Review Article

The Role of Grain Legumes in Enhancing Soil Health and Promoting Sustainable Agricultural Practices: A Review

ABSTRACT

It is commonly acknowledged that sustainable agricultural practices are essential, and that diversifying cropping systems is crucial to reaching this objective. Legumes made of grains are essential to farming systems because they provide benefits for both income creation and the security of food and nutrition. Legume-based cropping systems can help with a variety of agricultural issues, such as controlling pests and diseases, improving soil fertility, preserving biodiversity, and reducing food poverty. The function of legumes in sustainable agricultural systems is covered in this chapter, with an emphasis on the benefits of incorporating legumes into various agroecosystems and farming techniques. Legumes boost the potential for crop productivity, offering a calculated response to poor crop yields and assisting in the transition to more environmentally friendly farming methods. Additionally, due to their health and environmental benefits, it is crucial to focus on breeding grain legumes that optimize their natural ability for biological nitrogen fixation and thrive despite abiotic and biotic stresses, such as drought, salinity, extreme temperatures, and pathogen and insect infestations.

INTRODUCTION

Legumes, comprising over 20,000 species, represent the third-largest plant family and are a cornerstone of global food security, ranking just behind cereals in terms of consumption (Shafique *et al.*, 2014). These plants play a crucial role in diets worldwide by providing a significant source of nutritional protein when paired with cereals (Mashungwa*et al.*, 2019). One of the remarkable features of legumes is their ability to convert atmospheric nitrogen into ammonia through symbiotic relationships with rhizobia, a specific type of soil-borne bacteria, thereby enhancing soil fertility (Gonzalez-Rizzo *et al.*, 2009). This symbiosis enables legumes to adapt to adverse environmental conditions and nourish neighboring crops, contributing to sustainable agricultural practices (Popoola *et al.*, 2014).

Legumes are cultivated in various agricultural setups, including intercropping, monoculture, and rotational systems. Intercropping, long practiced by smallholder farmers in regions like Asia, Africa, and Latin America, is noted for maximizing yields from limited resources and space (Yu *et al.*, 2015). In arid areas, crops like pigeon peas (*Cajanus cajan*) are commonly interplanted with cereals due to their drought resilience (Semahegn, 2022). This method not only conserves space but also enhances cereal growth and productivity through nitrogen fixation and the enrichment of soil organic content (Yuvaraj *et al.*, 2020). When planning intercrops, farmers must consider various factors including species compatibility, planting timing, and the physical characteristics of the plants involved (Semahegn, 2022).

Conversely, monocropping legumes are generally discouraged due to its association with increased pest pressure, such as aphids, root-knot nematodes, and bruchid beetles, and nutrient depletion, particularly nitrogen, in the soil (Semahegn, 2022). Crop rotation, another sustainable practice, involves alternating different crops like maize and soybean or alfalfa on the same plot to optimize nutrient availability and water usage, which leads to maintained or increased yields (Zhen et al., 2016). Mixed cropping systems, incorporating legumes with cereals or tuber crops, leverage complementary resource use, reducing pest incidenceand soil erosion while improving biomass production and yield stability[91,92,93]

Recent years have seen a heightened focus on the roles of legumes in enhancing both human and animal nutrition and in addressing environmental degradation on smallholder farms (ICRISAT, 2016). Acknowledging these benefits, the Food and Agriculture Organization (FAO) of the United Nations highlighted the importance of pulses, designating 2016 as the International Year of Pulses to promote their cultivation (FAO, 2016). This review aims to underline the significant contributions of legume production systems to soil health and the sustainability of agricultural practices.

MATERIALS AND METHODS

The data utilized in this study were predominantly obtained from secondary sources, including scientific publications and official websites of esteemed research institutions. The collection process involved systematic desk research, where relevant materials were identified, downloaded, read, and referenced according to established best practices.

