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Review Article

Fertilization Strategies and Practices: A Study on Lentil

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Abstract
Lentil (*Lens culinaris*) has an important place in agriculture due to its high nutritional value and ability to fix nitrogen and contributes to sustainable agricultural practices by increasing soil fertility. Proper fertilization strategies in lentil farming play a critical role in terms of yield increase and soil health. Fertilization is optimized by providing the macro and micronutrients needed by the plant at the optimal timing and dosage. Lentils especially need nitrogen, phosphorus and potassium; nitrogen is essential for growth and development and is bio-fixed, phosphorus promotes root development and flowering, while potassium increases disease resistance and regulates water balance. Modern fertilization practices starts with soil analysis; available nutrient levels and pH values are determined to customize fertilization programs. Both organic and inorganic fertilizers are used in lentil farming. Organic fertilizers increase the organic matter content of the soil, supporting microbial activity and improving long-term soil health, while inorganic fertilizers provide a rapid source of nutrients to the plant. Recent research is examining the effects of fertilization strategies on lentil yield and quality and determining optimal fertilizer amounts and application timings. Over-fertilization can lead to economic losses and environmental pollution, while under-fertilization can negatively affect plant growth. The development of effective fertilization strategies in lentil agriculture will contribute to the achievement of efficient and environmentally friendly production targets.

Keywords: lentil, fertilizer, legumes, fertilization

1. Introduction

Lentil cultivation has been reported to have been practiced in the Middle East about 8,000 years ago. Therefore, lentil is known as the oldest variety of grain legumes. Lentils are widely cultivated worldwide, especially in Asia, America and Mediterranean countries. Nutritionally, lentils contain 23% protein, 59% carbohydrate, 1.8% fat and 0.2% ash. It also provides iron, calcium, phosphorus, magnesium, vitamin A and vitamin B. Worldwide lentil production has increased to an estimated 5.6 million hectares per year (Ramirez and Cantero., 2024). Turkey ranks 5th among the most produced legume crops and 4th in lentil and chickpea production worldwide (FAO., 2022).

Table 1. Top 10 lentil producing countries in the world (FAO, 2022)

Countries	Production (tons)
Canada	2 300 598
India	1 268 830
Australia	999 500
Türkiye	445 000
Russian Federation	257 895.62
Nepal	252 283
United States of America	248 980
Bangladesh	190 743
China, mainland	167 441.25
Kazakhstan	145 942.21

Lentil is gaining more and more attention in the agricultural industry due to its resilience to climate change, low water requirement and nitrogen fixing properties. The lentil plays an important role in improving soil fertility as it has the ability to fix nitrogen into the soil through its roots (Erskine et al., 2009). This feature allows lentils to be used both as a rotation crop and preferred in sustainable agriculture practices. Lentil is an economically important food source as it is drought resistant and can grow even in poor soils (Sarker et al., 2003).

Fertilization is an important method in plant breeding and increases productivity by meeting the nutrient needs of plants. In lentil cultivation, correct fertilization strategies are critical for achieving high yields and quality products. A balanced supply of essential nutrients such as nitrogen, phosphorus, potassium and micronutrients promote plant growth and increases disease resistance (Kumar et al., 2021). Fertilization strategies and practices are an important component of sustainable agricultural practices as well as increasing productivity in crop production. In order to achieve optimum yield and quality of lentil, correct fertilization strategies should be determined and applied (Sharma et al., 2021).

2. Essential nutrient content in lentils

Lentil (*Lens culinaris*) is a legume widely consumed in the world and attracts attention with its nutritional properties. Its essential nutrients include protein, folate, iron, manganese and phosphorus. It also contains various bioactive compounds such as flavonoids, phenolic acids, proanthocyanidins and phytic acid. These compounds contribute to the antioxidant capacity of lentils and processing methods (cooking, germination and fermentation) can alter the content of these compounds. For example, some processing processes can lead to the release of phenolic compounds and increase antioxidant activity (Amarowicz and Pegg, 2023). A study in Botswana investigated the presence of minerals such as calcium (Ca), iron (Fe), magnesium (Mg) and zinc (Zn), and heavy metals (cadmium and lead) in lentil, sugar bean and groundnut samples. Lentils were found to be rich in these essential minerals and had very low concentrations of heavy metals. This shows that lentils retain their nutritional value and are a healthy food source (Gontse et al., 2020). Lentils show genetic diversity in protein and other minerals (iron, zinc, selenium, folates, carotenoids and vitamins). Therefore, lentils have been recognized as an ideal crop for biofortification with micronutrients.

