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Legumes in Cropping System for Soil Ecosystem Improvement: A Review

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ABSTRACT

Legumes are versatile crops with great potential to produce protein-rich grains, naturally fix nitrogen, and enhance beneficial microbes in the soil. In the current context of climate change and global warming, incorporating legumes into crop rotation can help mitigate the negative effects of climate change and improve soil health. Researchers at the Division of Agronomy, FoA, SKUAST-J conducted a systematic and integrative review of published studies on the effects of legumes in cropping systems for soil ecology improvement. The review included research work from different parts of the world, particularly India. The literature search was conducted between August 2023 and November 2023 and around 150 review and research papers were screened from various databases such as ARCC journals, Google Scholar, Research Gate and Scopus. Out of these, 120 papers were used to write this comprehensive review article. The article provides a detailed documentation of the significant impact of legumes in cropping systems on soil ecology improvement. It emphasizes the potential effectiveness of legumes as a strategy for maintaining soil health.

Key words: Agricultural sustainability, Cropping system, Legumes, Soil health.

Agriculture is the backbone of developing nations with a prime focus on optimum productivity of crops and efficient use of natural resources in a suitable manner so that it can provide food and nutritional security in an efficient manner. After the inception of green-revolution, wheat and rice dominated the cropping systems due to promotional activities and institutional support (Maitra, 2020). As the high yielding fertilizer and resource responsive cultivars were released, agriculture shifted from "field to mouth" to "field to market". Due to productive as well as marketing advantages along with specialization of crop husbandry, farmers kept on cultivating rice and wheat years after years. This practice of sole cropping led to nutrient mining, weed and pest infestation, declining soil fertility and factor productivity *etc*. along with yield stagnation (Lal, 2016). Rapid increase in these anthropogenic disturbances always seeking to exploit the natural resources have questioned the agricultural sustainability (Verma *et al.,* 2015a). Consequently, legumes increase soil fertility through the action of microorganisms, which are imperative to affect the soil properties, including soil biological, chemical, and physical properties (Stagnari *et al.,* 2017; Nanganoa *et al.,* 2019; Vasconcelos *et al.,* 2020). Therefore, it is of prime importance to look into the overall fertility and productivity of the soil as well as agro-ecosystem.

Different perspectives on legumes in cropping systems

It is projected that the global population will reach 8.6 billion by 2030 and 9.6 billion by 2050, which will exert significant pressure on the agricultural sector to ensure food security, mitigate the impacts of climate change and enhance soil health (Yadav *et al.,* 2019; Lal, 2015). The incorporation of legumes into cropping systems plays a vital role in sustaining agricultural production. Legumes, such as pulses possess such important characteristics (Fig 1) that not only provide nutritious food for both humans and animals but also contribute to improving soil fertility (Tharanathan and Mahadevamma, 2021; Nees *et al.,* 2020).

The nutritional value of pulses, often referred to as the "poor man's meat" is highly regarded in the Indian diet. However, despite having a significant vegetarian population, India's focus on cereals has resulted in malnutrition issues. To address these deficiencies, it is crucial to increase the cultivation area and productivity of pulses (Lewis *et al.,*