RESULTS AND DISCUSSION

Global Status of Legumes

From 2016 to 2020, the worldwide annual production of grain legumes was approximately 115.28 million tons, as shown in Table 1. The top producers of these legumes are India, Myanmar, Canada, China, and Brazil, which collectively account for half of the global output. The primary legumes cultivated globally include common beans, chickpeas, cowpeas, lentils, pigeon peas, groundnuts, soybeans, and grass peas, with their respective production details also summarized in Table 1.

According to Nigrum et al. (2021), the common bean leads in cultivation across 126 countries, making it the most extensively grown legume. Groundnuts are cultivated in 114 countries, while soybeans are grown in 89. Other widely grown legumes are chickpeas, lentils, cowpeas, pigeon peas, and grass peas. These staples are cultivated on nearly 212 million hectares worldwide, yielding approximately 421 million tonnes annually.

In terms of production efficiency, soybeans dominate with 56.5% of the productivity share, followed by common beans at 14.2%, and groundnuts at 12.8%. Other legumes such as chickpeas contribute 6.0%, cowpeas 5.8%, pigeon peas 2.5%, and lentils 2.2% of the total global production area (Nigrum et al., 2021).

Table 1: Average Yearly Worldwide Production of Legumes from 2016 to 2020

Legume	Production in Million Tons
Field peas	- 14.9
Chickpeas	- 50.19
Cowpeas	- 9.80
Faba beans (Broad beans)	- 22.55
Lentils	- 13.34
Pigeon peas	- 4.50

Table 2: Comparative Chemical Composition of Selected Legumes (Percentage-Based)

Legumes	Botanical names	Proteins	Fat	Carbohydrates	Fibre
Soybean	*Glycine max*	37-41	18-21	30-40	4-6
Cowpea	*Vigna unguiculata*	22-26	1-2	60-65	4-5
Groundnut	*Arachis hypogaea*	20-33	42-48	22-25	3-4
Hyacinth beans	*Lablab Purpureus*	24-28	1-2	65-70	7-9

Importance of Pulses for Human and Animal Nutrition

Grain legumes are pivotal in soil enhancement, and they significantly contribute to the food, feed, and fuel sectors due to their diverse nutritional and chemical properties, which vary by type, species, and soil health. This section explores how grain legumes benefit these key areas.

Nutritional Resource for Agricultural Communities

Since the early domestication of crops, grain legumes have been an essential part of human diets for millennia. In agricultural settings, they play a critical role in ensuring food and nutritional security. Grain legume seeds include a wealth of micro- and macronutrients, proteins, carbohydrates, soluble vitamins, insoluble fiber, and several bioactive phytochemicals (refer to Table 2) (Watson et al., 2017). With an average protein concentration of 20% to 45%, legumes have a substantially higher protein content than cereals, which typically have a protein content of 7%–17% (Day, 2013; Zander et al., 2016). They are great providers of lysine, an essential amino acid needed for the formation of proteins. But sulfur-containing amino acids, such as cysteine and methionine, which are essential for cellular development and integrity, are typically absent from them (Friedman, 1996). With the exception of groundnuts and soybeans, most legumes are high in calcium and phosphorus and low in cholesterol.Legumes have significant health benefits that differ depending on the species. For example, it is well recognized that products derived from soybeans can help prevent heart and vascular illnesses by controlling hypertension and lowering cholesterol (Harland and Haffner, 2008; Sirtoriet al., 2009). Moreover, studies on people have demonstrated that lupin and soybean reduce cholesterol (Sirtori et al., 2012). Food legumes play important and diverse functions in agricultural systems and the diets of people who are economically disadvantaged, making them important crops for achieving development objectives that include decreasing poverty and hunger, improving human health and nutrition, and enhancing ecosystem resilience.

