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Sustainable Agriculture Approaches in Legumes

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Abstract
Legumes *(Leguminosae)* are regarded as a key element of sustainable agriculture. This plant group enhances soil fertility and contributes to environmental sustainability through their ability to biologically fix nitrogen, thereby reducing the need for chemical fertilizers. The nodules found in the roots of legumes capture atmospheric nitrogen in a form that plants can utilize, creating a natural source of nitrogen in the soil. This process plays a vital role in improving nitrogen-deficient soils and in meeting the nitrogen needs of other crops in subsequent planting seasons. Furthermore, the roots of legumes, which improve soil structure, increase organic matter content, and prevent erosion, make them a preferred choice in sustainable agricultural practices. The use of legumes in crop rotation allows the soil to rest and helps suppress harmful organisms. Organic farming, integrated pest management, and crop rotation are methods that can strengthen the role of legumes in agricultural systems. In conclusion, the role of legumes in sustainable agriculture is crucial for providing ecosystem services and enhancing the economic well-being of farmers. Therefore, expanding the cultivation of legumes and promoting sustainable agricultural practices are considered strategic approaches to ensuring the continuity of agricultural production for future generations.

Review Article

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1.Introduction

Legumes are a family belonging to the order Fabales. It includes nutritious foods such as lentils, chickpeas, beans, peas and soybeans, as well as forage crops such as alfalfa and vetch. Legumes play an important role in improving soil fertility and reducing dependence on synthetic nitrogen fertilizers by fixing atmospheric nitrogen through Rhizobium bacteria living symbiotically in root nodules (Peoples et al., 2009). Legumes play a critical role in achieving sustainability goals in agricultural production. Of great importance as both human nutrition and animal feed, legumes also provide a range of ecosystem services that maintain and improve the health of agroecosystems. Approximately 90 million tons of legumes are produced worldwide annually. Most of this is produced by countries such as India, Canada, Myanmar, Brazil and China. India is one of the leading countries in world chickpea production, while Canada is the leader in pea production. The most produced legumes in the world include beans, chickpeas, lentils and peas. These crops have a wide range of uses both as human food and animal feed due to their high protein and fiber content (FAO, 2021). In Türkiye, legume production is mostly concentrated in Southeastern Anatolia, Central Anatolia and Aegean regions. In 2022, approximately 1.1 million tons of legumes were produced in Türkiye (TUIK, 2022).

Sustainable agriculture aims to improve the long-term productivity and quality of agricultural production by conserving natural resources and supporting biodiversity. In this context, sustainable agriculture approaches include practices such as maintaining soil health, optimizing water use, and reducing the use of pesticides and fertilizers.

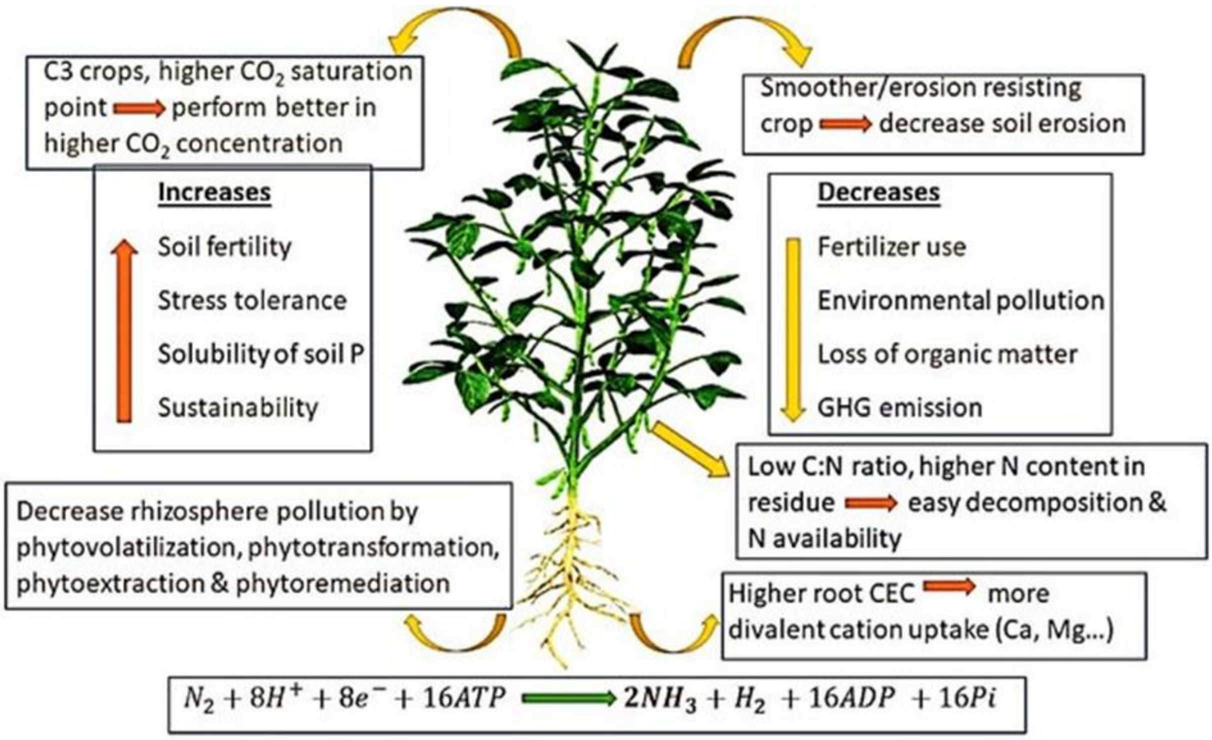

Figure 1. Important characteristics of legume crops (Jena et al., 2022).

Legumes offer several advantages in terms of ecosystem services. These include improving soil structure, increasing biodiversity and carbon sequestration. For example, the use of legumes in crop rotation systems increases soil organic matter, preventing soil erosion and improving water holding capacity (Jensen et al., 2010).

Furthermore, the nectar and pollen provided by legumes during flowering supports populations of pollinators such as bees and improves ecosystem health (Freibauer et al., 2004). Sustainable agricultural practices in legumes include various methods. Organic farming, low-input farming and agroecological methods can be considered in this context. Organic farming encourages natural biological processes by prohibiting the use of synthetic chemicals. Low-input agriculture aims to maintain productivity by using fewer external inputs compared to conventional methods. Agroecological methods increase sustainability by integrating ecological principles into agricultural practices (Gliessman, 2021).

