1. ***Review Article***

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

ABSTRACT

The imperative for sustainable agricultural practices ~~is~~ widely recognized~~, with the~~ diversification of cropping systems playing a key role in achieving ~~this~~ the goal. Grain legumes are vital to farming systems, offering benefits in terms of food and nutrition security as well as income generation. Utilizing legume-based cropping systems can address multiple agricultural challenges including pest and disease management, low soil fertility, biodiversity conservation~~,~~ and food insecurity. This ~~chapter~~ review discusses the role of legumes in sustainable agricultural systems, specifically focusing on the advantages of integrating legumes within different agroecosystems and farming practices. Legumes enhance crop productivity potential, providing a strategic solution to low crop yields and supporting the shift towards ~~more~~ sustainable agricultural practices. 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~~time~~,~~ and the physical characteristics of the plants involved (Semahegn, 2022).

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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 incidence and 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

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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

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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~~ grain 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 countries. 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).

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Table 1: Average Annual Global Production of Grain Legumes from 2016 to 2020

Legume	Production in Million metric tonnes
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

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Significance of Grain Legumes for Human and Livestock 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

Grain legumes have been a fundamental component of human diets for millennia, tracing back to the early domestication of crops, and are crucial for achieving food and nutritional security in agricultural settings. The seeds of grain legumes are rich in proteins, starch, soluble vitamins, insoluble fiber, and various micro- and macro-nutrients, along with numerous bioactive phytochemicals (see Table 2) (Watson *et al.*, 2017). Legumes contain significantly more protein than cereals, typically ranging from 20% to 45% protein content, compared to 7%–17% found in cereals (Day, 2013; Zander *et al.*, 2016). They are excellent sources of the essential amino acid lysine, vital for protein synthesis. However, they generally lack sulphur-containing amino acids like methionine and cysteine, which are crucial for cellular integrity and growth (Friedman, 1996). Most legumes, with the exceptions of soybeans and groundnuts, are low in fat and are also rich in minerals such as calcium and phosphorus. The health benefits of legumes are substantial and vary by species. Soybean-based products, for instance, are known to mitigate heart and vascular diseases by reducing cholesterol levels and managing hypertension (Harland and Haffner, 2008; Sirtori*et al.*, 2009). Further, soybean and lupin have been shown to lower cholesterol in humans (Sirtori*et al.*, 2012). The crucial and varied roles of food legumes within agricultural systems and the diets of economically disadvantaged populations make them key crops for meeting development goals aimed at reducing poverty and hunger, boosting human health and nutrition, and strengthening ecosystem resilience.

Role of Grain Legumes in Livestock Nutrition

Grain legumes serve as an excellent feed option for ruminants, either as part of concentrated compound feeds or whole plant feeds (Sherasia *et al*., 2018). Their utilization in ruminant diets depends on their chemical composition, how well they complement forage diets, and the rate and extent of their nutritional breakdown in the rumen (Watson *et al.*, 2017). Legumes primarily augment the protein content in animal feeds. The protein degradability of grain legumes in the rumen, similar to most cereal grains, often exceeds 80% (Luke, 2016). Soybeans stand out as the most popular legume and the principal source of supplemental plant protein in animal feeds. Świątkiewicz (2021) estimates that soybeans account for 84% of the high-protein oilseed meals used in compound livestock rations globally, especially in the poultry and pig industries. The reliance on soybean meal is particularly strong in the pig sector due to its high crude protein content (44%) and a favorable amino acid profile, which includes amino acids that are often deficient in other grain legumes like methionine, cysteine, and tryptophan (Watson *et al.*, 2017). However, current research is exploring other legume-based feeds to reduce dependency on soybeans. In the aquaculture sector, efforts are being made to evaluate the use of plant-based proteins, as detailed in a review by Ayadi *et al*. (2012). Studies have also shown that in the cattle and sheep industries, alternatives such as peas, lupins, rapeseed, or faba beans can replace soybean-based meals as the protein source during different lactation phases without adversely affecting milk production (Khorasani *et al*., 2001; Froidmont and Bartiaux-Thill, 2004; White *et al*., 2007; Van der Pol *et al*., 2008; Tufarelli*et al*., 2012).

Potential of Legumes in Nitrogen Fixation

Legumes enhance soil fertility through nitrogen fixation, benefiting biodiversity and soil quality (Yuvaraj *et al*., 2020; Okumu *et al*., 2017; Couto-Vazquez and González-Prieto, 2016). They form symbiotic relationships with nitrogen-fixing bacteria from various genera of Alphaproteobacteria, Azorhizobium, and Betaproteobacteria (Vasconcelos *et al*., 2020). These bacteria invade the roots and develop nodules, sites of biological nitrogen fixation. Here, the bacteria convert atmospheric nitrogen (N2) into ammonia, a readily available form of nitrogen for plants, facilitated by the nitrogenase enzyme (Howard and Rees, 1996; Ferguson *et al*., 2013; Ferguson *et al*., 2019). The efficiency of this biological process depends on the legume species, the bacterial species involved, and abiotic factors such as temperature, water availability, and soil mineral nitrogen content (Otieno *et al*., 2018; Swaroop and Lal, 2018; Kebede, 2021).