Biofortification is a promising method to address micronutrient deficiencies, especially in developing countries. This process can involve the utilization of genetic diversity and enhancement of nutrient content through traditional plant breeding methods (Kumar and Singh, 2021). A comprehensive review of the nutrient content of lentils revealed that this crop is low in fat, fiber and anti-nutritive factors. It was stated that anti-nutritive factors can be controlled by cooking and processing processes, thereby increasing the nutritive value of lentils. Lentils have the potential as a protein concentrate that can be used in the production of various products such as soybeans. It stands out as an important solution to malnutrition and protein deficiency, especially in developing countries (Sharma et al., 2022).

In a study of the macro- and micronutrient content of 234 different lentil germplasm, the identification of high nutrient variants was seen as an important step for the development of nutritious lentil varieties. This study showed significant correlations between nutrient contents. For example, a positive correlation was found between calcium and magnesium. This diversity can be used to develop more nutritious lentil varieties (Sarker et al., 2017). Lentils are an important food source as they are rich in both essential nutrients and bioactive compounds. Its regular consumption can provide several health benefits, in particular, it can help prevent cellular damage thanks to its antioxidant activities. Furthermore, the nutrient content of lentils can vary according to processing and cooking methods, so it is important to choose these methods carefully for optimal nutrient intake.

3. Fundamental fertilization studies in lentils

Effective fertilization practices are of great importance in lentil farming to increase yield and maintain plant health (Muehlbauer et al., 2002). Being a nitrogen-fixing legume, lentils convert atmospheric nitrogen into a soil-available form, reducing the need for nitrogen fertilizers (Gan et al., 2005). However, phosphorus and potassium fertilization is important for sustainability of soil fertility (Singh et al., 2016). Phosphorus fertilization promotes lentil root development and nodulation (Pahlavan-Rad et al., 2009). Potassium increases the water-holding capacity of the plant and strengthens its resistance to stress conditions (Sarker et al., 2018). The inclusion of zinc and boron as micronutrients in fertilization programs positively affects the overall health and yield of lentil (Rehman et al., 2017). Organic fertilizers improve soil structure and increase microbial activity (Sarıkamış et al., 2009). Integrated fertilization methods, the combination of both chemical and organic fertilizers, are recommended for sustainable agricultural practices (Saeed, 2012). Green manuring increases soil organic matter content prior to lentil planting, leading to better uptake of plant nutrients (Somasundaram et al., 2007). Soil analysis in lentil cultivation is critical for determining the right fertilization strategies (Naeem et al., 2010). Yield-enhancing microbial inoculants can be applied to the root zone of lentil to optimize nutrient uptake (Ahmed et al., 2008).

4. Nitrogen fixation and nodule formation in lentil

Lentil (*Lens culinaris*), as an important member of the legume family, plays an important role in agroecosystems through its ability to fix biological nitrogen (BAF). This process is carried out by Rhizobium bacteria that live symbiotically in the roots of the plant. Lentils convert free nitrogen in the atmosphere into plant-available form, reducing the need for nitrogen fertilizers and increasing soil fertility.

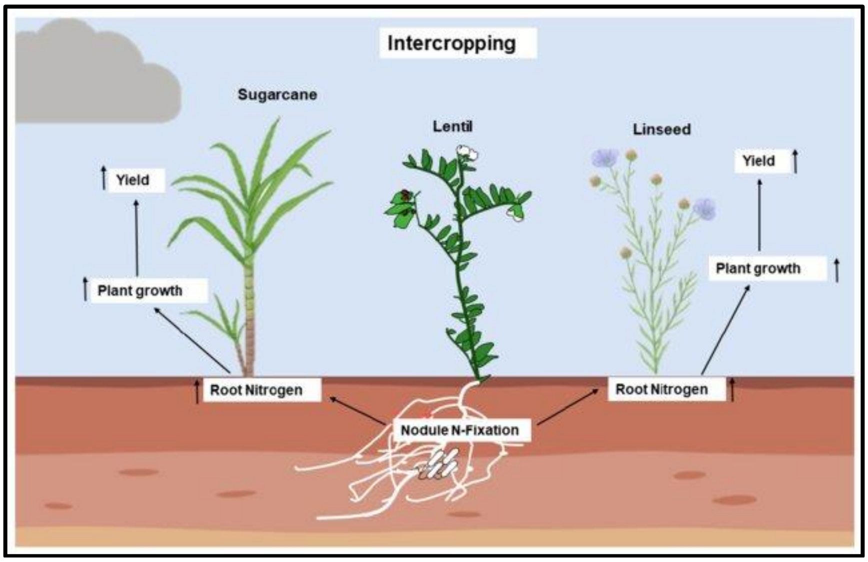

Figure 1. Co-cropping of lentils (Ramirez and Cantero, 2024)

The intercropping of lentils with other crops of economic value (Figure 1.) is a useful strategy that allows non-nodule-forming plants to obtain more nitrogen from legumes and thus achieve higher yields (Ramirez and Cantero, 2024).