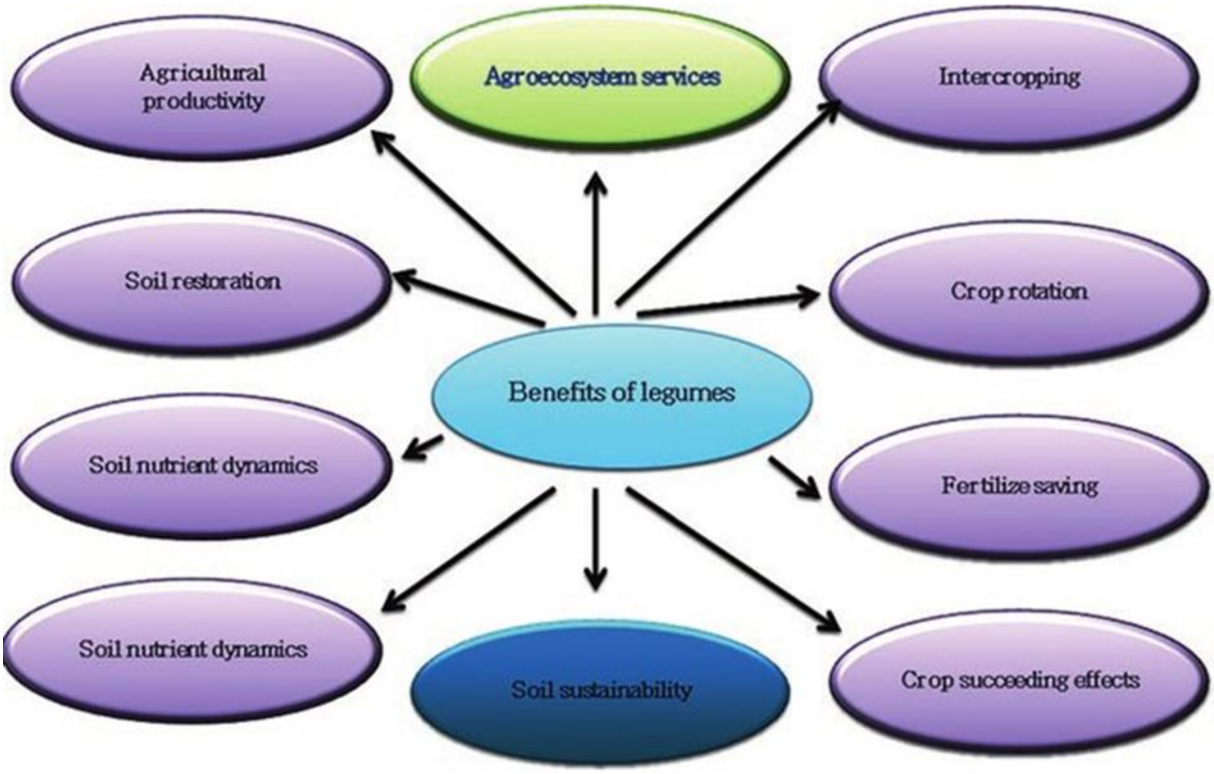

Figure 2. The role of legumes in agriculture (Meena et al., 2018).

Legumes play a critical role in ensuring sustainable agriculture. The ecosystem services provided by these crops and sustainable farming methods offer significant potential for reducing the environmental impacts of agricultural production and ensuring food security. Existing literature supports the role of legumes in sustainable agriculture approaches and emphasizes the importance of scaling up practices in this area. This chapter aims to present the scientific information and research results compiled from the existing literature by addressing sustainable agriculture approaches in legumes.

2. Ecological Role of Legumes

2.1. Contribution to soil fertility

Legumes (*Fabaceae* family) have an important role in agricultural ecosystems. They improve soil fertility through biological nitrogen fixation, organic matter contribution and promotion of microbial activity. In this chapter, the ecological role of legumes and their contribution to soil fertility will be discussed in detail.

