because of the more efficient use of water, light, and nutrients in intercropping, leading to increased yields (Bedoussac *et al*. 2015). The different rooting patterns of cereals and legumes in intercropping systems improve water uptake and transpiration, reducing water loss through evaporation or deep percolation (Sandeep Kumar *et al*. 2019; Maitra *et al*. 2021; Chappa *et al*. 2022). Additionally, the higher leaf cover in intercropping creates a cooler microclimate through transpiration, lowering soil temperature and evaporation rates (Miao *et al*. 2016). This cooling effect is significant when soil moisture is limited, as intercropping uses available water more effectively than sole cropping (Nyawade *et al*. 2020).

Soil exploration is more efficient in intercropping systems than in single-crop cultivation (Li *et al*. 2023). Combining two or more crops results in better soil coverage, reducing weed growth, runoff, and soil and nutrient loss (Huss *et al*. 2022). In intercropping systems, crops with different competitive abilities effectively use available resources like water, nutrients, and sunlight, converting them into biomass or yield (Lithourgidis *et al*. 2011; Mugi-Ngenga *et al*. 2023; Maitra *et al*. 2023c). The performance of intercropping systems can be influenced by factors such as the choice of cultivars, seeding ratios, and the competitive interactions between crops (Maitra *et al*. 2019; Paul *et al*. 2024).

Legumes in Intercropping System: Multifaceted benefits

The cereal-legume intercropping system is often advocated as a strategy to mitigate the risk of crop failure, especially under rainfed conditions. However, its primary goal is to enhance and sustain agricultural production (Ali *et al*. 2012; Chimonyo *et al*. 2023). This method efficiently uses water, soil nutrients, and light resources, leading to higher productivity (Demie *et al*. 2022). While cereals tend to deplete nutrients from the upper soil layers (Maitra *et al*. 2019; Ladha *et al*. 2022), legumes fix atmospheric nitrogen and enrich soil fertility, reducing competition for limited soil nutrients (Jensen *et al*. 2020). Legumes also access nutrients from deeper soil layers with their extensive taproot systems (Nadeem *et al*. 2023). This intercropping practice is crucial in subsistence agriculture, providing a variety of food crops to resource-poor smallholders (McAlvay *et al*. 2022). Additionally, cereal-legume intercropping aids in soil and water conservation on marginal lands (Chimonyo *et al*. 2023), ensures yield stability (Fu *et al*. 2023), manages weeds effectively (Leoni *et al*. 2022), and enhances the quality, availability, and preservation of fodder for animal consumption (Leoni *et al*. 2022).

The diverse rooting patterns, growth characteristics, nutrient requirements, and crop durations of different plants give them the adaptability to thrive in challenging conditions. Intercropping legumes like soybeans with cereals such as maize, sorghum, and pearl millet reduces competition for essential growth factors within these systems. Additionally, the shorter stature of legumes like soybean, green gram, black gram, cowpea, and groundnut makes them suitable for intercropping with various cereals (Chikowo *et al*. 2022).

When legumes and non-legumes are grown together in an intercropping system, they should adequately prefer to utilize available resources and minimize competition fully. To ensure the success of a cereal-legume intercropping system, factors such as spatial arrangement, plant density, and the maturity of the component crops must be considered (Leoni *et al*. 2022). An additive intercropping system is used for widely spaced cereals like maize, often resulting in higher yields from the total area. Conversely, for closely spaced cereals such as rice, wheat, and finger millet, a replacement series of intercropping systems is employed, where legumes replace some cereal plants. This replacement system sometimes uses close spacing or a higher seeding rate to ensure yield benefits.

Nitrogen Transfer by Legumes to Non-legume in Intercropping Systems

When cereals and legumes are grown together in an intercropping system, the cereal's nitrogen (N) nutrition is enhanced by the transfer of biologically fixed N from the legume (Willey *et al*. 1983). This transfer helps increase the productivity and sustainability of the cereal-legume intercropping system (Zhao *et al*. 2022; Kinyua *et al*. 2023). Although cereals intercropped with legumes receive some nitrogen, it may not be sufficient for optimal growth (Stern, 1993; Crews *et al*. 2022). Information on the amount of nitrogen transferred from legumes to intercropped cereals and the optimal nitrogen dose for cereal-legume intercropping systems is limited. The extent of nitrogen uptake also depends on how much nitrogen is made available to the intercropped cereal. Determining the adequate nitrogen amount for cereal crops in intercropping systems to maximize the benefits of biologically fixed nitrogen from legumes would be valuable (Lai *et al*. 2022).

Legume-based Intercropping System for Soil Quality Improvement

Leguminous crops are known for restoring soil fertility (Bedoussac *et al*. 2015; FAO, 2023). They possess unique traits such as deep rooting, nitrogen fixation, leaf shedding, and the mobilization of insoluble soil nutrients (Ebbisa, 2022). These characteristics help improve the soil's chemical, biological, and physical properties, addressing the productivity decline often seen in continuous cereal-cereal systems (Ganeshamurthy, 2009; Savci, 2012). Integrating pulses into intensive cereal-based systems is a crucial aspect of the integrated plant nutrient supply system. Therefore, pulses provide a viable option for enhancing soil health, conserving natural resources, and promoting agricultural sustainability (Fig. 1). The impacts of intercropping pulses with non-legumes on soil physicochemical and biological properties are narrated under the following subheadings.