4.1. Nitrogen fixation process

Nitrogen fixation starts when Rhizobium bacteria convert atmospheric nitrogen (N2) into ammonia (NH3). This process takes place thanks to the enzyme nitrogenase, which the bacteria possess. The ammonia is then absorbed by the plant roots and converted into amino acids and other nitrogenous compounds necessary for plant growth (Sprent, 2001). In this process, the plant provides carbohydrates and energy to the bacteria and the bacteria provide nitrogen to the plant, thus forming a mutualistic relationship (Peoples et al., 2009).

4.2. Nodule formation and development

Nodule formation starts when bacteria infect root hairs. Bacteria infect root cells through flavonoid signaling and reach the root cortex through the infection tube. Here cell division is triggered and nodules form (Oldroyd and Downie, 2008). The nodules provide the environment necessary for nitrogen fixation and enable the bacteria to convert free nitrogen into ammonia. The nitrogen fixing efficiency of lentil is greatly influenced by environmental factors. Factors such as soil pH, moisture, temperature and the availability of nutrients determine nodule formation and nitrogen fixing capacity. For example, slightly acidic or neutral pH levels are most favorable for nodulation (Ramaekers et al., 2010). Furthermore, micronutrients such as phosphorus, calcium and molybdenum support nodule formation and optimize nitrogen fixation (Schulze et al., 2006).

4.3. Agricultural importance of nitrogen fixation

Nitrogen fixation is an important process in agricultural production because it increases the nitrogen content of the soil, providing nutrients essential for plant growth. This process is carried out by Rhizobium bacteria that live on the roots of legume plants, converting free nitrogen in the atmosphere into a form usable by plants. Nitrogen fixation reduces the use of chemical fertilizers, making agriculture more sustainable. Legumes such as lentils can be used in crop rotations due to their ability to fix nitrogen, increasing soil fertility.

This is particularly important in organic farming, where the biological balance of the soil is maintained, productivity increases in the long term. Nitrogen-fixing plants grow well even on soils with low nitrogen content, which allows marginal soils to be brought into agriculture. Furthermore, when nitrogen-fixing crops are intercropped with other crops, their nitrogen needs are also met. This process increases plant resilience to stress conditions and improves overall plant health. Nitrogen fixation also has economic benefits (Telles et al., 2023). These benefits include reducing costs and enhancing environmental sustainability by reducing reliance on nitrogen fertilizers in the agricultural sector. For example, nitrogen-fixing crops minimize the need for external fertilizers by using natural nitrogen sources in the soil. This results in significant economic savings for farmers, in addition, environmental problems caused by the overuse of nitrogen fertilizers can be reduced by the widespread use of nitrogen-fixing crops (Bloch et al., 2020). This process improves long-term agricultural productivity by improving soil quality and preventing pollution of water resources (Vasconcelos et al., 2020). Research on the environmental and economic benefits of nitrogen fixation emphasizes that this practice is an important component for sustainable agriculture. For example, nitrogen-fixing plants increase the natural fertility of the soil by converting free nitrogen in the atmosphere into a usable form in the soil (Langholtz et al., 2021). This results in less use of chemical fertilizers and thus lower agricultural production costs (Soumare et al., 2020). At the same time, reducing fossil fuels used in the production of nitrogen fertilizers contributes to environmental sustainability by reducing the carbon footprint (Goyal et al., 2021).

In conclusion, nitrogen fixation has an important role in agricultural production both economically and environmentally. The biological nitrogen fixing capacity of lentil is critical for increasing agricultural productivity. When intercropped with other crops, lentils enrich the nitrogen content of the soil and reduce the need for chemical fertilizers. This provides both economic and environmental benefits (Gan et al., 2005). Furthermore, lentil cultivation improves soil structure and increases soil water holding capacity (Sarker et al., 2018). Many scientific studies have focused on the nitrogen fixing capacity of lentils and the agricultural importance of this process. For example, Peoples et al. (2009) examined the effects of lentil's biological nitrogen fixing ability on nitrogen cycling in agricultural systems. These studies showed how lentils support productivity by increasing the nitrogen content of the soil. Oldroyd and Downie (2008) detailed the genetic and molecular mechanisms of nodule formation and identified key factors in this process.