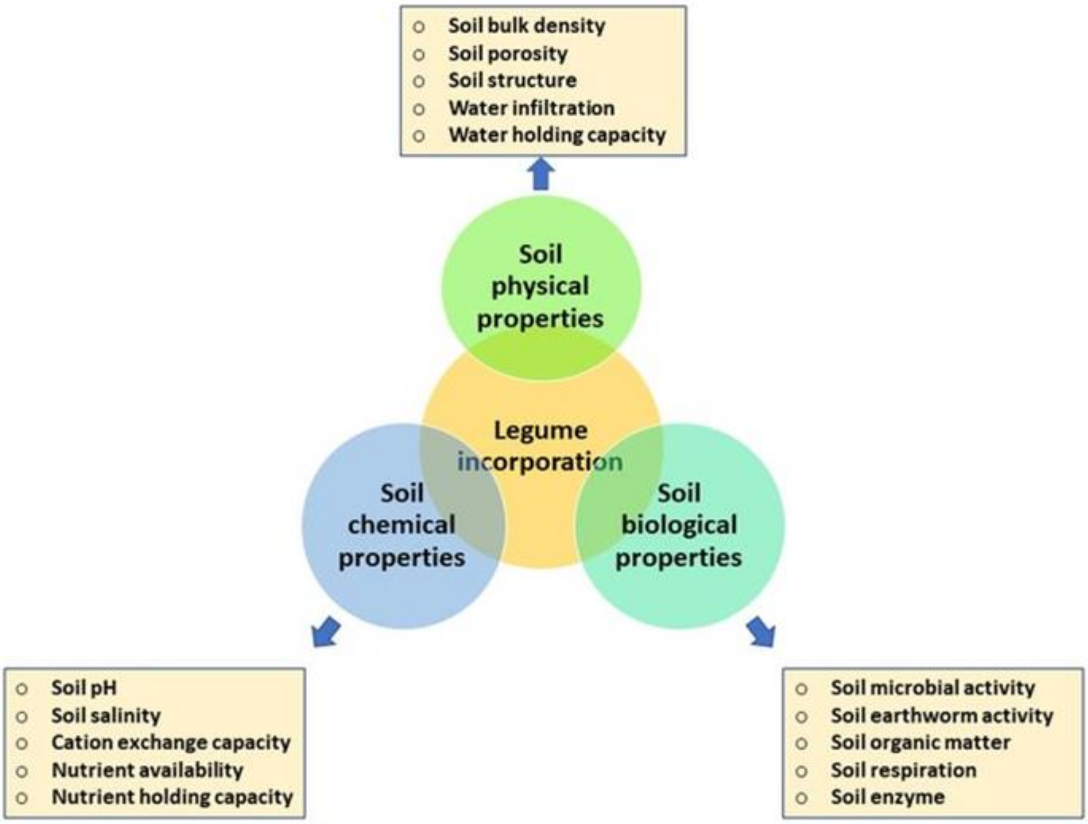

Figure 3. Effect of legume addition on physical, chemical and biological properties of soil (Jena et al., 2022).

Legumes biologically fix atmospheric nitrogen by forming a symbiotic relationship with bacteria of the genus Rhizobium. This process not only fulfills the nitrogen needs of the plants, but also increases the nitrogen content of the soil, creating a fertile environment for subsequent plantings. This symbiotic relationship takes place in the root nodules of legumes, which contain nitrogenous compounds formed by Rhizobium bacteria (Peoples et al., 2009). Nitrogen fixation increases agricultural productivity by promoting plant growth, especially in nitrogen-poor soils. Legumes promote soil microbial activity through root exudates and organic matter cycling. Organic compounds released from plant roots provide a source of nutrients for microorganisms, which increases microbial biodiversity. Drinkwater et al. (1998) reported that microbial biomass and respiration rates increased in areas where legumes were planted and that this was directly related to organic compounds released from plant roots. Some legumes enhance soil microbial activity by forming symbiotic relationships with mycorrhizal fungi. Mycorrhizal fungi bind to plant roots and increase nutrient and water uptake, while at the same time releasing compounds that promote microbial activity (Smith and Read, 2008). These relationships support plant growth and improve soil health by facilitating plant access to hard-to-access nutrients such as phosphorus.

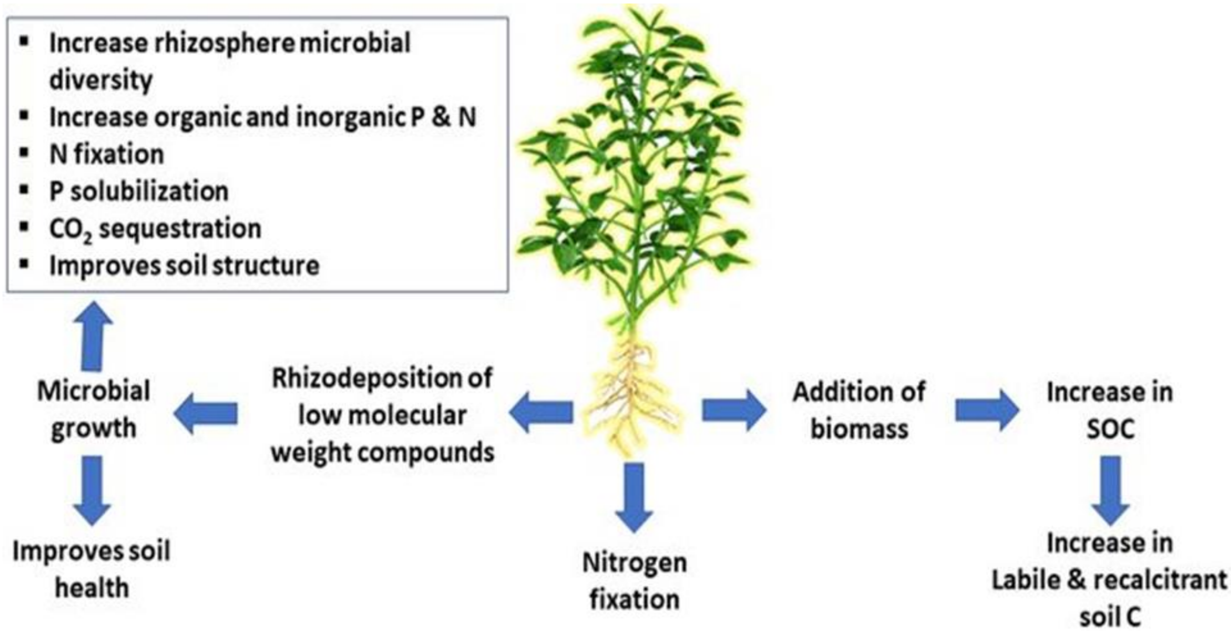

Figure 4. Biological effect of legume addition (Jena et al., 2022)

Legumes produce high levels of organic matter, which is incorporated into the soil and improves soil fertility. Organic matter improves soil water holding capacity and nutrient cycling. Fageria (2007) emphasizes that the organic matter contribution of legumes improves soil physical, chemical and biological properties. These plants stabilize the soil structure, reducing erosion and protecting microbial habitats. Legumes improve the physical structure of the soil thanks to their root structure. By stabilizing the soil, the roots increase water infiltration and improve the water holding capacity of the soil. This ensures that plants have access to sufficient water even during periods of drought. Furthermore, root exudates promote the formation of soil aggregates, which improves the overall health of the soil structure (Bronick and Lal, 2005).

Legumes contribute to soil fertility by increasing the bioavailability of nutrients. Nitrogen added to the soil through nitrogen fixation becomes available to other plants. Furthermore, the organic matter contribution of legumes increases the bioavailability of other nutrients (phosphorus, potassium, etc.) in the soil. Giller and Cadisch (1995) state that the contribution of legumes to nutrient cycling is critical for sustainable agricultural practices. Legumes support biodiversity by maintaining soil health. These plants provide suitable habitats for a variety of microorganisms in the soil, thereby improving the overall health of the soil ecosystem. Altieri and Nicholls (2018) emphasize that legumes support soil health and ecosystem services through biodiversity enhancement. Peoples et al. (2009) noted that legumes increase productivity in agricultural systems through biological nitrogen fixation and that these crops play an important role, especially in soils with low nitrogen content. Furthermore, Lupwayi and Kennedy (2007) showed that legume cropping systems increase soil microbial diversity, which contributes to soil health.