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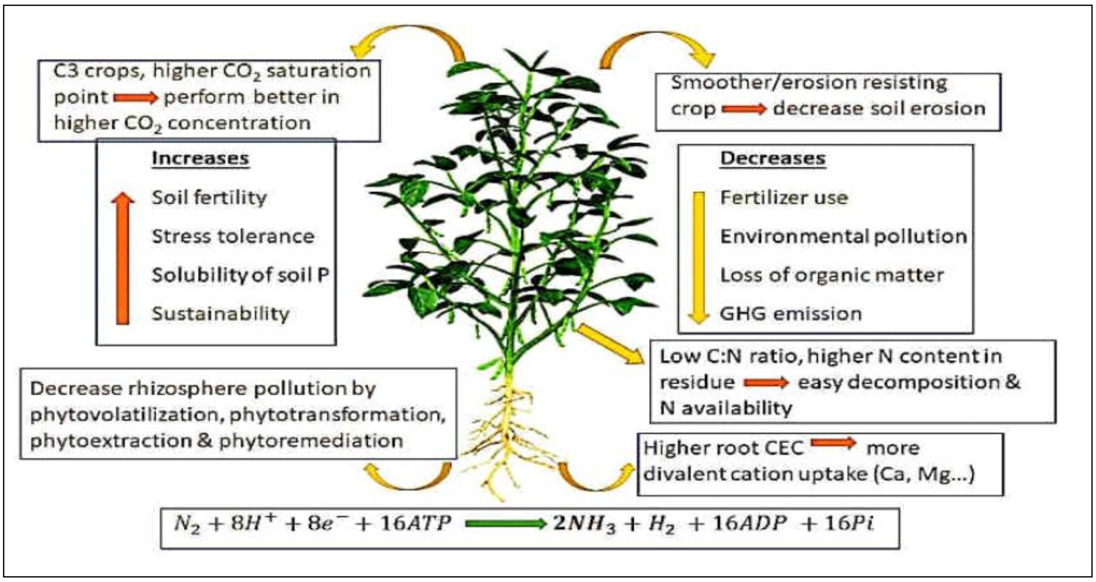

Fig 1: Important characteristics of legume crops.

2015). Legumes, such as pulses, are abundant in carbohydrates, protein, fats, calcium, iron, riboflavin, thiamine and dietary fibres. They play a significant role in meeting global dietary protein requirements. Moreover, legumes not only provide essential nutrition but also contribute to the enhancement of subsequent crop productivity, making them indispensable for sustainable cropping systems (Dhakal *et al.,* 2016).

Legumes besides being dietary staples, also benefit animal health, improve soil fertility through nitrogen fixation and phosphorus solubilization and can serve as biofuels (Meena *et al.,* 2015a; Jensen *et al.,* 2022). They also contribute to lowering both biological and environmental stresses and advancements like organic techniques and reduced tillage have increased their production (Meena *et al.,* 2016). These practices, coupled with effective crop rotation, enhance agricultural and environmental sustainability. Studies show that incorporating legumes can boost cereal yields by 15-25% (Kirkegaard *et al.,* 2018). Legume inclusion reduces reliance on agrochemicals, supporting sustainable production, particularly in organic farming systems (Verma *et al.,* 2015a and b). Moreover, it significantly enhances essential soil nutrients compared to monoculture (Stagnari *et al.,* 2017).

Legumes and biological nitrogen fixation (BNF)

Nitrogen is a primary essential nutrient for crop production and is the vital factor for crops aftersolar radiation and water. Legumes have the capability to fix the atmospheric nitrogen through legume-rhizobia symbiotic association. This biological nitrogen fixation (BNF) not only help the legume to fulfil its nitrogen need but also enrich the soil nitrogen status to improve the succeeding crop yield (Carranca, 2019). Plants get nitrogen from soil either through et al., decomposition of legume residue on their incorporation or from atmospheric nitrogen fixation through leguminous plants (Yong *et al.,* 2015 and Verma *et al.,* 2015b). Those leguminous plants which fix and add atmospheric nitrogen to soil called "N-donor" plants and those which receives this soil nitrogen called "N-receiving" plants (Moyer-Henry *et al.,* 2016). This phenomenon of transfer of nitrogen from N-donor to N-receiver varies from 10-85% of the N demand of N receiving plants (Paynel *et al.,* 2018) and by adoption of suitable legume in cropping system the nitrogen demand of crops can be fulfilled through BNF (Rahman *et al.,* 2014). The extent of this biological nitrogen fixation varies from zero to several hundred-kilogram nitrogen per hectare (Soumare *et al.,* 2020).