Role of Grain Legumes in Livestock Nutrition

When added to whole plant feeds or concentrated compound feeds, grain legumes are a great feed choice for ruminants (Sherasia et al., 2018). The way they supplement forage diets, how quickly and thoroughly they break down nutritionally in the rumen, and their chemical makeup all influence how they are used in ruminant diets (Watson et al., 2017). Primarily, legumes increase the amount of protein in animal feed. Like most cereal grains, grain legumes have a protein degradability in the rumen that frequently surpasses 80% (Luke, 2016). The most widely consumed legume and the main supplier of extra plant protein in animal diets is soybeans.According to Świątkiewicz (2021), 84% of the high-protein oilseed meals used in compound livestock feeds worldwide—particularly in the pig and poultry industries—come from soybeans. Because of its high crude protein content (44%) and advantageous amino acid profile—which includes amino acids like methionine, cysteine, and tryptophan that are sometimes lacking in other grain legumes—soybean meal is very heavily used in the pig industry (Watson et al., 2017). In order to lessen reliance on soybeans, current research is looking into alternative feeds made of legumes. Ayadi et al. (2012) provided a review that outlines the efforts being made to assess the usage of plant-based proteins in the aquaculture sector.Also, research has demonstrated that substitutes for soybean-based meals in the sheep and cattle sectors, such as peas, lupins, rapeseed, or faba beans, can be used as the protein source during various stages of lactation without having a negative impact on milk production (White et al., 2007).

Legumes' Potential for Fixing Nitrogen

By fixing nitrogen, legumes improve soil fertility, which benefits soil quality and biodiversity (Yuvaraj et al., 2020; Okumu et al., 2017; Couto-Vazquez and González-Prieto, 2016). They associate symbiotically with bacteria that fix nitrogen, including those belonging to the Betaproteobacteria, Azorhizobium, and Alphaproteobacteria genera (Vasconcelos et al., 2020). These bacteria cause nodules, which are biological locations for fixing nitrogen, when they infiltrate the roots. Here, the nitrogenase enzyme helps the bacteria transform atmospheric nitrogen (N2) into ammonia, a type of nitrogen that plants can easily absorb (Howard and Rees, 1996; Ferguson et al., 2013; Ferguson et al., 2019). The type of legume, the type of bacteria involved, and abiotic elements like temperature, water availability, and the amount of nitrogen in the soil minerals all affect how efficient this biological process is (Otieno et al., 2018).

Climatic-Smart Crops: Legumes

Besides improving soil health, legumes are recognized as climate-smart crops due to their role in environmental quality enhancement through carbon sequestration and mitigation of other pollutants. According to a meta-analysis by Kumar et al. (2018), compared to other plant species, legumes store 30% more soil organic carbon (SOC). The quantity of organic carbon that legumes can sequester and return to the soil depends on a variety of factors, including the kind of legume, growth habits, root morphology, leaf structure, climate, soil structure, cropping system, and stage of agronomic techniques (Kumar et al., 2018). Guan *et al.* (2016) reported that perennial legumes increase SOC, a process influenced by factors such as turnover, root cell epidermal sloughing, and root exudation of soluble carbon compounds. For example, Gregorich *et al.* (2005) observed a linear increase in nitrous oxide emissions from soils treated with mineral fertilizers. Legumes have shown potential in reducing greenhouse gas (GHG) emissions, especially nitrous oxide, when used as green manures compared to nitrogen fertilizers, which tend to increase emissions. For instance, the application of alfalfa and other legume crops as green manures has been associated with lower annual nitrous oxide emissions, prompting recommendations for their consideration in national GHG records for agriculture (Abberton, 2010). In order to improve soil stability and increase organic matter, which is essential for soil formation, fertility, and yields, legumes are widely used as cover crops and intercrops (Martin Körschens, 2002; Howieson et al., 2008). Otieno et al.'s (2020) research showed that dry beans produced at high and sustainable levels could be achieved by using leftover fertilizer from previous maize crops. However, it's vital to recognize that the management of agroecosystems incorporating legumes also significantly affects their ability to reduce GHG emissions.