4.4. Optimization of nitrogen fixation

Nitrogen fixation plays an important role in improving the agricultural productivity of legumes and optimization of this process is critical for the success of sustainable agricultural practices. The efficiency of the nitrogen fixation process depends on several biological and environmental factors. Proper management of these factors maximizes the nitrogen-fixing capacity of legumes and improves soil fertility. Various agronomic practices and technologies have been developed to enhance the nitrogen-fixing capacity of legumes. For example, by using microbial inoculants, it is possible to increase root nodulation and nitrogen fixation (Ahmed et al., 2008). Furthermore, integrated fertilization strategies can optimize nitrogen fixation and contribute to sustainable agricultural practices by including a combination of both chemical and organic fertilizers (Saeed, 2012). Inoculation of lentil seeds with Rhizobium plays an important role in meeting the nitrogen requirement of the plant. This method both reduces the use of chemical fertilizers and offers an environmentally friendly approach (Zahran, 1999).

5. Soil analysis and determination of fertilization program

Soil analysis and determining the right fertilization programs are vital to improve yield and quality in lentil production. These processes aim to achieve healthy and high-yielding crops by providing the nutrients needed by plants at optimal levels. In this section, the importance of soil analysis and determination of fertilization programs will be discussed in detail.

5.1. Importance of soil analysis

Soil analysis is the first step necessary to increase productivity in agricultural production. Determining the physical and chemical properties of soil helps to provide the right amounts of nutrients needed by plants. Soil analysis provides important information such as pH value, organic matter content, levels of macro and micronutrients (Jones, 2001). Soil analysis can be done by various methods. Laboratory analyses determine the levels of soil pH, electrical conductivity (EC), organic matter, nitrogen (N), phosphorus (P), potassium (K) and other nutrients. These analyses are carried out by taking soil samples from certain depths and sending them to laboratories (Benton Jones, 2001). Soil pH directly affects the capacity of plants to take up nutrients. Lentils perform best in neutral and slightly acidic soils (pH 6.0-7.5). A favorable soil pH ensures that nutrients are easily taken up by the plant (Brady and Weil, 2008). Soil organic matter content is critical for water holding capacity, aeration and nutrient retention. Sufficient organic matter supports microorganism activity and increases soil fertility (Stevenson, 1994).

Lentil requires certain nutrients during growth and development. The correct fertilization program provides the nutrients required by the plant at optimal levels, resulting in high yields and high-quality products (Muehlbauer McPhee, 2005). Macronutrients (N, P, K) and micronutrients (Zn, Fe, Mn, Cu, B) are essential for plant growth. Soil analysis determines the levels of these elements and helps to establish fertilization programs to address deficiencies (Havlin et al., 1999). Integrated nutrient management (INM) optimizes soil fertility and plant nutrition using a combination of organic and inorganic fertilizers. This approach supports sustainable agricultural practices and maintains long-term soil health (Gruhn et al., 2000). Timing of fertilizer application ensures efficient use of plant nutrients. Fertilizer applications before planting, during planting and during growth periods are important in meeting plant nutrient requirements Planning fertilization programs based on soil analysis results is a critical step in increasing yield and quality in lentil production. These programs include the timely application of nutrients in the right amounts in accordance with the growth stages of the plant (Havlin., 2020).

5.2. Fertilizer type and properties

Fertilizers are organic or inorganic substances applied to the soil to support the growth and development of plants. Fertilizers provide essential nutrients that plants need and increase soil fertility. Macronutrients required for healthy plant growth include nitrogen (N), phosphorus (P) and potassium (K), while micronutrients include zinc (Zn), iron (Fe), copper (Cu) and molybdenum (Mo) (Havlin.,2020). Nitrogen deficiency is characterized by slow plant growth and yellowing of leaves. Phosphorus deficiency negatively affects root development and disrupts the plant's energy metabolism. Potassium deficiency weakens the plant's water balance and disease resistance (Hossain et al., 2019).

Micronutrients are essential in small amounts for plant growth and health, but their deficiency can lead to serious problems. Zinc deficiency is characterized by stunted growth and small leaves. Iron deficiency causes leaf yellowing, called chlorosis. Molybdenum deficiency negatively affects nitrogen fixation and enzyme activities (Singh and Singh, 2013). Fertilizers that can be used in lentil fertilization include nitrogen fertilizers, phosphorus fertilizers, potassium fertilizers and fertilizers containing micronutrients. Fertilizers can be divided into chemical, organic, microbial and green fertilizers.

5.3. Chemical fertilizers

Produced from inorganic compounds, these fertilizers enable plants to receive nutrients quickly and directly. Nitrogen fertilizers (urea, ammonium nitrate), phosphorus fertilizers (superphosphate) and potassium fertilizers (potassium sulphate) are examples of chemical fertilizers. These fertilizers are fast-acting and quickly correct plant nutrient deficiencies (Sutton, 2011). The application of chemical fertilizers at the appropriate amount and time increases productivity and minimizes environmental impacts (Tilman et al., 2002). Studies on the types and effects of chemical fertilizers show that when used correctly, they can increase crop productivity, but their overuse can cause environmental impacts (Kumar et al., 2020). Excessive use of chemical fertilizers can contaminate soil and water resources and adversely affect plant health (Brady and Weil, 2008).

