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Optimizing Spacing and Nutrient Management for Enhanced Growth and Yield of Summer Green Gram (*Vigna radiata* L.): A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Summer green gram (*Vigna radiata* L.), a vital legume in many agricultural systems, requires precise agronomic practices to maximize its growth and yield. This review examines the influence of optimized plant spacing and nutrient management on the performance of summer green gram. Proper spacing is crucial for minimizing competition for resources among plants, ensuring adequate sunlight, and promoting effective pest and disease control. Different plant densities and their impact on biomass production, pod formation, and seed quality are analysed. Nutrient management,

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particularly the balanced application of macro and micronutrients, plays a significant role in enhancing physiological and biochemical processes in the plant. The review highlights the importance of integrating organic and inorganic fertilizers to improve soil fertility, boost microbial activity, and increase nutrient uptake efficiency. Studies indicate that appropriate nitrogen, phosphorus, and potassium levels, along with essential micronutrients like zinc and boron, are vital for optimal plant development and yield. The synergistic effects of spacing and nutrient strategies on green gram's growth parameters, including plant height, leaf area index, nodulation, and chlorophyll content, are explored. This comprehensive review synthesizes current research findings and offers practical recommendations for farmers and agronomists aiming to enhance green gram productivity sustainably. By adopting optimal spacing and tailored nutrient management practices, significant improvements in yield and resource use efficiency can be achieved, contributing to food security and agricultural sustainability. The review underscores the need for continued research to refine these agronomic practices under diverse environmental conditions to fully realize the potential of summer green gram cultivation.

Keywords: Micronutrients; productivity; sustainability; soil fertility; microbial activity, nutrient uptake.

1. INTRODUCTION

Green gram, also known as mung bean (*Vigna radiata* L.), is a significant legume crop cultivated extensively in tropical and subtropical regions [1]. It plays a crucial role in sustainable agriculture and food security due to its nutritional value, soil health benefits, and adaptability to various agro-climatic conditions [2]. Pulses hold a significant place in Indian agriculture, with India being a leading producer. Pulses are a crucial part of the cropping systems for farmers nationwide. Currently, the average per capita consumption of pulses in India is 14 kg per year, which falls short of the WHO's recommendation of 20 kg per year [3]. India cultivates pulses on nearly 23 million hectares, yielding an annual production of 17.02 million tonnes and an average productivity of 617 kg per hectare [4]. Greengram or mungbean (*Vigna radiata* L.) is one of India's most vital food legumes and ranks as the third most important pulse crop [5]. It is a rich source of protein (24%) and also provides carbohydrates (60%), fat (1.5%), amino acids, vitamins, and minerals [6]. In India, Greengram is grown on 3.80 million hectares, with an annual production of 1.1 million tonnes. As a short-duration crop, it fits well within multiple cropping systems, providing an excellent opportunity for farmers to enhance their income and productivity. Green gram is prized for its high protein content, vitamins, and minerals, making it a staple in many diets. It contains approximately 24% protein, which is significantly higher than most other legumes, making it an essential component of vegetarian diets [7,8,9,10,11].

Besides its nutritional value, green gram improves soil fertility through biological nitrogen fixation, reducing the need for synthetic fertilizers and enhancing soil health. Its ability to grow in poor soils and under minimal irrigation makes it a resilient crop in regions facing water scarcity and poor soil conditions [12]. Despite its benefits, green gram productivity is often limited by suboptimal agronomic practices, including inappropriate plant spacing and inadequate nutrient management. These limitations can lead to reduced plant growth, lower yield, and inefficient use of resources. Addressing these issues is critical for maximizing the potential of green gram cultivation and ensuring food security, especially in regions where it is a primary crop. Plant spacing is a fundamental agronomic practice that directly impacts plant growth, development, and yield. Proper spacing ensures that each plant has adequate access to sunlight, water, and nutrients, reducing competition and promoting healthy growth [13]. The method of distributing plants per unit area is an effective method for taking advantage of various environmental factors and the best way to control the percentage and efficiency of interception of effective rays in the process of photosynthesis. The amount of penetrating light and heat available to the plant are factors affected by plant spacing. These factors change according to the growing season and geographical location, and affect most of the plant's physiological processes. Proper spacing ensures reduced competition and promotes healthy growth. In green gram cultivation, optimal spacing can vary depending on factors such as soil type, climate, and specific cultivar characteristics.