Using Legumes to Make Biofuels

Legume residues, which often contain higher protein concentrations than cereal crops—up to 10%—offer significant potential as a source of biofuel. Their biomass not only has high protein content but also allows for the extraction of protein as a by-product in biofuel production (Jensen *et al*., 2012). Since the early 20th century, various high oil and starch content plants like canola *(Brassica napus*)and soybean (*Glycine max*) have been used for biodiesel production (Biswas *et al*., 2011). For example, peanut oil was used in diesel engines for the first time in 1904. These legumes have seeds that must be crushed in order to extract the oil, which is subsequently extracted and transesterified to create biodiesel. In order to lessen dependency on fossil fuels, these oil crops can also be converted into high-value biochemicals and biomaterials. In the United States, soybeans are currently a primary feedstock for biodiesel, although in Europe, canola and rapeseed are more frequently utilized. Because of their high biomass yield per unit area and capacity to yield sizable amounts of oil from their seeds each year, these plants are ideal for the production of biodiesel. Plants grown particularly for energy production, as well as plant parts, leftovers, and other biomass can be used as feedstocks to produce energy.(US Department of Energy, 2013).

Systems for Producing Grain Legume

According to Watson and Stoddard (2017), grain legumes are crops that can be grown in a variety of ways, depending on the intended purpose, climatic conditions, and soil composition. These forms include dry grain, green fodder, arable silage, and green manure. Peas (Pisum sativum L.), lentils (Lens culinaris Medik.), common beans (Phaseolus vulgaris

L.), soybeans (Glycine max (L.) Merr.), faba beans (Vicia faba L.), chickpeas (Cicer arietinum L.), lupins (Lupinus spp.), and soya beans (Vanlauweet al., 2019). Legumes grow well as stand-alone crops or as excellent intercrops with cereals like maize and sugarcane. Solitary cropping has been replaced with intercropping, which has grown in significance in recent years. Higher cane equivalent yield, daily productivity, land equivalent ratio, and area time equivalent ratio were seen when growing French beans alongside fall sugarcane (Kumar et al., 2015).

Intercropping

When two or more crop species from different families are grown side by side for secondary purposes like soil improvement and nitrogen fixation, the result is known as intercropping. According to Meena and Lal (2018), this approach is used to improve species interaction, boost biodiversity, and assist farmers in adjusting to climatic abnormalities. The primary crop, accessible legume species, maturation times, growth stature, and farmer preference all play a role in the choice of intercrops for legumes. The species characteristics, potential for automation, growing status of the main crop and intercrop, current meteorological circumstances, and soil fertility must all be taken into account while planning planting patterns and spacing. When compared to monoculture, legume-based intercropping systems usually yield more from the same field and increase the effectiveness of natural resource utilization (Inal et al., 2007).According to Fustecet al. (2010), leguminous crops have an advantage over monoculture farming methods because they improve soil functions through biological nitrogen fixation. Legume-based intercropping minimizes the need for inorganic nitrogen fertilizers, which supports sustainable agricultural production methods and encourages environmentally friendly agriculture.

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Crop Rotation

Unlike monoculture, which is the continuous cultivation of a single crop, crop rotation is a farming method where different crops are cultivated in a predetermined repeating sequence on the same land (Sumner, 2018). When legumes are incorporated into rotations with maize or sorghum, this method improves crop production systems' sustainability and productivity (Keeler et al., 2009). Grain legumes can be grown as alternate crops in rotation to help the soil recover and diversify production, as noted by Schwember (2020). Crop rotation reduces pest and disease occurrences, increases soil fertility, and boosts soil biodiversity (Espinoza et al., 2012).Knight (2012) found that the frequency of legume rotation affects soil microbial activities and nitrogen fixation. However, Brouwer (2006) observed a trend in agricultural production systems toward specialization, which has resulted in a progressive loss of biological diversity and functions, such as the substitution of mineral fertilizers for biological nitrogen fixation or pesticides for ecological pest management (Zander et al., 2021). It is recommended that farmers rotate diverse crop species with different life cycles in order to optimize nutrient availability and minimize pest and disease problems (Cook, 2013; Garrison et al., 2014; Reckling et al., 2016).