Legumes as Climate-Smart Crops

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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. Kumar *et al.* (2018) conducted a meta-analysis indicating that legumes store 30% more soil organic carbon (SOC) than other plant species. The type of legume, growth habits, root morphology, leaf structure, climate, soil structure, cropping system, and stage of agronomic practices all influence their capacity for carbon sequestration and the amount of organic carbon they return to the soil (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. Legumes also contribute significantly to ecosystem services by reducing dependency on synthetic fertilizers, thereby lowering greenhouse gas emissions (Watson *et al*., 2017; Stagnari*et al*., 2017). 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). Legumes are frequently employed as intercrops and cover crops, enhancing soil stability and boosting organic matter, which is crucial for soil formation, fertility, and yields (Martin Körschens, 2002; Howieson *et al*., 2008). Research by Otieno *et al*. (2020) demonstrated sustainable and high production levels of dry beans utilizing residual fertilizer from preceding maize crops. However, it's vital to recognize that the management of agroecosystems incorporating legumes also significantly affects their ability to reduce GHG emissions.

Legumes as 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), juncea (B. juncea), and soybean (Glycine max) have been used for biodiesel production (Biswas *et al*., 2011). Peanut oil, for instance, was first utilized in diesel engines in 1904. The oil from these legumes is extracted by crushing the seeds and squeezing out the oil, which is then transesterified to produce biodiesel. These oil crops can also be transformed into high-value biochemicals and biomaterials, helping reduce reliance on fossil fuels. Currently, soybean serves as a major feedstock for biodiesel in the United States, while canola and rapeseed are more commonly used in Europe. These plants are highly suitable for biodiesel manufacture due to their ability to produce significant amounts of oil from their seeds annually and their high biomass yield per unit area. Biomass feedstocks for energy production can derive from plants grown specifically for energy, or from plant parts, leftovers, industrial wastes, and materials from animal and human activities (US Department of Energy, 2013).

Grain Legume Production Systems

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Grain legumes are versatile crops produced in various forms—such as dry grain, green forage, arable silage, and green manure—depending on climatic and soil conditions and the intended use (Watson and Stoddard, 2017). Several species are cultivated, including pea (Pisum sativum L.), lupins (Lupinus spp.), faba bean (Vicia faba L.), chickpea (Cicer arietinum L.), lentil (Lens culinaris Medik.), common bean (Phaseolus vulgaris L.), and soybean (Glycine max (L.) Merr.) (Vanlauwe*et al.*, 2019). Legumes may be grown as standalone crops or intercropped with cereals like maize and sugarcane very well. Intercropping has become more important in recent years, replacing solitary cropping. Growing of French bean with autumn sugarcane recorded higher cane equivalent yield, per day productivity, land equivalent ratio and area time equivalent ratio (Kumar *et al.*, 2015).

Intercropping

Intercropping involves growing two or more crop species from different families simultaneously, with one being the primary crop and the others serving secondary roles such as nitrogen fixation and soil improvement. This practice is utilized to enhance species interaction, increase biodiversity, and help farmers cope with climate anomalies (Meena and Lal, 2018). The selection of legume intercrops depends on the primary crop, legume species available, maturity periods, growth stature, and farmer preference. Planting configurations and spacing must consider species characteristics, mechanization potential, growth status of the main crop and intercrop, and prevailing climatic conditions and soil fertility. Legume-based intercropping systems typically result in higher production from the same field and improve the efficiency of natural resource use compared to mono-cropping (Inal *et al.*, 2007). Fustec*et al.* (2010) noted that leguminous crops enhance soil functions through biological nitrogen fixation, offering advantages over monoculture farming systems. Practicing legume-based intercropping promotes eco-friendly agriculture by minimizing the use of inorganic nitrogen fertilizers, thus supporting sustainable agricultural production systems.

Crop Rotation

Crop rotation is a farming system where different crops are grown in a specific recurrent sequence on the same land, as opposed to the continuous cultivation of a single crop (monoculture) (Sumner, 2018). This system enhances productivity and sustainability in crop production systems, especially when legumes are included in rotations with maize or sorghum (Keeler *et al.*, 2009). Schwember (2020) highlighted that cultivating grain legumes as alternative crops in rotation allows for soil recovery and diversifies production. Through crop rotation, soil biodiversity is enhanced, soil fertility is improved, and incidences of pests and diseases are reduced (Espinoza *et al.*, 2012). Legumes as part of crop rotations also improve soil structure, soil permeability, microbial activity, water holding capacity, and organic matter content, reducing reliance on chemical fertilizers and increasing biological diversity, thus boosting crop yields and the sustainability of production systems (Kumar *et al.*, 2022). Knight (2012) indicated that nitrogen fixation and soil microbial functions are influenced by the frequency with which legumes are rotated. However, Brouwer (2006) noted a trend toward specialization in agricultural production systems, which has led to a gradual reduction in diversity and a degradation of biological functions, such as replacing ecological

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pest management with pesticides or biological nitrogen fixation with mineral fertilizers (Zander *et al*., 2021). Farmers are encouraged to rotate different species of crops with varying life cycles to maximize pest and disease management while optimizing nutrient availability (Cook, 2013; Garrison *et al*., 2014; Reckling *et al*., 2016).