1.1 Nutrient Management for Enhanced Green Gram Productivity

Nutrient management is another critical factor in optimizing green gram growth and yield. The balanced application of macro and micronutrients ensures that plants receive the necessary elements for their physiological and biochemical processes.

1.1.1 Key nutrients and their functions

1. Nitrogen (N): Nitrogen is essential for vegetative growth, as it is a major component of amino acids, proteins, and chlorophyll. In green gram, adequate nitrogen levels promote vigorous plant growth and higher biomass production [14]. However, since green gram can fix atmospheric nitrogen through symbiosis with Rhizobium bacteria, the need for nitrogen fertilizers is reduced, though not entirely eliminated.

2. Phosphorus (P): Phosphorus is vital for energy transfer and storage in plants. It plays a significant role in root development, flower initiation, and seed formation. Inadequate phosphorus can lead to poor root systems and reduced yields.

3. Potassium (K): Potassium is crucial for various physiological processes, including photosynthesis, enzyme activation, and water regulation by regulating the osmotic pressure of the cell. It enhances the plant's ability to withstand stress conditions such as drought and disease, thereby improving overall yield and quality [15].

4. Micronutrients: Elements like zinc (Zn), boron (B), and molybdenum (Mo) are required in smaller quantities but are equally important for plant health. Zinc is involved in enzyme function and protein synthesis, boron in cell wall formation and reproductive development, and molybdenum in nitrogen metabolism [16].

1.2 Integrated Nutrient Management

Integrated nutrient management (INM) combines the use of organic and inorganic fertilizers to provide a balanced nutrient supply to the crops. This approach not only enhances soil fertility and microbial activity but also improves the efficiency of nutrient uptake by plants. Organic amendments such as compost and green manure can improve soil structure and water-holding capacity, while inorganic fertilizers provide readily available nutrients to meet the immediate needs of the plants [17].

1.2.1 Synergistic effects of spacing and nutrient management

The interaction between plant spacing and nutrient management practices is crucial for optimizing green gram productivity. Research has shown that these two factors are interdependent and must be managed together to achieve the best results.

1. Enhanced Growth Parameters: Optimal spacing and nutrient management together improve growth parameters such as plant height, leaf area index, and chlorophyll content. These factors contribute to increased photosynthetic efficiency and better overall plant health [18].

2. Improved Nodulation and Nitrogen Fixation: Proper spacing ensures that plants are not overcrowded, which can enhance root development and nodulation. Combined with adequate nutrient supply, this promotes efficient biological nitrogen fixation, reducing the need for nitrogen fertilizers and improving soil health [19].

3. Higher Yield and Quality: The synergistic effect of optimized spacing and nutrient management leads to better pod formation, seed quality, and ultimately higher yields [20]. This is essential for meeting the growing demand for green gram in both domestic and international markets.

Optimizing plant spacing and nutrient management are key strategies for enhancing the growth and yield of summer green gram. By understanding the specific requirements of the crop and implementing tailored agronomic practices, farmers can achieve significant improvements in productivity and resource use efficiency. This review aims to provide a comprehensive understanding of these factors and offer practical recommendations for sustainable green gram cultivation. Continued research and extension efforts are necessary to refine these practices and adapt them to diverse environmental conditions, ensuring the long-term success of green gram as a vital crop in global agriculture.