Mixed Cropping

Planting a mix of legumes along with cereals or tuber crops is known as mixed cropping, and it is especially popular in marginal agroecological settings. In order to maximize the use of the resources available, this strategy complementarily uses soil nutrients, light, and water (Nigliet al., 2008; Dore et al., 2011). It not only reduces the prevalence of pests, diseases, and soil erosion but also enhances biomass and overall yields (Staniak*et al.*, 2014). Adjustments can be made to this cropping system to adapt to variables such as the onset of the rainy season or variations in soil fertility across fields (Weltzien *et al.*, 2017). Importantly, legume-cereal mixtures require lower nitrogen fertilizer inputs than sole cereal crops, resulting in higher protein content in cereal seeds. Research by Zarea *et al.* (2008) found that mixed cropping of forage legumes enhances the bacterial community in the soil, increasing the presence of free-living N_2-fixing bacteria and Azotobacter. Additionally, experiments involving yellow lupine mixed with wheat and oats showed the competitive potential of legumes against cereals (Staniak*et al.*, 2014). The allelopathic interactions within these mixtures can significantly affect plant growth and yield.

Monocropping

Due to its negative effects on the ecology and economy when compared to more varied farming methods using legumes, monocropping—the practice of cultivating a single crop again on the same land—is frequently prohibited (Nigliet al., 2008; Dore et al., 2011; Kebede, 2020). Studies showing that legume monocrops produced higher cumulative N_2O emissions than treated wheat suggest that this technique may cause problems like nitrate leaching and increased N_2O emissions (Senbayramet al., 2016). Farmers are recommended to use legumes in intercropping, rotational, or mixed cropping systems in order to address these restrictions.

Grain Legumes' Role in Sustainable Agriculture Production

The increasing number of people on the planet puts more strain on water and land resources, which is further compounded by pollution, global warming, and declining soil fertility (Swaroop and Lal, 2018). Legumes offer a viable alternative to support soil stability and enhance soil health when included in crop rotation and intercropping systems. They are integral to integrated soil fertility management, capable of fixing atmospheric nitrogen in symbiosis with rhizobia bacteria, thus providing significant organic matter that improves the soil's chemical, physical, and biological properties (Sa *et al.*, 2017). Studies have shown that including legumes as intercrops, particularly in maize farms, not only improves productivity but also maintains nutrient availability (Choudhary and Choudhury, 2018). Chimonyo*et al.* (2019) reported increased maize productivity within a legume-maize cropping system, attributed to improved soil water holding capacity and fertility. This enhancement in soil quality due to legume integration into cropping systems underlines their role in improving soil resilience to erosion and other degradative processes (Kintl*et al.*, 2015).

Table 3: Summary of Legume-Based Practices and Their Impact on Soil Health.

Use of residue and a system based on legumes for soil health	parameter evaluated	References
Maize-legume rotation **Legume residue**	Soil organic carbon, total N, exchangeable Ca, Mg, available P,	Uzoh *et al.* (2019); Kolawole (2013)

	and exchange K.	
Legume intercrop	Increased soil organic carbon improves the physical, chemical, and biological soil environment while lowering pest damage.	Hu *et al.* (2021)
Legume cover crops	Reduction of nitrous oxide emissions, BNF, conservation, and stocks of SOC and nitrogen.	Nees *et al.* (2010)
Legume residue	Physical properties of soil, i.e., structure, texture, density, stability, porosity.	Jena *et al.* (2022)

Enhancing Ecosystems through Legume Integration in Farming Systems

By increasing soil biodiversity and beneficial soil microorganisms, the addition of legumes to farming systems greatly enhances ecosystems (Meena et al., 2014). According to Lal (2013), these plants promote mineralization, provide defense against illnesses and pests, and lessen soil erosion. According to Sugiyama and Yazaki (2012), legumes have large root systems and release root exudates that significantly enhance the structure, dynamics, and general quality of soil nutrients.They are vital to the recycling of important nutrients like as carbon, phosphorus, and nitrogen. Green manure is made from a variety of legumes, including fenugreek (*Trigonella foenum-graecum* L.), velvet beans (*Mucuna pruriens* Bak.), vetches (*Vicia sativa* L.), clovers (*Trifolium* sp.), lupin (*Lupinus angustifolius* L.), and *Sesbania rostrata* and *Crotalaria spectabilis.* In this way, these plants improve the organic matter and nutrient availability of the soil, stimulating nitrogen stocks in rotational systems and improving the nutritional base for subsequent plantings (Hauggaard-Nielsen and Jensen, 2005).