Giller and Cadisch (1995), emphasized the role of legumes in sustainable agricultural practices and detailed the positive effects of these crops on soil microbial communities. In particular, organic matter cycling and nitrogen fixation processes were reported to increase the efficiency of sustainable agricultural systems by enhancing soil microbial activities. Smith and Read (2008) showed that mycorrhizal associations contribute to soil fertility by increasing the bioavailability of plant nutrients. Legumes have an important ecological role in agroecosystems and contribute to soil fertility in many ways. They improve soil health through biological nitrogen fixation, organic matter contribution and promotion of microbial activity. Future research needs to further study the long-term effects of legumes in different cropping systems and farming practices to optimize their contribution to soil fertility.

2.2. Biological nitrogen fixation

One of the most well-known ecological contributions of legumes is biological nitrogen fixation. Legumes bring nitrogen from the atmosphere into the soil in a form usable for plants thanks to the Rhizobium bacteria with which they have a symbiotic relationship in their root nodules. This process is an important part of the nitrogen cycle and reduces the need for chemical nitrogen fertilizers in agricultural production (Peoples et al., 2009). Biological nitrogen fixation is one of the cornerstones of sustainable agricultural practices. Overuse of synthetic nitrogen fertilizers can lead to problems such as environmental pollution and contamination of water resources. Biological nitrogen fixation by legumes minimizes these problems and offers a more environmentally friendly agricultural practice. For example, legume species such as soybean and vetch can fix 50-300 kg of nitrogen per hectare per year (Giller, 2001).

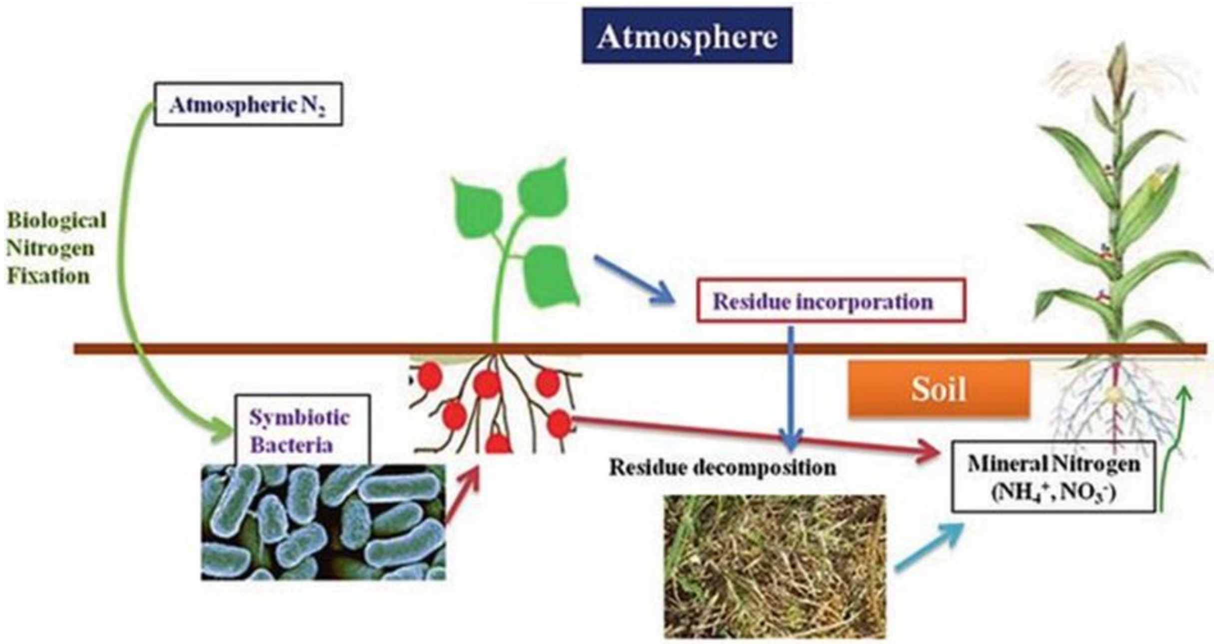

Figure 5. Soil N fixation and mineralization in legumes (Meena et al., 2018)

2.3. Carbon sequestration

Legumes can help lower carbon dioxide (CO2) levels in the atmosphere through carbon sequestration. Plants take CO2 from the atmosphere through photosynthesis and convert it into biomass. Legumes store this biomass in their roots and in the soil, enabling long-term sequestration of carbon. This process contributes to increasing soil organic carbon and improving soil quality (Lal, 2004). The carbon sequestration potential of legumes is recognized as an important strategy for reducing greenhouse gas emissions in agricultural systems. Legumes such as chickpea, lentil and vetch are particularly effective in carbon sequestration due to their high biomass production and root systems (Freibauer et al., 2004). The use of these crops plays an important role in mitigating the negative impacts of agricultural activities on climate change.