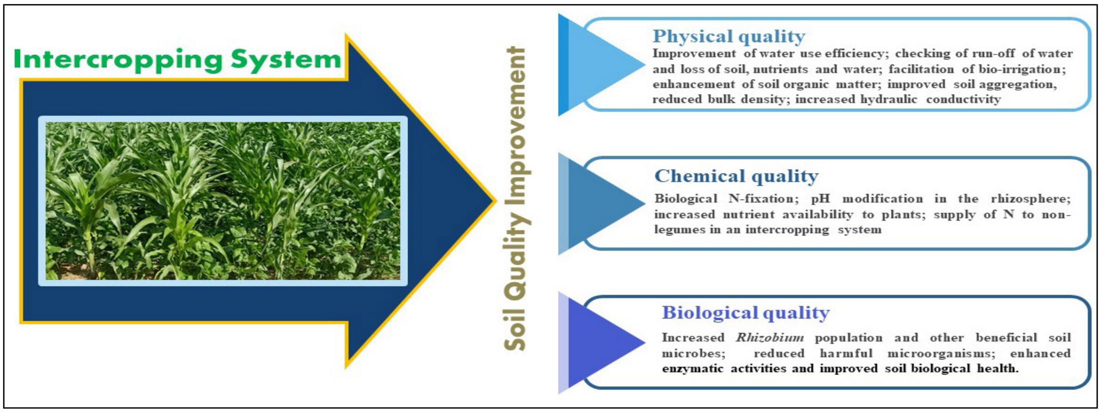

Fig. 1: Legumes-based intercropping system for the improvement of soil quality

Soil Physical Properties

Smallholder farmers favour the cereal-legume intercropping system for its flexibility, profit maximization, risk reduction of total crop failure, soil preservation, weed control, and integrated nutrient management (FAO, 2012; Rahman, 2021). Water availability is a crucial factor affecting productivity in grain legume intercropping systems. Enhancing water use efficiency (WUE) in these systems helps maximize resource use, particularly by conserving water through early foliage cover and increased leaf area (Maitra *et al*. 2023c). However, under limited water conditions, WUE in intercropping can be higher than in sole crop cultivation, which may result in reduced yields (Gou *et al*. 2017).

Intercropping with various crops helps control soil erosion by preventing raindrops from directly striking the soil surface, thereby minimizing the sealing of surface pores. This practice improves water infiltration and reduces runoff (Maitra *et al*. 2021). Experiments have shown that deep-rooted pigeon pea acts as a bio-irrigator, sharing moisture with shallow-rooted finger millet (Saharan *et al*. 2018; Singh *et al*. 2020). Chai *et al*. (2013) also noted a 95% increase in water use efficiency (WUE) in a maize-pea intercropping system compared to a pure peas stand. Taller crops in mixed intercropping systems serve as wind barriers for shorter crops, while the dense canopy of legumes functions as a cover crop. Intercropping also conserves resources and promotes soil health by reducing runoff, soil erosion, and nutrient loss (Gitari *et al*. 2019; Maitra *et al*. 2023). A higher level of ground cover in intercropping minimizes the chances of runoff, soil erosion, and nutrient loss (Nyawade *et al*. 2019; Maitra, 2020). For example, in agroforestry, Gliricidia alley cropping can reduce runoff by 28.2% and soil loss by 49.3-51.1% compared to no alley cropping. When sown in contour, the combination of finger millet and black gram showed the lowest runoff (10.2%) and minimal soil and nutrient loss, as black gram provided substantial ground cover (Dass *et al*. 2010). Legumes improve soil organic matter (SOM), enhancing soil structure, cultivability, air circulation, water retention, and buffering capacity (Vasconcelos *et al*. 2020; Kebede, 2021). The decomposition of SOM releases nutrients for plant growth and promotes better soil aggregation, stability, and resistance to erosion (Yadav *et al*. 2017). Grain legume residues with narrow carbon-to-nitrogen (C/N) ratios decompose quickly, boosting SOM and improving soil aggregation while reducing bulk density. For instance, incorporating mung bean stover in a rice-wheat-mung bean sequence decreased soil bulk density and increased hydraulic conductivity (Ganeshamurthy *et al*. 2006).

Soil Chemical Properties

Enhanced nutrient uptake in intercropping systems can occur both spatially and temporally. Spatially, increased root mass facilitates nutrient uptake, while temporally, improved nutrient uptake occurs when the nutrient demand among component crops is not synchronized. In systems where species exhibit diverse establishment and uptake behaviors, such as cereal-legume intercropping, the efficient utilization of available nutrients leads to higher nitrogen (N) uptake compared to monocrops (Fujita and Ofosu-Budu, 1996). Legumes can alter the soil pH in the rhizosphere, creating a microenvironment that enhances nutrient availability for cereals (Goyal and Habtewold, 2023). Since pulses derive a significant portion of their nitrogen from the air as diatomic nitrogen rather than from the soil as nitrate (NO_3), their overall effect is to lower soil pH.