Challenges of Sustainable Productivity and the Role of Legumes

Sustainable productivity poses significant challenges, particularly for developing countries where the misuse of agrochemicals has deteriorated soil health. Inappropriate and excessive use of fungicides to combat soil-borne diseases negatively impacts microbial composition, soil fertility, and grain production (Shahid *et al*., 2020). Legume-based crop rotations offer a more environmentally friendly solution by significantly enhancing soil microbial health and supporting nutrient mineralization, thus improving soil functions and overall productivity.

Legume Residues' Contribution to Soil Sustainability

Due to their relatively high nitrogen content, legume wastes are significant sources of mineral nitrogen for crops that come after (Kebede, 2021). Parts of decomposed legume plants play a major role in the transmission of nutrients below ground (Louarnet al., 2015). Legumes minimize soil moisture loss, lower evapotranspiration rates, and improve soil rootability by acting as both live and dead soil coverings (Moura et al., 2015).Using legume crop residues as an alternative method to improve soil fertility is noted by Sangare *et al.* (2016), although these residues do not immediately provide nitrogen but contribute to a long-term nitrogen pool in the soil (Formowitz*et al.*, 2009). Studies have shown that incorporating organic residues into the soil leads to increased crop yields (Gachengo*et al.*, 1999). High-biomass legume trees markedly enhanced carbon stocks in the litter and total organic carbon, according to research by Moura et al. (2014). According to Moura (2009), it's critical to consistently supply residues in order to preserve a balance between carbon inputs and rates of breakdown. It is suggested that the efficiency of mineral fertilizers as a soil amendment be increased by mixing them with the organic leftovers of legumes (Kouelo et al., 2013).

Constraints of Legume production

Legume production faces several significant constraints that hinder its potential benefits. Pests and diseases pose a major threat, leading to substantial yield and quality losses. Abiotic stresses, such as drought, extreme temperatures, and poor soil fertility, further challenge legume growth and productivity. Farmers often struggle with limited access to high-quality, disease-resistant seed varieties, which is critical for successful cultivation. Inadequate agronomic practices, including improper planting density, insufficient fertilization, and ineffective pest control, can also limit yields. Market constraints, such as poor infrastructure, price fluctuations, and limited market access, discourage investment in legume production. Additionally, insufficient investment in research and development restricts the availability of improved legume varieties and advanced cultivation techniques. Policy and institutional gaps exacerbate these issues by impeding the dissemination of necessary knowledge and resources. Addressing these constraints through targeted interventions, research, and supportive policies is essential to optimizingProducing legumes and utilizing them to their maximum capacity in sustainable agriculture (Panda *et al.*, 2019).

Conclusion

Food legumes play an important and varied function in farming systems and diets, especially in underprivileged populations. This makes them essential for accomplishing development objectives including decreasing hunger and poverty, boosting human health and nutrition, and strengthening ecosystem resilience.It is essential to incorporate legumes into agricultural systems to ensure resilient and sustainable agricultural livelihoods. Understanding the unique characteristics of each legume type and how they function within an agricultural context is key to addressing issues of low crop yields and promoting sustainable production.However, legume production faces several constraints, including pest and disease pressures, abiotic stresses like drought and extreme temperatures, limited access to quality seeds, inadequate agronomic practices, market constraints, lack of research and development, and policy and institutional gaps. Addressing these challenges through targeted interventions, research, and supportive policies is crucial for optimizing legume production and fully harnessing their potential to contribute to sustainable agricultural development and global food security.

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