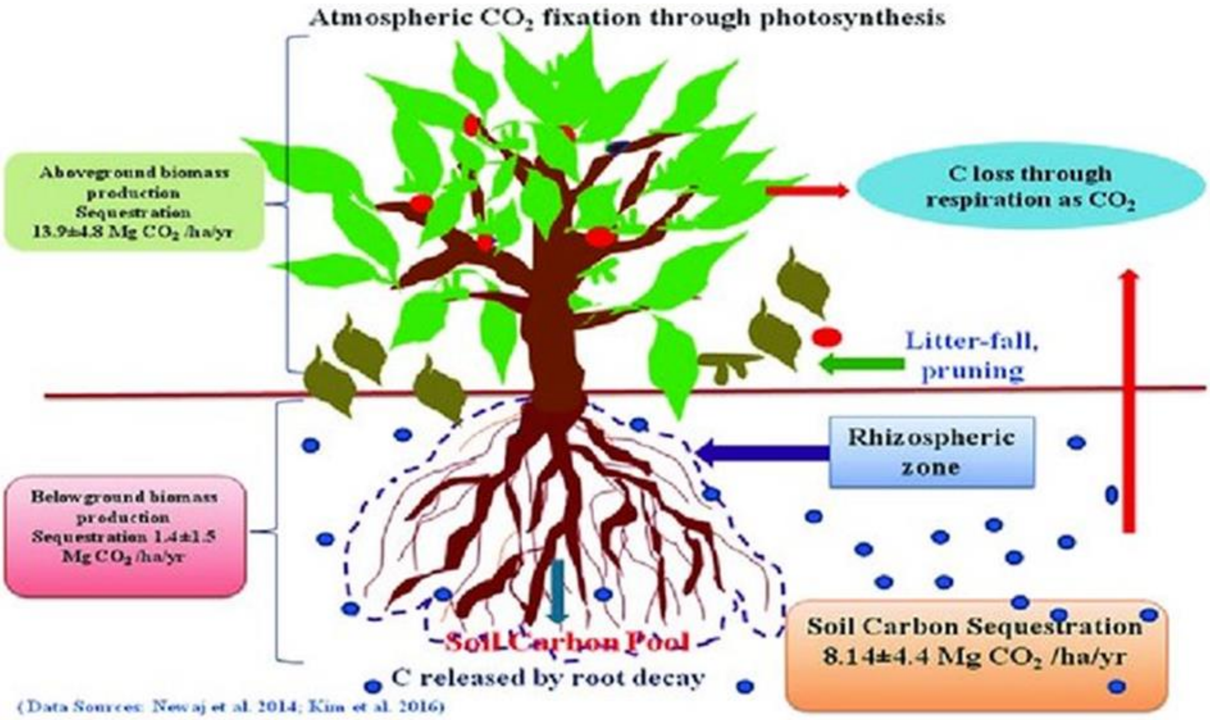

Figure 6. Mechanism of C sequestration in legumes (Kumar et al., 2018)

The ecological role of legumes is critical in enhancing the sustainability of agroecosystems. Increasing soil fertility, reducing the need for synthetic fertilizers through biological nitrogen fixation and contributing to the fight against climate change through carbon sequestration, legumes are indispensable elements of sustainable agricultural practices. Existing literature supports these ecological roles of legumes and emphasizes the importance of their wider use in agricultural systems.

3. Ecosystem Services and Sustainable Agriculture Approaches in Legumes

3.1. Improving soil structure

Legumes have the ability to bind atmospheric nitrogen through nodules on their roots, which increases soil nitrogen levels, improving soil fertility and structure. By increasing their organic matter content, they also improve soil water holding capacity and overall health. In particular, long-term studies show that legume cropping significantly improves soil physical properties and has an important place among sustainable agricultural practices (Neri et al., 2020). It has also been noted that modern intensive farming systems have degraded soil structure and that legume-supported cropping systems can improve this situation (Everwand et al., 2017).

3.2. Biodiversity and pollinator support

Cultivation of legumes increases biodiversity in agroecosystems and helps to maintain pollinators. Growing a variety of plant species together increases habitat diversity, allowing different species to live. During flowering periods, legumes provide essential sources of nectar and pollen for pollinators, which supports the sustainability of pollinator populations and increases the efficiency of agricultural production (Neri et al., 2020). The important role of legumes in increasing biodiversity and supporting pollinators in agroecosystems is also emphasized by the EU's Common Agricultural Policy (CAP) (Everwand et al., 2017).

3.3. Water management and erosion control

Legumes are also effective in water management and erosion control. Their deep root systems stabilize the soil, reducing erosion and facilitating water infiltration. These plants also increase the water-holding capacity of the soil, allowing water to be used more efficiently even during dry periods. Furthermore, the root structures of legumes minimize water loss by reducing surface runoff of water and promote water accumulation in the soil (Neri et al., 2020). The use of legumes is recommended to reduce the negative impacts of intensive agriculture on aquatic ecosystem services (Bogunović et al., 2023).

4. Sustainable Agriculture Methods

4.1. Organic agriculture practices

Organic farming promotes the conservation of natural resources and sustainable agricultural practices by minimizing the use of chemical fertilizers and pesticides. In organic farming, legumes enrich the soil thanks to their nitrogen-fixing capacity and provide the nitrogen needed for other crops. Research has demonstrated the positive effects of legumes on plant growth and yield in organic farming systems (Savvas et al., 2017). In particular, the use of legumes increases soil organic matter content, improving water holding capacity and soil health (Aschi et al., 2023). Furthermore, the use of legumes in organic farming increases biodiversity in agroecosystems and supports pollinator populations (Ramanjaneyulu et al., 2020).

4.2. Low input agriculture methods

Low-input agriculture is a method of farming that relies on natural processes and minimal use of chemical fertilizers and pesticides. This method is adopted to reduce environmental impacts and increase economic sustainability. Legumes play an important role in low-input farming systems because their ability to fix nitrogen reduces the need for chemical fertilizers. Research shows that legumes improve soil fertility and support crop yields in low-input farming systems (Pickoff et al., 2021). Furthermore, these methods maintain natural balance by conserving and increasing agrobiodiversity (Aschi et al., 2023).

4.3. Agroecological practices

Agroecology aims to increase sustainability by integrating the ecological and social components of agricultural systems. Legumes play a central role in agroecological practices because they support ecosystem services and increase the resilience of agricultural systems. These practices are used to improve soil health, optimize water management and increase biodiversity (Everwand et al., 2017). Furthermore, agroecological practices provide natural means of pest management, reducing the use of chemical pesticides and protecting environmental health (Ramanjaneyulu et al., 2020). The use of legumes in agroecological practices supports ecosystem services by increasing soil organic matter content and improving water holding capacity (Savvas et al., 2017).

5. Crop Rotation and Soil Health

5.1. The role of legumes in crop rotation

Legumes occupy an important place in crop rotation and play a critical role in improving soil health and fertility. Crop rotation is practiced by growing different crop species sequentially in the same field, and the inclusion of legumes improves soil health in several ways. Legumes increase the nitrogen content of the soil through their ability to fix atmospheric nitrogen, which provides a natural source of nitrogen for subsequent crops (Nadeem et al., 2019). Research has shown that the inclusion of legumes such as soybeans in crop rotation increases soil organic matter accumulation and supports microbial activity (Dai.,et al,, 2023).