Agro techniques for legumes in cropping system

Various agro-techniques for legumes in cropping system mentioned in the Fig 2.

Sequential cropping

Crop rotation is considered to be incomplete if legumes are not included in a cropping system. The amount of nitrogen addition to soil through legume inclusion depends on the legume crop taken for the system (Squire *et al.,* 2019). Legumes in cropping system not only improves biomass production but also enhance soil carbon and nitrogen status (Lal, 2021). The increased carbon and nitrogen status in soil not only makes soil microbes active but also benefits the succeeding crops (Akinnifesi *et al.,* 2017; Lithourgidis *et al.,* 2021). Significant yield level in succeeding maize crop even without chemical source of fertilization has been reported when cultivated after legume crops (Lopez and Mundt, 2020).

Intercropping

Intercropping is an ancient agricultural practice of mixed cropping that involves planting two or more crop species together in the same space and at the same time. The most common combination for this practice is legumes/

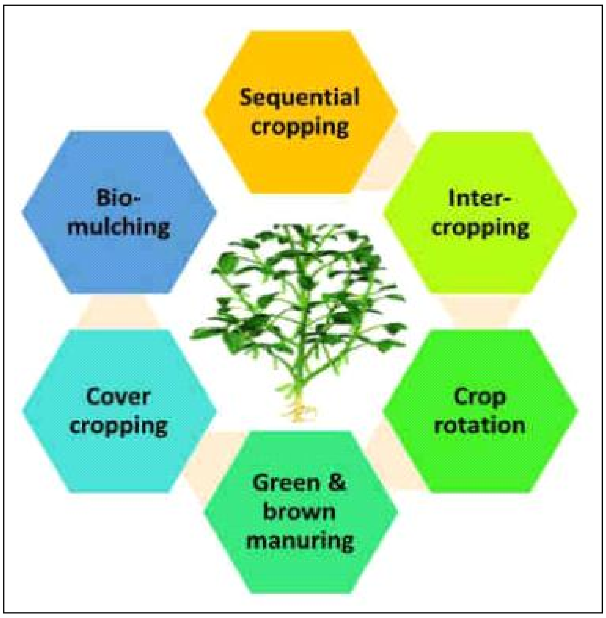

Fig 2: Legumes in Cropping Systems.

cereals. The main aim is to enhancing the resource efficiency (Inal *et al.,* 2017) and stabilizes the agroecosystem (Maitra and Ray, 2019; Maitra *et al.,* 2021). Legumes helps in maintaining soil fertility (Hauggaard-Nielsen *et al.,* 2019), suppresses weeds population in the crop field (Liang *et al.,* 2020) *etc*. Thus, it is a low-input agro-technique (Ashoka *et al.,* 2017) to enrich soil nitrogen status and to limit chemical nitrogen fertilization (Maitra *et al.,* 2021).

The legumes commonly used as intercrops improving the yield of the main crop as well as the system (Sarkar *et al.,* 2020 and Ghaley *et al.,* 2015). Non-legume crop in association with the legume crop benefited from the biological nitrogen fixation (Garg 2017) or through nitrogen transfer throughroot exudates, leaf leachates *etc*. (Addo-Quaye *et al.,* 2021). Biologically fixed nitrogen by legumes directly available to non-legume crop grown together, known as direct N availability (Adeniyan *et al.,* 2017 and Dahmardeh *et al.,* 2020) or added to the crop field to supplement the succeeding crop called residual N availability. Crops grown along with legume crops can provide better yield. Legume in intercropping can restore the soil nitrogen status by BNF (Fujita *et al.,* 2019 and Meena *et al.,* 2017a, Maitra *et al.,* 2021).