Legume residues initially lead to some nitrogen immobilization, but their prolonged use in intercropping systems ultimately enhances soil nutrient levels by increasing Soil Organic Matter (SOM) (Wortmann *et al*. 2000; Kebede, 2021). SOM, in turn, improves soil physical, chemical, and biological properties, potentially reducing erosion and boosting water and nutrient availability (Tahat *et al*. 2020; Paramesh *et al*. 2023). The concept of nitrogen "sparing" involves legumes providing nitrogen to the intercrop. By fixing atmospheric nitrogen, legumes reduce their dependence on mineral nitrogen from the soil, thereby conserving soil mineral nitrogen for other crops, particularly cereals in intercropping systems. Certain legumes, such as pigeon pea, have robust deep roots that enable them to access plant nutrients from deep soil layers inaccessible to cereal crops. These nutrients are later returned to the soil surface through residue decomposition, supporting nutrient cycling. Additionally, beneficial rhizobacteria, known as Plant Growth Promoting Rhizobacteria (PGPR), enhance root depth and density (Baudoin *et al*. 2009), thereby enabling plants to absorb higher quantities of primary, secondary, and micronutrients from a larger soil volume (Elkoca *et al*. 2010).

Soil Biological Properties

The amount of nitrogen fixed by legumes in legume-based intercropping systems depends on several factors, including the specific legume type, crop structure, intercrop density, farming methods, and the competitive interactions between the crops. In a maize and cowpea intercropping setup, it was estimated that cowpea contributes approximately 41 kg of nitrogen per hectare to the soil through Biological Nitrogen Fixation (BNF) (Eaglesham *et al*. 1981). Additionally, Fujita *et al*. (1992) noted a 20% increase in sorghum yield in soils with high available nitrogen when intercropped with soybeans. While sorghum mainly utilizes soil nitrogen and applied fertilizers, soybeans rely heavily on BNF. Research suggests that nearby non-legumes can benefit from nitrogen transferred by legumes (Thilakarathna *et al*. 2016; Reilly *et al*. 2022; Mirriam *et al*. 2022). This nitrogen transfer occurs through root exudates, nitrogen released from leaves, leaf litter, and faunal excreta within the intercropping system (Canarini *et al*. 2019; Valenzuela, 2023). Moreover, Rhizobium species associated with legumes have been found to suppress the growth of certain soil-borne pathogens like *Fusarium* spp. and *Phytophthora* spp. (Buonassisi *et al*. 1986; Omar *et al*. 1998). The presence of Rhizobium enhances the population of other beneficial microbes such as *Pseudomonas* spp. (Hayat *et al*. 2010).

Nitrogen fixed by a leguminous crop component can become available to the cereal intercrop during the growing season, referred to as immediate nitrogen exchange (Vanlauwe *et al*. 2019; Kebede, 2021). Furthermore, the benefits to associated non-leguminous crops in intercropping systems depend on crop densities, the proximity of legume and non-legume crops, and the developmental stages of the legume (Maitra *et al*. 2021). Pulses are noted for their ability to improve the soil microbial environment (Maitra and Ray, 2019), releasing unused nitrate fixed through symbiotic nitrogen fixation into the soil (Reinprecht *et al*. 2020; Soumare *et al*. 2020). Additionally, they release low molecular weight organic compounds as exudates, which serve as substrates for soil microorganisms, thereby increasing microbial populations. Grain legumes create favourable conditions for the growth and development of soil microorganisms. The soil microbial biomass, consisting of viable microorganisms, parasites, soil microfauna, and algae, benefits from organic inputs from grain legume crops (Kumar and Goh, 2000). Soil enzymatic activity, including dehydrogenase, urease, protease, phosphatase, and β-glucosidase, is enhanced by grain legume crops (Jat *et al*. 2021; Kanté *et al*. 2021; Mir *et al*. 2023). In cereal-legume intercropping systems, interspecific facilitation in phosphorus uptake occurs when one species increases soil phosphorus availability, benefiting the intercropped companion species (Maitra and Ray, 2019).

CONCLUSION

The importance of intercropping systems involving both legumes and non-legumes is widely acknowledged for enhancing productivity, profitability, and maintaining soil health through improvements in physical, chemical, and biological soil parameters. This approach offers significant potential to increase food production on marginal and degraded lands, especially in the context of climate change in developing nations. However, effectively harnessing available resources necessitates identifying suitable cereals and legumes specific to each location and arranging them optimally. Moreover, determining the ideal nitrogen fertilizer application rates is crucial to maximizing nutrient productivity and profitability across diverse legume-nonlegume intercropping systems. To encourage widespread adoption of such intercropping systems, particularly among marginalized and resource-constrained farming communities, large-scale demonstrations and the dissemination of scientific knowledge through extension services are essential for the sustainable advancement of global agriculture.

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