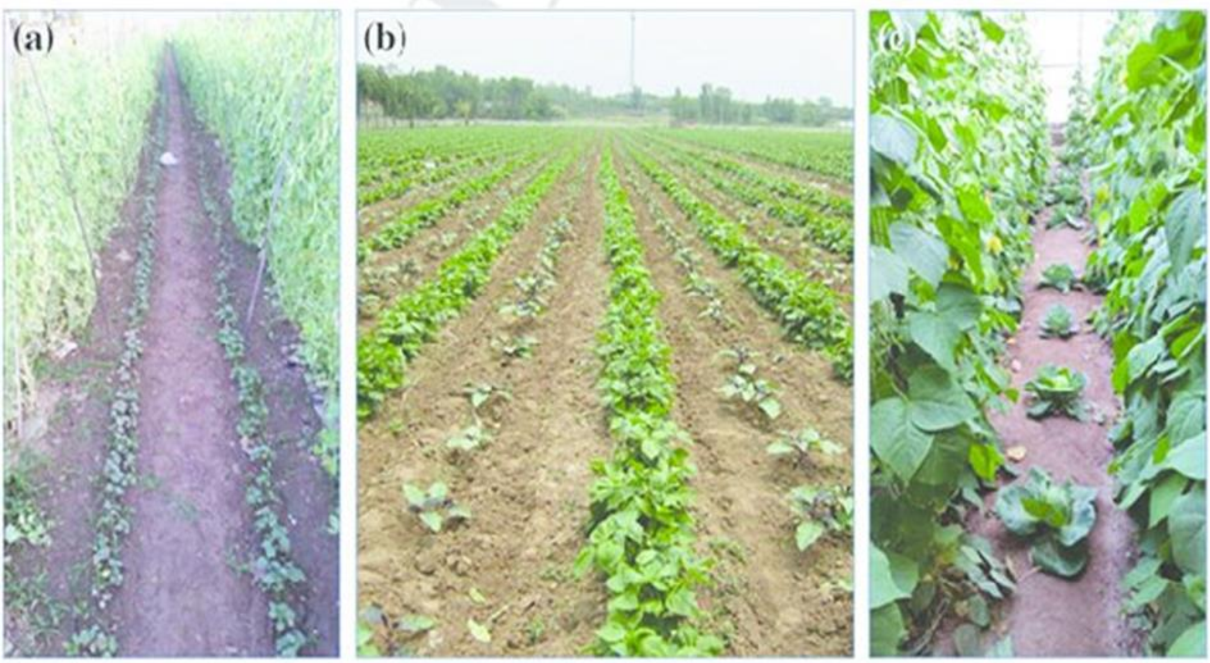

Figure 7. Co-planting of vegetable legumes and horticultural crops in China, a) double rows of summer okra grown between maturing winter peas in Hebei province; b) single rows of bush beans planted with eggplant rows in Shandong province; c) intermittent winter cabbage grown following a caged summer-fall bean crop in a greenhouse near Beijing (Blair et al., 2016).

The role of legumes in crop rotations is particularly important for improving soil structure and increasing microbial diversity. For example, planting different legume species increases soil organic matter content, improving water holding capacity and nutrient availability (Oliveira et al., 2019). Furthermore, the root systems of legumes stabilize the soil, preventing erosion and maintaining the physical structure of the soil (Giacometti et al., 2021).

5.2. Soil microbial activity and organic matter

Sustainable agriculture is an approach that aims to balance the environmental, economic and social dimensions of agricultural production. Legumes play an important role in sustainable agricultural systems. This is due to their ability to fix atmospheric nitrogen and their positive impact on soil microbial activity. One of the most prominent characteristics of legumes is their ability to biologically fix atmospheric nitrogen through their symbiotic relationship with Rhizobium bacteria. This process supports plant growth by increasing the nitrogen content of the soil and at the same time promotes soil microbial activity. During the nodulation process, nitrogenous compounds produced by Rhizobium bacteria constitute a source of nutrients for soil microbial communities. The efficiency of the nitrogen fixation process varies depending on the type of legume, the soil conditions in which it grows and the Rhizobium species involved in the symbiotic relationship (Peoples et al., 2009).

Legumes produce high levels of organic matter, which is incorporated into the soil and increases microbial biodiversity. Exudates secreted by plant roots provide a source of energy and carbon for microorganisms, contributing to a more diverse and active microbial community in the soil. Drinkwater et al. (1998) showed that legume contributions to organic matter cycling promote microbial activity by increasing the carbon and nitrogen content of the soil. Some legumes enhance soil microbial activity by forming symbiotic relationships with mycorrhizal fungi. By attaching to plant roots, mycorrhizal fungi increase nutrient and water uptake, while at the same time releasing compounds that promote microbial activity. Mycorrhizal associations promote plant growth and improve soil health by facilitating plant access to hard-to-access nutrients such as phosphorus (Smith and Read, 2008). In addition, they improve soil structure, increase water holding capacity and reduce erosion. Root structures stabilize the physical structure of the soil and protect microbial habitats. This ensures the continuity of microbial activities and supports soil health. Fageria (2007) emphasizes that the effects of legumes on improving soil water holding capacity and structure are important in sustainable agricultural systems. Legumes enrich soil microbial communities and strengthen biological control mechanisms against pathogens. Various microorganisms play an important role in disease management by suppressing plant pathogens. This supports environmental sustainability by reducing the use of chemical pesticides. Altieri and Nicholls (2018) state that legumes are an effective tool in disease management through biodiversity enhancement.