5.4. Nitrogen fertilization

Although lentil is a nitrogen fixing plant, the application of nitrogen fertilizers before planting promotes the early development of the plant. Nitrogen promotes the development of green parts of plants and helps to build stronger root systems (Peoples et al., 2009). Minimal nitrogen applications before or during planting promote plant development without negatively affecting the nodulation process (Miller et al., 2002).

5.5. Phosphorus fertilization

Phosphorus enhances root development and nodulation of lentils. Phosphorus deficiency can negatively affect plant growth and nitrogen fixation. The use of phosphorus fertilizers such as superphosphate increases the productivity of lentils (Ramaekers et al., 2010). Phosphorus is also important for energy transfer and cell division, so correct phosphorus fertilization optimizes plant metabolism (Schulze et al., 2006). Phosphorus fertilization should be made according to the results of soil analysis and the amount needed by the plant should be provided (Havlin et al., 1999).

5.6. Potassium fertilization

Potassium improves water regulation and stress tolerance of plants. For lentil, potassium is critical for strengthening cell walls and developing disease resistance. Fertilizers such as potassium sulfate can be used in lentil agriculture (Sarker et al., 2003). Potassium is also essential for enzyme activity and protein synthesis, which directly affects plant health and productivity (Marschner, 2011). Lentil needs sufficient potassium during the growth period. Potassium fertilization should be made according to the results of soil analysis and deficiencies should be eliminated (Brady and Weil, 2008).

5.7. Micronutrient elements

Micronutrients are essential for plant growth and development. In particular, the addition of elements such as zinc, boron and molybdenum to the soil increases yield and quality. Micronutrient deficiencies can adversely affect plant development, which can lead to yield losses (Rengel, 2015).

5.8. Organic fertilizers

Organic fertilizers are obtained from organic materials of plant and animal origin. Compost, stable manure and green manure fall into this category. Organic fertilizers increase soil organic matter content and support water holding capacity and microbial activity (Brady and Weil, 2008). Research on the types and effects of organic fertilizers shows that they can improve soil health and support plant growth by providing slow release of nutrients (Singh et al.,2023).The use of organic fertilizers improves soil structure and can ensure sustainable soil fertility in the long term. (Pimentel et al., 2014). It also improves the overall health of the soil, reducing problems such as soil salinity and acidity caused by chemical fertilizers (Eghball, 2002).

5.9. Microbial fertilizers

Fertilizers that encourage the growth of beneficial microorganisms in the root zones of plants. Bacteria such as Rhizobium, mycorrhiza and Azospirillum are used in such fertilizers. Microbial fertilizers provide benefits such as nitrogen fixation and phosphorus solubility (Vessey, 2003). These fertilizers increase soil microbial diversity while promoting plant growth (Compant et al., 2005). The use of microbial fertilizers supports the overall health and productivity of the lentil (Ahmed et al, 2008). Microbial inoculants increase soil biological activity by supporting the natural nitrogen cycle (Döbereiner, 1997).

5.10. Mycorrhiza applications

Mycorrhizal fungi form a symbiotic relationship with plant roots to increase the uptake of nutrients. These fungi are particularly effective in phosphorus uptake and promote plant growth. Mycorrhizal applications are an effective method to improve lentil nutrition (Smith and Read, 2008).

5.11. Microbial inoculants

Microbial inoculants can increase nitrogen fixing capacity by applying nitrogen fixing bacteria (e.g. Rhizobium spp.) to seeds or soil. This method is particularly effective in nitrogen-poor soils, promoting the formation of more nodules on the roots of plants (Ahmed et al., 2008). The use of inoculants enhances plant-bacteria symbiosis and increases the efficiency of nitrogen fixation (Brockwell et al., 2002).

6. Advanced biotechnological approaches and fertilization

Genetic engineering can be used to give lentil traits that enable them to utilize nutrients more efficiently. For example, plant varieties with improved nitrogen use efficiency allow for higher yields with less fertilizer (Muehlbauer McPhee, 2005).

Biotechnological research offers new approaches to optimize plant nutrition and fertilization programs. Omics technologies such as genomics, proteomics and metabolomics help us better understand the effects of nutrients on plant growth and development (Kumar et al., 2021).