2. EFFECTS OF PLANT SPACING ON GROWTH AND YIELD

Plant spacing is a critical factor in the cultivation of summer green gram (*Vigna radiata* L.) that significantly affects its growth and yield. Proper spacing ensures that each plant receives adequate resources such as light, water, and nutrients, which are essential for healthy growth and optimal yield [21]. This section delves into the various effects of plant spacing on the growth parameters and yield of summer green gram, highlighting the importance of finding the ideal plant density for this crop.

2.1 Resource Utilization and Competition

Light Interception: Adequate spacing ensures that plants receive sufficient sunlight for photosynthesis. In densely planted fields, plants can shade each other, reducing the amount of light that reaches the lower leaves [22]. This can limit photosynthetic activity, leading to reduced growth and lower yield. Conversely, when plants are spaced too far apart, the field may not utilize available sunlight efficiently, leading to underperformance in terms of biomass production.

Water and Nutrient Uptake: Proper spacing reduces competition among plants for water and nutrients. When plants are too close together, their root systems compete for the limited nutrients and moisture available in the soil, which can lead to deficiencies and stunted growth [23]. Adequate spacing allows each plant's roots to explore a larger soil volume, enhancing nutrient uptake and water absorption, which are crucial for robust plant development and higher yields.

2.2 Growth Parameters

Plant Height and Canopy Development: Optimal spacing influences plant height and canopy structure. Plants grown at appropriate distances tend to have better air circulation and light penetration, promoting healthier and more vigorous growth. Properly spaced plants develop a well-structured canopy that maximizes photosynthesis, leading to increased biomass and better overall plant health [24]. While close distances cause shading and competition for light is greater, the amount of light penetrating the lower part of the plant decreases, which leads to an increase in the concentration of the hormone indole acetic acid (IAA), which encourages cell elongation, and thus leads to an increase in plant height.

Leaf Area Index (LAI): The leaf area index, which is the leaf area per unit ground area, is a critical factor in determining the photosynthetic capacity of a crop. Proper spacing results in an optimal LAI, where the leaves are efficiently arranged to capture sunlight without excessive overlapping or gaps [25]. This balance enhances photosynthetic efficiency and contributes to higher yields.

Root Development: Adequate spacing allows for better root growth and development. When plants are spaced too closely, their root systems can become entangled and compete for space, limiting their ability to access water and nutrients. Well-spaced plants have more room for root expansion, leading to better anchorage, nutrient uptake, and overall plant stability.

2.3 Yield Components

Pod Formation and Seed Quality: Proper plant spacing directly influences pod formation and seed development. In overcrowded conditions, the competition for resources can lead to fewer pods per plant and lower seed quality. Adequate spacing ensures that each plant has sufficient resources to support the development of a higher number of pods with well-formed seeds, enhancing both the quantity and quality of the yield [20]. The increase in pods is due to leaving sufficient space for the plant to grow and branch, and for light to reach the lower nodes that give active flowers, and with the availability of ventilation and appropriate temperature, in addition to the effectiveness of photosynthesis, greater fertilization of the formed flowers occurs.

Harvest Index: The harvest index, which is the ratio of economic yield (seeds) to biological yield (total biomass), is a key indicator of crop productivity. The harvest index also shows the plant’s efficiency in converting the products of photosynthesis into an economic crop. Optimal spacing can improve the harvest index by ensuring that a higher proportion of the plant’s energy and resources are allocated to seed production rather than vegetative growth [18]. This leads to a more efficient conversion of biomass into harvestable yield.

2.4 Pest and Disease Management

Air Circulation and Microclimate: Proper spacing improves air circulation within the crop canopy, reducing humidity levels and creating a less favourable environment for many pests and diseases [26]. Good airflow helps in drying out the foliage, which can reduce the incidence of fungal infections and other moisture-related diseases. This can decrease the reliance on chemical pesticides and promote more sustainable pest management practices.