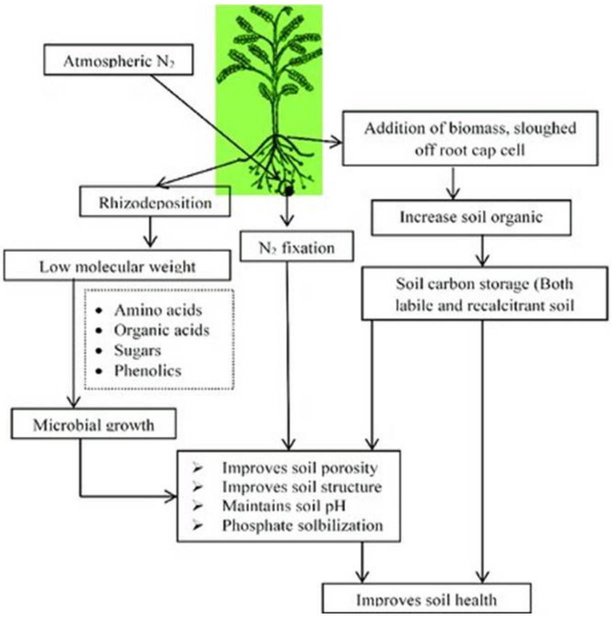

Figure 8. Impact of legumes on soil health (Islam et al., 2023)

Legumes contribute to nutrient cycling by improving soil health. These plants increase the bioavailability of nutrients in soil by accelerating the cycling of organic matter. They also promote microbial activity by feeding soil microorganisms through their root exudates. This allows more efficient utilization of plant nutrients and improves soil fertility. Giller and Cadisch (1995) emphasize that the contribution of legumes to nutrient cycling is critical for sustainable agricultural practices. In a study by Smith et al. (2011), it was observed that microbial biomass and respiration rates increased in areas where legumes were planted. This increase was directly related to the organic compounds and nitrogenous compounds released from plant roots. Likewise, Lupwayi and Kennedy (2007) showed that legume cropping systems increase soil microbial diversity, which contributes to soil health. Giller and Cadisch (1995) emphasized the role of legumes in sustainable agricultural practices and detailed the positive effects of these crops on soil microbial communities. In particular, the processes of organic matter cycling and nitrogen fixation were reported to increase the efficiency of sustainable agricultural systems by enhancing soil microbial activities. Furthermore, Drinkwater et al. (1998) examined the effects of leguminous plants on ecosystem services and detailed their contribution to soil microbial activity.

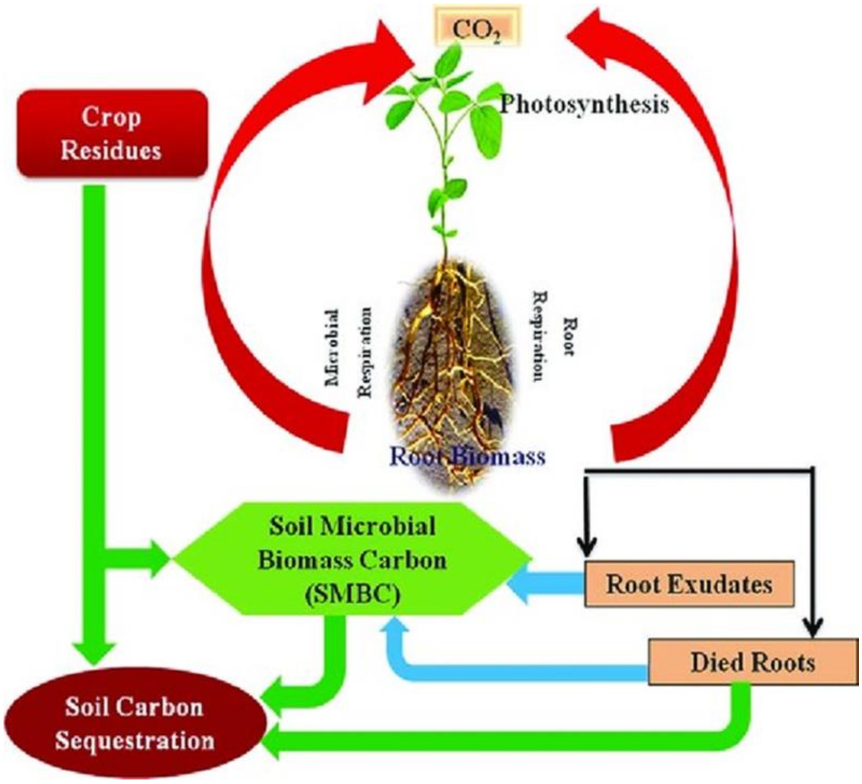

Figure 9. Soil microbial biomass carbon and sequestration through legumes (Kumar et al., 2018)

Soil microorganisms are critical for the sustainability of ecosystem functions. These microorganisms provide important ecosystem services such as the breakdown of organic matter, mineralization of nutrients and production of compounds that support plant growth. Legumes promote these microbial activities through root exudates and organic matter cycling. This increases plant access to nutrients and supports the productivity of ecosystems (Smith and Read, 2008).

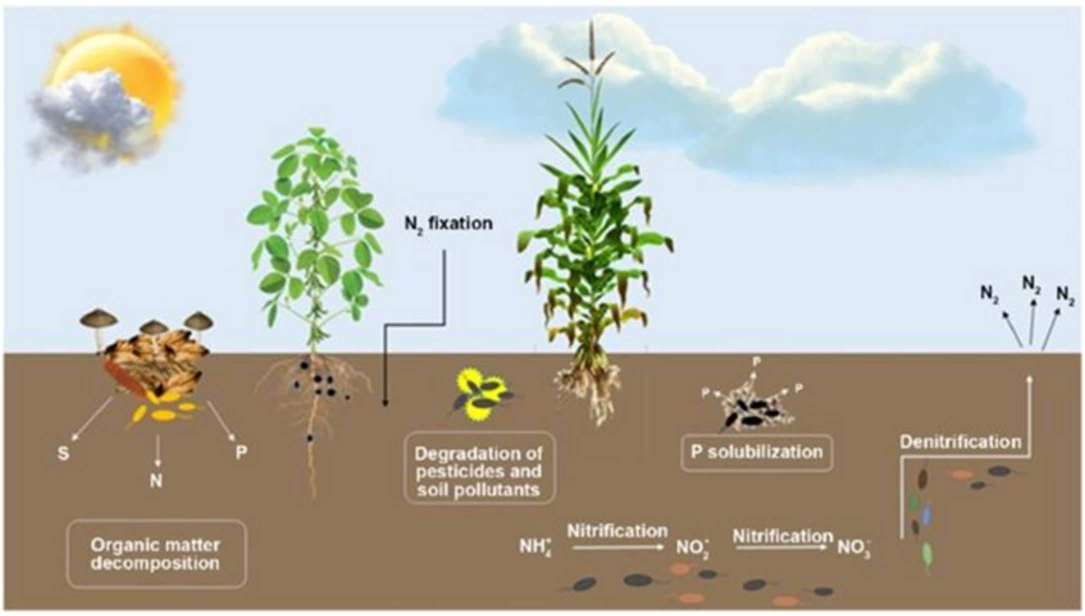

Figure 10. The role of microorganisms in nutrient cycling in agricultural soils (Martyna, 2019)