6.1. Plant-bacteria relations and fertilization

Symbiotic microorganisms, such as Rhizobium bacteria, play a critical role in meeting the nitrogen requirements of the lentil. Bacterial inoculation and biotechnological approaches improve plant nutrient uptake by optimizing plant-microorganism relationships (Zahran, 1999).

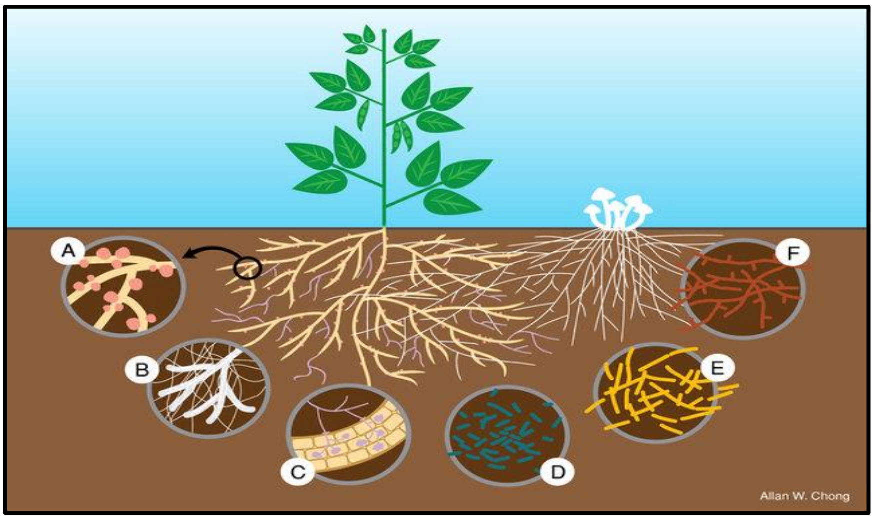

Figure 2. Diagram of underground interactions of a nodule-forming legume with various microorganisms (Martinez Hidalgo and Hirsch, 2017).

Figure 2; A, Magnified view of nitrogen-fixing nodules on the roots of the plant (circled). B, Ectomycorrhizal relationships are often established with legume tree roots. But fungi are excluded. C, Arbuscular mycorrhizal fungi interact with legume roots using the same symbiotic pathway used by Rhizobium. D, Gram-negative bacteria found in soil, such as Pseudomonas, Klebsiella and Ochrobactrum species, settle in the rhizosphere and some species can form nodules on legumes. E, Gram-positive microorganisms such as Bacillus, Paenibacillus, Lysinobacillus and others are found in the rhizosphere and also in nodules. F, Actinomycetes, such as Micromonospora, Streptomyces and nitrogen-fixing Frankia, enhance plant growth (Martinez Hidalgo and Hirsch, 2017).

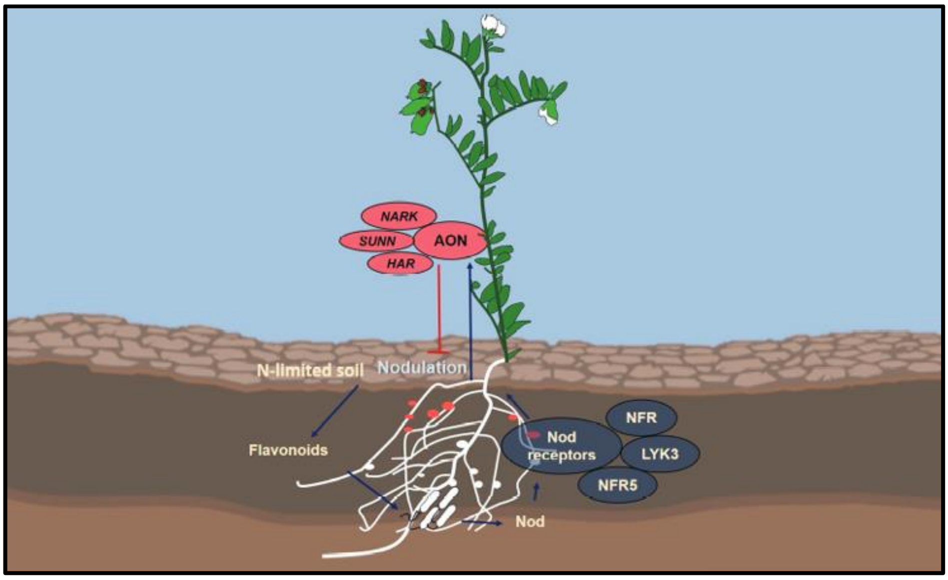

Figure 3. Legume-Rhizobium relationship (Ramirez and Cantero, 2024).