Mixed Cropping

Mixed cropping involves planting a combination of legumes with cereals or tuber crops, a practice particularly common in marginal agroecological environments. This method utilizes growth factors complementarily, including soil nutrients, light, and water, optimizing the use of available resources (Nigli*et 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 N2-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.

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Monocropping

Monocropping, the practice of growing a single crop repeatedly on the same land, is often discouraged due to its economic and environmental drawbacks compared to more diverse farming systems involving legumes (Nigli*et al*., 2008; Dore *et al*., 2011; Kebede, 2020). This method may lead to issues such as nitrate leaching and increased N_2O emissions, as seen in studies where legume monocrops produced higher cumulative N_2O emissions than fertilized wheat (Senbayram*et al*., 2016). Due to these limitations, farmers are advised to employ legumes within intercropping, rotational, or mixed cropping systems to mitigate these issues.

Contribution of Grain Legumes to Sustainable Agricultural Production

As global populations rise, pressure on water and land resources intensifies, exacerbated by soil degradation due to global warming, pollution, and loss of 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

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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.

Legume-based system and use of residue Soil health	**Soil parameters showing improvement ~~evaluated~~**	**References**
Maize-legume rotation	Total N, avail P, exchange K, Mg	Uzoh *et al.* (2019)
Legume residue	Soil organic carbon, total N, exchangeable Ca and Mg	Kolawole (2013)
Legume intercrop	Soil organic carbon, improving chemical, biological, and physical soil environment, reducing pest damage	Hu *et al.* (2021)
Legume cover crops	Conservation, SOC and nitrogen stocks, BNF, reduction in nitrous oxide emission	Nees *et al.* (2010)
Legume residue	Physical properties of soil, i.e., structure, texture, density, stability, porosity	Jena *et al.* (2022)

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Enhancing Ecosystems through Legume Integration in Farming Systems

Incorporating legumes into farming systems significantly strengthens ecosystems by boosting beneficial soil microbes and enhancing soil biodiversity (Meena *et al*., 2014). These plants facilitate nutrient mineralization, offering protection against pests and diseases, and reducing soil erosion (Lal, 2013). Legumes possess extensive root systems and secrete root exudates that greatly improve soil nutrient dynamics, structure, and overall quality (Sugiyama and Yazaki, 2012). They play a crucial role in recycling essential nutrients like nitrogen, phosphorus, and carbon. Various legumes, such as lupin (Lupinus angustifolius L.), vetches (Vicia sativa L.), velvet bean (Mucuna pruriens Bak.), fenugreek (Trigonella foenum-graecum L.), and clovers (Trifolium sp.), along with Crotalaria spectabilis and Sesbania rostrata, are utilized as green manure. When used in this capacity, these plants enhance soil organic matter and nutrient availability, enriching the nutrient base for successive plantings and boosting nitrogen stocks within rotational systems (Hauggaard-Nielsen and Jensen, 2005).

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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.

Contribution of Legume Residues to Soil Sustainability

Legume residues are valuable sources of mineral nitrogen for subsequent crops due to their relatively high nitrogen content (Kebede, 2021). Decomposed legume plant parts significantly contribute to below-ground nutrient transfer (Louarn*et al.*, 2015). Serving as both live and dead soil covers, legumes help reduce soil moisture loss, lower evapotranspiration rates, and enhance soil rootability (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 (Kouyate *et al.*, 2000; Gachengo*et al.*, 1999; Shafi *et al.*, 2007; Bakht *et al*., 2009). Research by Moura *et al.* (2014) demonstrated that high-biomass legume trees significantly increased carbon stocks in the litter and total organic carbon. Moura (2009) emphasized the importance of regularly adding residues to maintain a balance between carbon inputs and decomposition rates. Combining mineral fertilizers with organic residues from legumes is promoted as a method to enhance their efficiency in soil amendment (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 optimizing legume production and realizing their full potential in sustainable agriculture (Panda *et al*., 2019).

Conclusion

The diverse and pivotal role of food legumes in farming systems and diets, particularly in impoverished communities, makes them crucial for achieving developmental goals such as reducing poverty and hunger, improving human health and nutrition, and enhancing 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

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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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