Crop rotation

Crop rotation is also an intensive strategy with recurrent succession of crops to enhance the output of the system in terms of crop productivity through inclusion of suitable crops (Boudreau and Mundt, 2016; Fininsa 2016). Inclusion of legume in the system is mostly encouraged due to their advantages *viz*. BNF, nutrient recycling, increase soil carbon and nitrogen stock *etc* (Keeler *et al.,* 2019). Legume based crop rotation not only enhance soil quality and system productivity but also breaks weedand pathogen cycle, reduce agrochemical inputs, increase biodiversity of the agricultural ecosystem. Leguminous crops produce higher biomass and improve soil organic carbon, that further increase the soil microbial population and maintain soil health (Hauggaard-Nielsen *et al.,* 2019). The inclusion of legumes in cropping system produces more biomass using limited resource base, improves soil carbon and nitrogen stock and can be adopted suitably in any cropping system and can be used in sustainable land development programs (Lithourgidis *et al.,* 2021). As the legumes are involved in BNF and supply it to both current season as well as succeeding crops in the cropping system, these can also be considered for N-economy (Mahmud *et al.,* 2020; Praharaj and Maitra, 2020). The quantity of nitrogen fixed and supplied to current and succeeding crops depends mainly on the legume species, cross inoculation group associated, soil type, climate, duration of the crops, *etc* (Chen *et al.,* 2019; Spehn *et al.,* 2022).

Green and brown manuring

Legume are preferred for green manuring as they fix atmospheric nitrogen in soil, produce more biomass within short time period, rich in nutrients and low in C:N ratio (Maitra *et al.,* 2018). Green manuring can partially or completely fulfil the N need of succeeding crop (Tiwari *et al.,* 2014 and Meena *et al.,* 2015b). Amelioration of degraded soils can easily be done by addition of green foliage into the soil (Maitra *et al.,* 2018) and thus provides a healthy agro-ecosystem for crops (Blackshaw *et al.,* 2019; Larkin and Griffin, 2017; Tillman *et al.,* 2014; Agbenin, 2021).

Cover crop

Legumes are close growing crops and hence serves as cover crop. Also, the de nse foliage ofmost legumes reduces the erosive action of rainfall to a large extent. Legumes release many root exudates such as organic acids to the soil which acts as a binding agent and reduces soil erodibility by improving aggregate stability (Sanchez-Navarro *et al.,* 2019). Legumes act as both fertility restorer and a measure of erosion control in such areas. Legumes can also be grown in alternate strips along with some erosion susceptible crops to keep the soil loss below acceptable threshold. The benefits of using legume as cover crop is due to the fact that it ensures food and nutritional security while protecting the soil from erosive agents and improving the soil health (Blanchart *et al.,* 2016; Doane *et al.,* 2019).

Synergy between legumes and soil health improvement

Modern, intensive agriculture system is mainly agrochemical dependent directing towards degradation of soil health. Due to intensive cultivation and fault soil management practices, severe constraints like increase in soil compaction and erosion, reduction in soil productive potential and reduction in soil microbial activity have been well recognized (Unger and Kaspar, 2018). It was reported that legume can accumulate about 2.6 kg N ha^{-1} day^{-1} and their incorporation can be equivalent to 50-100 kg N ha^{-1}