During the interaction with rhizobium, legumes release flavonoids that are sensed by the bacteria and the synthesis of nodulation factors (Nod) is activated. Nod factors are sensed by legume roots through receptors such as NFR, LYK3 and NFR5 (Nod receptors). Since nodulation is an energetically costly process, the plant engages in the autoregulation of nodulation (AON) process, which involves genes such as NARK, SUNN and HAR that control nodule formation. Blue arrows indicate activation, while red arrows indicate suppression. Overuse of fertilizers not only creates health and pollution problems, but also affects the establishment of biological mechanisms used by legumes to cope with N2 deficiency in agricultural soils (Ramirez and Cantero, 2024).

Soil analysis and determining the right fertilization programs are critical for increasing yield and quality in lentil production. Soil analysis helps to determine the nutrients needed by plants and to eliminate deficiencies. The right fertilization programs provide the nutrients that plants need during growth and development periods, resulting in high yield and quality products. These strategies are indispensable for sustainable agricultural practices and economic agricultural production.

7. Agricultural and Biotechnological Strategies to Improve Yield and Quality

Various agronomic and biotechnological strategies are used to improve yield and quality in lentil production. These strategies range from modern agricultural techniques to genetic engineering practices. In this section, various agronomic and biotechnological strategies used to improve yield and quality in lentil production will be discussed.

7.1. Improving soil fertility and structure

Soil fertility is a critical factor in lentil production. The use of organic fertilizers and compost is recommended to improve the physical and chemical properties of the soil. Adding organic matter improves soil water holding capacity and aeration (Campbell, 2018). In addition, regulating soil pH and adding essential micronutrients have positive effects on yield.

7.2. Water management

Lentils are sensitive to water stress. Optimal irrigation methods are important in increasing plant growth and yield. Methods such as drip irrigation and sprinkler irrigation ensure efficient use of water and meet the water needs of the plant (Singh et al., 2017). Water management strategies are critical to increase lentil production, especially in arid regions.

7.3. Planting time and frequency

The right sowing time is critical for lentils to achieve optimum growth conditions. Determining the optimal sowing time depending on the region and climatic conditions increases yields. For example, early sowing allows plants to have a longer growth period, which can increase yields (Sarker et al., 2013). Sowing density affects competition between plants and disease risk. Optimal planting density ensures the most efficient use of resources per plant. Too dense planting can increase competition between plants and reduce yields, while too sparse planting can lead to inefficient use of resources (Erskine et al., 1989).

7.4. Disease and pest management

Lentil crops are susceptible to various fungal, bacterial and viral diseases. Integrated disease management (IPM) strategies are effective in controlling diseases. These strategies include the use of resistant varieties, biological control agents and chemical spraying. IPM increases productivity while minimizing the environmental impact of diseases (Bayaa et al., 1997). Pests can cause serious losses in lentil production. Biological control methods in pest management are an effective strategy to reduce pest populations. For example, the use of natural enemies can be effective in controlling pests (Sharma et al., 2012).

8. Genetic and biotechnological approaches

8.1. Genetic diversity and breeding

Increasing genetic diversity increases the resilience of plants to environmental stresses. High yielding and resistant lentil varieties have been developed using traditional breeding methods and modern techniques such as marker-assisted selection (MAS). These methods accelerate plant breeding processes and allow the development of more resistant plant varieties (Sarker and Erskine, 2006).

8.2. Genetic engineering

Genetic engineering techniques enable the rapid introduction of desired traits in the genetic makeup of lentil. For example, transferring drought and salinity tolerance genes into lentil can improve plant performance. These methods allow the development of lentil varieties that are more resistant to climate change and environmental stress factors (Muehlbauer and McPhee, 2005).

8.3. Omics technologies

Omics technologies such as genomics, proteomics and metabolomics are helping us to better understand plant biology. By studying plant development and stress responses, these technologies enable us to develop strategies to improve yield and quality. Omics technologies revolutionize plant biology research and support breeding and biotechnology studies (Kumar et al., 2021).

9. Ecological and sustainable practices

9.1. Green fertilization and rotation

Sustainable agricultural practices have gained importance to solve the environmental problems faced by modern agriculture. Green manuring and crop rotation are among these practices. These methods are used to improve soil fertility, control diseases and pests, and conserve biodiversity. In this article, definitions, benefits, examples and citations from the academic literature on green manuring and crop rotation will be examined in detail.