Pest Pressure: Adequate spacing can also reduce pest pressure by making it more difficult for pests to move from plant to plant. Dense plantings can create a continuous habitat that facilitates the rapid spread of pests, whereas well-spaced plants can act as a barrier, slowing down pest movement and reducing infestation levels.

The effects of plant spacing on the growth and yield of summer green gram are multifaceted and significant. Optimal spacing ensures efficient resource utilization, promotes healthy plant development, and enhances yield components [21]. It also contributes to better pest and disease management, leading to more sustainable cultivation practices. Farmers and agronomists must consider the specific needs of their crop and environmental conditions when determining the ideal plant spacing to maximize productivity and ensure the long-term success of summer green gram cultivation. Continued research and field trials are necessary to refine these recommendations and adapt them to diverse agro-ecological zones, ultimately supporting the goal of sustainable agriculture and food security.

3. EFFECTS OF NUTRIENT MANAGEMENT ON GROWTH AND YIELD

Nutrient management is a cornerstone of effective agricultural practices, significantly influencing the growth and yield of summer green gram. Proper nutrient management involves the balanced application of essential macro and micronutrients, ensuring that plants receive the necessary elements for optimal physiological and biochemical processes [27]. Various components of an integrated nutrient management illustrated in Fig. 1. This section explores the effects of nutrient management on the growth parameters and yield of summer green gram, emphasizing the importance of integrated nutrient strategies for maximizing crop performance.

3.1 Integrated Nutrient Management (INM)

Combining Organic and Inorganic Fertilizers: Integrated Nutrient Management (INM) combines organic and inorganic fertilizers to provide a balanced and sustainable nutrient supply. Organic amendments such as compost, farmyard manure, and green manure improve soil structure, enhance microbial activity, and increase the soil’s water-holding capacity [17]. Inorganic fertilizers supply readily available nutrients to meet the immediate demands of the crop.

Enhancing Soil Fertility and Health: INM practices enhance soil fertility by improving the physical, chemical, and biological properties of the soil. Organic amendments increase the organic matter content, promoting soil aggregation and improving soil aeration and drainage. The improved soil structure facilitates better root growth and nutrient uptake [28]. The presence of beneficial microorganisms in organic matter enhances nutrient cycling and availability. Organic matter is not only a means of improving productivity, but also an important tool for reducing the amount of chemical fertilizers added.

3.2 Effects on Growth Parameters

Plant Height and Biomass: Proper nutrient management leads to increased plant height and biomass. Adequate nitrogen promotes vegetative growth, resulting in taller plants with more extensive leaf area. Phosphorus enhances root development, enabling better nutrient and water uptake, which supports overall plant growth [24]. Potassium strengthens stems and improves the plant's structural integrity, contributing to higher biomass.

Leaf Area Index (LAI): A well-managed nutrient regime ensures a higher leaf area index (LAI), which is crucial for maximizing photosynthetic efficiency [25]. Adequate nitrogen and potassium levels result in larger, healthier leaves that can capture more sunlight, enhancing photosynthetic activity and leading to increased growth and yield.

Nodulation and Nitrogen Fixation: Proper nutrient management, particularly with adequate phosphorus and molybdenum, enhances nodulation and nitrogen fixation in green gram [29]. Well-nodulated plants have a greater capacity to fix atmospheric nitrogen, reducing the need for nitrogen fertilizers and improving soil fertility. This symbiotic relationship is crucial for sustainable green gram cultivation.

3.3 Effects on Yield Components

Pod Formation and Seed Quality: Balanced nutrient management significantly improves pod formation and seed quality. Adequate phosphorus and potassium levels enhance flowering, pod setting, and seed filling. Micronutrients such as boron play a crucial role in reproductive development, ensuring that pods are well-formed and seeds are of high quality [29]. Proper nutrient management leads to higher pod numbers per plant, increased seed weight, and improved overall yield.