application of chemicalnitrogenous fertilizers (Ladha *et al.,* 2018). However, Dhaincha at 45-60 DAS can accumulate 5.5 kg N ha^{-1} day^{-1} and can fix about 300 kg N ha^{-1} (Ladha *et al.,* 2018). Legume crops play a vital role in the nitrogen cycle fixing atmospheric nitrogen and can supply the available nitrogen to current season crop as well as succeeding crops. Biological nitrogen fixationenhance 9.7-20.5% residual nitrogen content in rice field (Yu *et al.,* 2014). Almost half of the total above ground biomass nitrogen partitioned into below ground biomass (Carranca *et al.,* 2015). Incorporation of legume residue adds about 50-60 kg ha^{-1} of N to the soil that can be used by the succeeding crop and the loss of N in this case is significantly lower than chemical fertilizer application (Singh, 2020; Dhakal *et al.,* 2016). Soil health keeps on decreasing by adopting continuous cereal based cropping system (Kumar *et al.,* 2016). To overcome this problem, inclusion of suitable legume in the cropping system can be a sustainable option to maintain the soil fertility as well as productivity (Dhaliwal *et al.,* 2021; Singh *et al.,* 2021). Legume crops through the process of biological N fixation can save 150-200 kg N ha^{-1} $year^{-1}$ (Peyraud *et al.,* 2009) and can fulfil 90% of their own nitrogen requirement on proper *rhizobium* inoculation (Yadav *et al.,* 2019). Over the decomposition of these legume residues on incorporation, some N recycled in soil (Meena *et al.,* 2015b) and this N cycling regulated by quality of the residue, soil microbial activity and soil environment, pH, aeration *etc*. (Srinivasarao *et al.,* 2022). The residues of legumes can improve soil physical, chemical and biological health (Grandy *et al.,* 2022 and Mousavi *et al.,* 2019). It has also been reported that, taking crops having different rooting depths and minimal soil disturbance, legumes optimize micro and macro- pores in soil that increases infiltration of water to deeper root zone depth (Kumar and Goh, 2016). Legume crops along with biological nitrogen fixation can add high quality soil organic matter and nutrient cycling (Dhakal *et al.,* 2016).

Effect of legume on soil physical, chemical and biological properties

Incorporating legumes into cropping systems brings numerous benefits to soil health, enhancing its physical, chemical and biological properties (Fig 3).

Improvement in soil physical properties

Physical properties of soil are fairly constant towards crop husbandry practices, but important criteria associated with aeration, erosion, runoff, infiltration rate, nutrient and moisture holding capacity of soil (Dexter, 2014). Therefore, proper soil physical condition is essential for optimum tillage, root growth, ground water recharge, prolonged soil moisture availability and deprived soil physical condition may lead to difficulty in farm activities (Schoenholtz *et al.,* 2020, Dexter 2014, Meena *et al.,* 2015a). Inclusion of legumes in soil acts as soil conditioner and improves soil physical properties significantly (Srinivasarao *et al.,* 2022). Leguminous crops used as cover crops and their incorporation in soil significantly influence soil physical properties and also improves soil microbial population, increasing soil organic matter (Lal 2015). Furthermore, legume residue inclusion improves soil water stable aggregates and improves soil physical condition preventing soil erosion (Lithourgidis *et al.,* 2021 and Mousavi *et al.,* 2019). Legume crops also improves water status and soil infiltration by increasing soil aggregate stability (Mousavi *et al.,* 2019; Schädler *et al.,* 2021).