9.2. Green fertilization

Green manuring is an agricultural practice in which farmers grow and mix certain plants into the soil to increase soil nutrients and improve its structure. Green manure crops generally include legume species that grow fast and add organic matter to the soil. Green manure plants increase productivity by increasing the organic matter content of the soil. It also improves the water holding capacity and aeration of the soil. This supports root development of plants and increases the uptake of nutrients (Campbell, 2018). Legumes in particular increase the nitrogen content of the soil by fixing nitrogen from the atmosphere. This provides an important nutrient for subsequent cropping periods (Zahran, 1999). The root systems of green manure crops stabilize the soil structure and prevent erosion. Furthermore, these plants increase soil water permeability and reduce surface runoff (Tilman et al., 2002). Vetch (Vicia spp.), a legume, is widely used for green manuring. The vetch plant adds significant amounts of nitrogen and organic matter to the soil during the growth process. This plant is usually grown before or after cereal sowing and is applied by mixing it into the soil.

9.3. Crop rotation

Crop rotation is the method of planting different plant species consecutively in a given agricultural area. This practice ensures that diseases and pests are controlled, soil structure is maintained, nutrients are utilized in a balanced way. Rotation prevents the accumulation of diseases and pests by preventing the successive planting of plants susceptible to the same pathogen or pest. This reduces the need for chemical pesticides and maintains ecosystem health (Altieri, 2018). Different plants take up nutrients from different layers of the soil and prevent soil depletion of a particular nutrient. For example, deep-rooted plants take nutrients from the lower soil layers, while surface-rooted plants take nutrients from the upper layer (Bullock, 1992). Rotation keeps weed populations under control by planting different plant species. This reduces the need for chemical herbicides and preserves natural vegetation (Liebman and Dyck, 1993). Corn (Zea mays) and soybean (Glycine max) rotation is a common practice. While maize is a nitrogen consuming crop, soybean fixes nitrogen and contributes nitrogen to the soil. This rotation is beneficial for the nutrient balance of the soil and increases crop productivity.

Crop rotation also maintains soil nutrient balance and fertility. When green manuring and crop rotation are used together, the sustainability of agricultural production can be significantly increased. The use of legumes as green manure enriches the nitrogen content of the soil thanks to their nitrogen fixing capacity. These methods minimize environmental impacts by reducing the use of chemical fertilizers. As a result, green manuring and crop rotation are important agricultural practices for maintaining soil health and increasing agricultural productivity. Green manuring and crop rotation are effective methods to increase nitrogen fixing capacity. Green manures support nitrogen fixation of legumes by increasing soil organic matter content (Somasundaram et al., 2007). Crop rotation, planting legumes alternately with other crops, balances soil nitrogen levels and ensures sustainable productivity.

10. Adaptation to climate change

10.1. Climate tolerant varieties

Climate change is an important factor affecting agricultural production. The development of lentil varieties that are resistant to climate change will reduce production risks and these varieties are more resistant to stress conditions such as extreme temperature, drought and salinity (Araus et al., 2002).

10.2. Climate forecasting and planning

Planning planting and harvesting times using meteorological data and climate forecasts can increase yield and quality. Climate models are an important tool in farmers' decision-making processes. These models help to predict climatic changes that affect plant growth and agricultural planning can be made accordingly (Challinor et al., 2007). Various agronomic and biotechnological strategies are applied to improve yield and quality in lentil production. Strategies such as soil and water management, planting time and frequency, fertilization strategies, disease and pest management, genetic and biotechnological approaches, ecological and sustainable practices, and climate change adaptation are critical to achieve successful results in lentil production. These strategies provide economic benefits to farmers by increasing yield and quality in lentil production and support sustainable agricultural practices.

11. Conclusion

Fertilization strategies and practices in lentil cultivation are of great importance to increase productivity and promote sustainable agriculture. Lentils enrich soil nitrogen content through biological nitrogen fixation, reducing the need for chemical fertilizers and providing environmental benefits (Brockwell et al., 2002). However, for optimum yields, macronutrients such as phosphorus and potassium as well as micronutrients such as zinc and molybdenum need to be applied at the right rate (Ramaekers et al., 2010). Root nodulation and nitrogen fixation can be enhanced by using microbial inoculants, which supports the overall growth and productivity of the plant (Ahmed et al, 2008). Soil pH and conditions have a direct impact on nodulation and nitrogen fixation, and proper management of these factors is critical (Thies et al., 1995). Integrated farming practices and the use of organic fertilizers maintain long-term soil health by increasing soil biological activity (Saeed,2012). Methods such as green manuring and crop rotation improve soil structure and help control plant diseases and pests (Somasundaram et al., 2007).

In conclusion, effective fertilization strategies and practices in lentil farming are important for both increasing crop productivity and maintaining soil health. These strategies support the success of sustainable agricultural practices and minimize environmental impacts. Adopting the right fertilization methods will provide both economic and environmental benefits in lentil cultivation, forming the basis for future farming practices (Rubio et al., 2011).

Declaration of Author Contributions
The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest
All authors declare that there is no conflict of interest related to this article.

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