Legumes not only increase soil microbial activity, but also contribute to other ecosystem services. These plants reduce soil erosion, increase water holding capacity and support biodiversity. Furthermore, the ability of legumes to fix biological nitrogen promotes environmental sustainability by reducing the use of synthetic fertilizers. These characteristics enable legumes to play an important role in sustainable agricultural systems (Peoples et al., 2009). Legumes play an important role in sustainable agriculture approaches by enhancing soil microbial activity. These plants improve soil health through nitrogen fixation, organic matter contribution and mycorrhizal associations. In future research, the long-term effects of legumes in different cropping systems and their impact on the functional diversity of microbial communities should be studied in more detail. Furthermore, further studies on farming practices and management strategies are needed to optimize the effects of legumes on soil microbial activity.

6. Entomological and Disease Management

6.1. Biological control methods

Biological control is an environmentally friendly method that aims to control harmful organisms through their natural enemies. This method protects the health of agricultural ecosystems by reducing the negative effects of chemical pesticides. Biological control in legume cropping involves the use of microorganisms that promote plant growth and fight pathogens. For example, root colonizing bacterial species such as Pseudomonas and Bacillus species protect the root systems of plants and develop resistance to diseases (Sharma et al., 2020). At the same time, biopesticides ensure the protection of plants by using natural substances that act on pests. Such biological control agents are harmless to the environment and human health (Mishra et al., 2018). Among the biological control methods, the use of natural parasites and essential oils against bruchid beetles in stored legumes attracts attention. These methods allow control of pests without the use of chemical insecticides (Yamane, 2013).

Furthermore, the use of Trichoderma and Pseudomonas species against Fusarium wilt protects plant roots against pathogens and promotes plant growth (Sharma et al., 2020).

6.2. Integrated pest management (IPM) strategies

Integrated Pest Management (IPM) is a comprehensive strategy that combines a range of methods for the control of pest organisms. IPM minimizes the use of chemical pesticides while increasing environmental and economic sustainability. This strategy integrates biological, cultural, physical and chemical control methods. For example, IPM strategies against fungal foliar diseases such as Ascochyta blight and Botrytis mold in legumes include the use of resistant varieties, proper timing of planting and harvesting, and application of biological control agents (Vandana et al., 2020). IPM strategies optimize the timing of interventions against pests by monitoring pest populations and setting thresholds. These strategies ensure maximum productivity with minimal damage to the environment and human health (Mishra et al., 2018). Furthermore, IPM involves education and information to help farmers make informed decisions.

7. Climate Change and Adaptation Strategies

7.1. Impacts of climate change on legumes

Climate change affects many agricultural crops, including legumes, in various ways. Rising temperatures, changing rainfall patterns and increasing carbon dioxide levels can negatively affect legume yields and quality. These effects of climate change reduce water productivity, particularly by shortening the growing period of legumes due to temperature increases and rainfall irregularities (Bahl, 2015). Furthermore, increasing temperatures and changing humidity can increase the potential for the spread of diseases and pests in legumes, leading to production losses. Climate change can also affect the phenological stages of legumes, i.e. flowering and fruit set periods. This is a critical issue, especially for legumes growing in the warmer seasons. Although increased carbon dioxide levels may enhance growth in some legume species, this can often lead to reduced nutritional value and deterioration of product quality (Mohapatra et al., 2022).

7.2. Innovative approaches in sustainable agriculture

Sustainable agriculture involves a variety of innovative approaches to adapt to climate change and sustain agricultural production. These approaches include the application of climate-smart agricultural techniques, increasing genetic diversity and utilizing new technologies. Climate-smart agricultural techniques aim to reduce greenhouse gas emissions and increase water productivity by increasing soil organic carbon (Swami, 2023). Increasing genetic diversity can help develop legume species that are resilient to climate change. Selection and development of heat- and drought-tolerant species plays an important role in mitigating the negative impacts of climate change (Bahl, 2015). Furthermore, innovative practices such as greenhouse technology and genetic engineering are critical for increasing legume production and adapting to climate change (Kumar.,et al,, 2023). New and innovative soil-plant management systems are being implemented as part of climate-smart sustainable agriculture (CSSA) practices. These systems enable agricultural production to be adapted to climate change. For example, conservation tillage systems (CTS) based on conservation agriculture (CA) can be used to return crop residues to the soil, protecting soil health and enhancing environmental sustainability (Swami, 2023).

8. Conclusions and Recommendations

Legumes play an important role in sustainable agricultural practices. They improve soil health in crop rotation systems, increase biodiversity and support sustainability in agroecosystems. The nitrogen-fixing ability of legumes improves soil fertility and reduces the need for chemical fertilizers, thereby minimizing environmental impacts (Dai.,et al,, 2023). Furthermore, planting legumes increases soil organic matter content, supporting water-holding capacity and microbial activity (Oliveira et al., 2019). Legumes are also effectively used in biological control methods. Root colonizing bacteria such as Pseudomonas and Bacillus protect plant roots against pathogens and develop disease resistance (Sharma et al., 2020). Integrated Pest Management (IPM) strategies combine various biological and cultural methods to control pest populations in legumes and minimize the use of chemical pesticides (Vandana et al., 2020). Climate change can have several negative impacts on legumes. Rising temperatures, changing rainfall patterns and increasing carbon dioxide levels can reduce legume yields and quality (Bahl, 2015). However, sustainable agricultural practices and innovative approaches play a critical role in mitigating these negative impacts. Climate-friendly agricultural techniques aim to reduce greenhouse gas emissions and improve water productivity by increasing soil organic carbon (Swami, 2023). Consequently, the use of legumes in sustainable agriculture improves agricultural productivity and soil health while enhancing environmental sustainability. Integration of these crops with crop rotation, biological control and climate-smart agricultural practices constitutes an important step in increasing the success of sustainable agricultural systems.

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