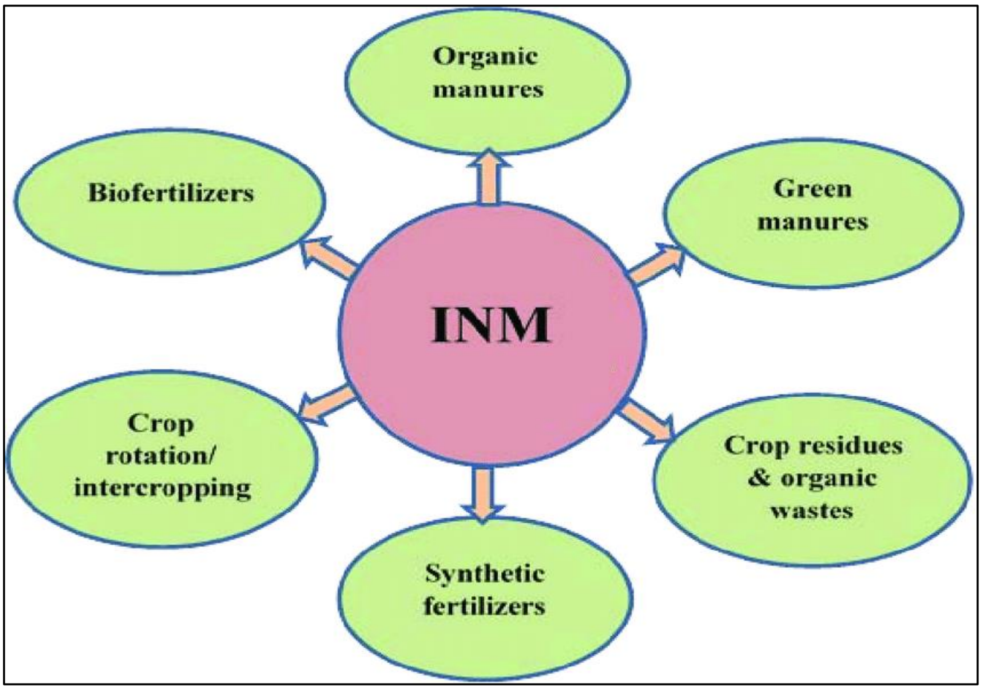

Fig. 1. Various components of an integrated nutrient management

Harvest Index: The harvest index, which measures the ratio of economic yield (seeds) to total biomass, is positively influenced by balanced nutrient management. Efficient nutrient use ensures that a higher proportion of the plant's biomass is allocated to seed production rather than vegetative growth [30-31]. This results in a more efficient conversion of biomass into harvestable yield, enhancing the overall productivity of green gram.

A field experiment was conducted at Tamil Nadu Agricultural University, Agricultural College and Research Institute, Killikulam in randomised block design and replicated thrice and the test variety of the crop Greengram (CO 6) was used. The plant geometry of 30 × 30 cm, 25 × 25 cm and 30 × 10 cm was adopted. The Soil Test Crop Response (STCR) based fertilizer application, RDF, FYM and ZnSO4 was applied in soil as basal. The foliar spray of Pulse Wonder and Pink-pigmented facultative me-thylotrophs (PPFM) spray was done at one week after flowering and 1% KNO3 at 50 per cent flo-wering. Adoption of planting geometry of 30 × 30 cm, application of RDF, 12.5 t of FYM and 25 kg ZnSO4 as basal and foliar spraying of 1% KNO3 at 50 per cent flowering recorded higher dry matter production of 2865 kg/ha. Yield attributes *viz.,* number of pod clusters plant^{-1} (10.34), number of pods plant^{-1} (53.40), number of seeds pod^{-1} (13.23), Higher grain yield of 1775 kg·ha^{-1}, haulm yield (2920 kg·ha^{-1}), harvest index (0.38), net return (57,806 Rs·ha^{-1}) and B:C ratio (2.43) were associated with the treatment comprising of 30 × 30 cm spacing, application of RDF, 12.5 t of FYM and 25 kg ZnSO4 as basal and foliar spraying of 1% KNO3 at 50 per cent flowering in Table 1 [32].