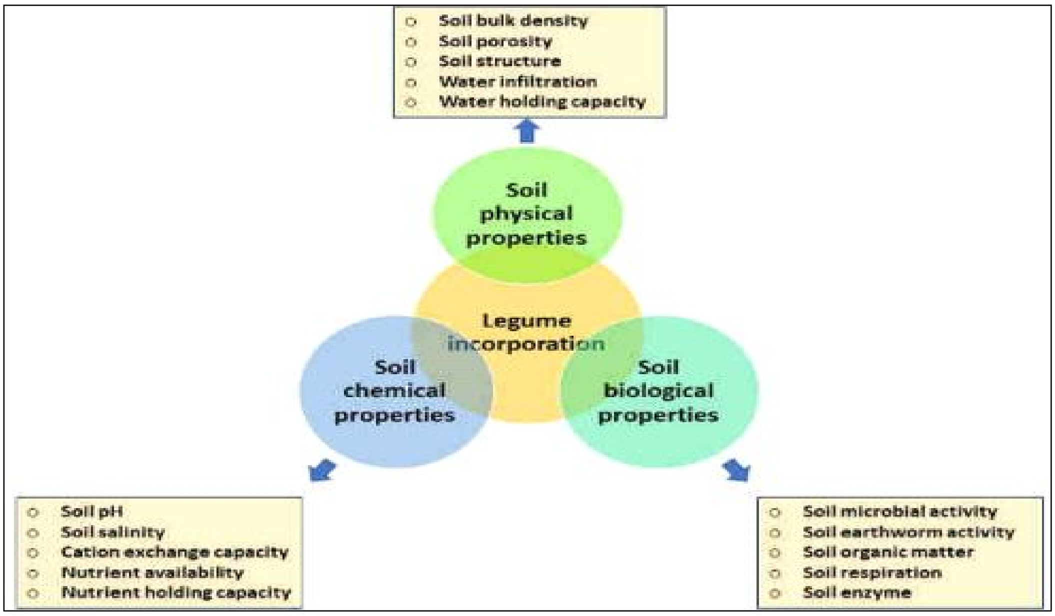

Fig 3: Effect of legume on soil physical, chemical and biological properties.

Improvement in soil chemical properties

Soil chemical properties and nutrient concentration play a pivotal role in nutrient dynamics, influencing crop yield (Meena *et al.,* 2015a). The inclusion of legume crops significantly impacts soil chemical properties by adding organic matter and through biological nitrogen fixation (BNF), which sustains soil fertility and optimizes overall productivity (Kelly *et al.,* 2019). Legumes are known to positively affect available nutrients, soil pH and soil organic carbon stock. Their presence alters soil pH by releasing organic acids, potentially enhancing phosphorus availability (Meena *et al.,* 2017b) and stimulating soil microbial activity (Lopez and Mundt, 2022), crucially influencing nutrient dynamics. Legume incorporation not only enriches soil nitrogen content but also contributes substantial essential nutrients, organic matter and aids in sequestering atmospheric carbon dioxide (Turnbull and Bowman, 2020; Sharma and Behera, 2019; Lal, 2015). The decomposition rate of legume biomass and subsequent nutrient release depend on various factors like nutrient content, soil type, climate, plant density and management practices (Adeboye *et al.,* 2015). Factors such as pH, aeration, moisture and temperature also influence biomass decomposition rate and nutrient release (Liang *et al.,* 2020). Incorporating legume plants at an early age facilitates faster biomass decomposition (Melero *et al.,* 2017). The excessive use of agrochemicals leads to pesticide contamination, causing soil and water pollution and negatively impacting soil biodiversity (Prell and Poole, 2016; Khan *et al.,* 2019; Jin *et al.,* 2015). Implementing best management practices in agriculture aids in recovering from agrochemical contamination and promotes the development of holistic agroecosystems (Deakin and Broughton, 2019; Lal, 2021). Legume inclusion in soil acts as a barrier, preventing the carryover of pesticides into the soil and water bodies, thereby minimizing erosion and run off (Fester *et al.,* 2014). Certain gram-negative bacteria species exhibit symbiotic nitrogen fixation capabilities with legumes *via* their roots, enabling atmospheric nitrogen fixation. Hydrogen, a byproduct of this process, possesses bioactive properties that enhance plant abiotic stress tolerance (Cui *et al.,* 2013). Rhizobia, involved in symbiotic nitrogen fixation, directly eliminate soil pollutants (Jin *et al.,* 2015), indirectly enhancing other degrading microbes and enzymes, which contribute to metal bioremediation (Fester *et al.,* 2014).

Improvement in soil biological properties

Incorporating legumes into cropping systems significantly improves soil biological properties by enhancing nitrogen fixation and phosphorous availability, thereby boosting soil fertility and microbial activity (Fig 4). Nitrogen is limiting macro-nutrient in most of the agricultural soil and the requirement of nitrogen in plant is also higher than other mineral nutrients (Brookes, 2015 and Suman *et al.,* 2016). *Rhizobia* in association with legume synthesize nitrogenase enzyme which help in atmospheric nitrogen fixation. Biological nitrogen fixation assimilates as protein and glycoproteins in plant biomass (Klauer and Francesch, 2017 and Lansing and Franceschi, 2020). Phosphorous is one of the essential mineral elements for plant growth, but its availability in soil is limited by soil reaction and complexation with Fe, Al, Ca and Mg (Sinclair and Vadez, 2022 and Meena *et al.,* 2017a). Legume inclusion in cropping system help in releasing several acids in the form of root exudates (Shen *et al.,* 2022 and Nuruzzaman *et al.,* 2016) and enhancing phosphatase enzyme activity (Gilbert *et al.,* 2016). Hydrogen gas is released as byproduct during biological nitrogen fixation which encourage microbial activity, microbial carbon and microbial nitrogen in root zone. This microbial carbon and microbial nitrogen comprise of 1-7% of total soil carbon and nearly 5% of total soil nitrogen respectively (Anderson

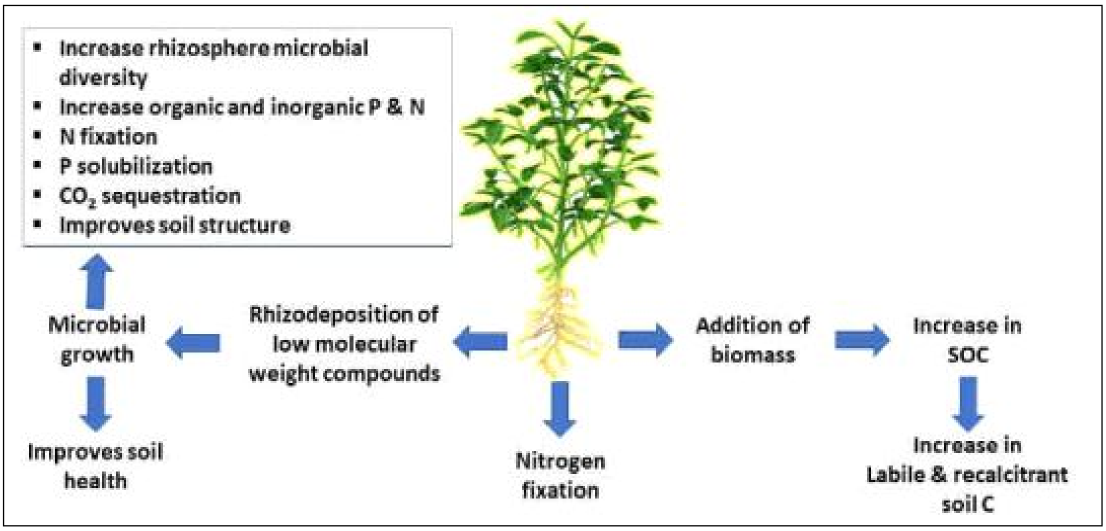

Fig 4: Effect of legume on Soil Biological Properties.

and Domsch, 2019, Insam *et al.,* 2019) which contributes most to the labile carbon and nitrogen fraction in soil (Insam *et al.,* 2019). Inclusion of legumes in cropping system enhances the soil microbial activity (Alvey *et al.,* 2016) and small change in the concentration of nitrogen, cellulose, lignin content or C:N ratio of residue trigger the divergence of soil microbial status (Meena *et al.,* 2014, Schelud'ko *et al.,* 2019) and tripartite symbiotic association of mycorrhiza-legume-rhizobium which further enhance the plant nutrition (Hayman, 2016 and Scheublin *et al.,* 2014). Soil phosphorous has limited mobility and legume generally require more phosphorous for their growth and especially for the nodule formation. (Zahran, 2019).

CONCLUSION

From the above points it is revealed that the complex mechanisms and optimizing management practices involving legumes in cropping systems is crucial for sustainable agriculture. Future research should focus on identifying suitable legume species, exploring diverse cropping systems and developing best practices to maximize the benefits mentioned above while mitigating potential challenges.

Conflict of interest

All authors declared that there is no conflict of interest.

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