Effective nutrient management is essential for maximizing the growth and yield of summer green gram. The balanced application of macro and micronutrients supports critical physiological and biochemical processes, leading to improved plant health, increased biomass, and higher yields [33]. Integrated nutrient management practices that combine organic and inorganic fertilizers enhance soil fertility, promote sustainable farming practices, and contribute to the long-term productivity of green gram. Farmers and agronomists must adopt tailored nutrient management strategies to meet the specific needs of their crops and environmental conditions, ensuring sustainable and profitable green gram cultivation.

Table 1. Effect of planting geometry, soil and foliar nutrition on grain yield ($kg \cdot ha^{-1}$) and yield attributing traits in mungbean

Treatments	Dry matter ($kg \cdot ha^{-1}$)	No. of pod cluster $plant^{-1}$	No. of pods $plant^{-1}$	No. of seeds pod^{-1}	Grain yield ($kg \cdot ha^{-1}$)
a. Spacing 25 × 25 cm					
T1: STCR based fertilizer application	1581	6.00	35.2	11.13	1161
T2: STCR based fertilizer application + ZnSO4 + Pulse Wonder	1689	6.35	36.5	11.21	1219
T3: STCR based fertilizer application + ZnSO4 + Pulse Wonder + PPFM spray	1927	7.00	41.4	12.41	1409
T4: RDF + FYM + ZnSO4	2025	7.43	41.7	12.43	1428
T5: RDF + FYM + ZnSO4 + 1% KNO3	2167	7.67	42.8	12.47	1488
b. Spacing 30 × 30 cm					
T6: STCR based fertilizer application	1667	7.00	39.1	12.29	1224
T7: STCR based fertilizer application + ZnSO4 + Pulse Wonder	1915	7.25	40.9	12.40	1385
T8: STCR based fertilizer application + ZnSO4 + Pulse Wonder + PPFM spray	2362	8.32	52.8	12.85	1586
T9: RDF + FYM + ZnSO4	2605	9.41	52.9	12.97	1689
T10: RDF + FYM + ZnSO4+ 1% KNO3	2865	10.34	53.4	13.23	1775
c. Spacing 30 × 10 cm					
T11: RDF + FYM + ZnSO4	1435	5.33	23.5	9.40	1053
SEd	**70**	**0.49**	**1.7**	**0.29**	72
CD (P = 0.05)	**146**	**1.02**	**3.5**	**0.61**	150

Source: Keerthi et al. [32]

4. FACTORS LIMITING THE PRODUCTIVITY OF LEGUMES

Legumes, including important crops like Greengram, play a crucial role in agriculture due to their nutritional benefits and ability to fix atmospheric nitrogen. However, several factors can limit their productivity. Understanding these factors is essential for devising strategies to improve legume yield and ensure food security.

4.1 Abiotic Factors

1. Soil Fertility: Soil fertility is a critical factor affecting legume productivity. Legumes require a balanced supply of macro and micronutrients for optimal growth. Deficiencies or imbalances in essential nutrients such as nitrogen (despite their nitrogen-fixing ability), phosphorus, potassium, and micronutrients like zinc and boron can severely limit growth and yield. Poor soil fertility often leads to stunted growth, poor root development, and reduced nodulation.

2. Water Availability: Water stress, either due to drought or insufficient irrigation, can significantly impact legume productivity [34]. Legumes are sensitive to water deficits during critical growth stages such as flowering and pod development. Insufficient water can lead to flower drop, poor pod setting, and reduced seed filling, ultimately lowering yield.

3. Temperature Extremes: Legumes are sensitive to temperature extremes. High temperatures during flowering can cause flower drop and reduce pod set, while low temperatures can slow down growth and delay maturity. Optimal temperature ranges are essential for the physiological processes that drive growth and development in legumes.

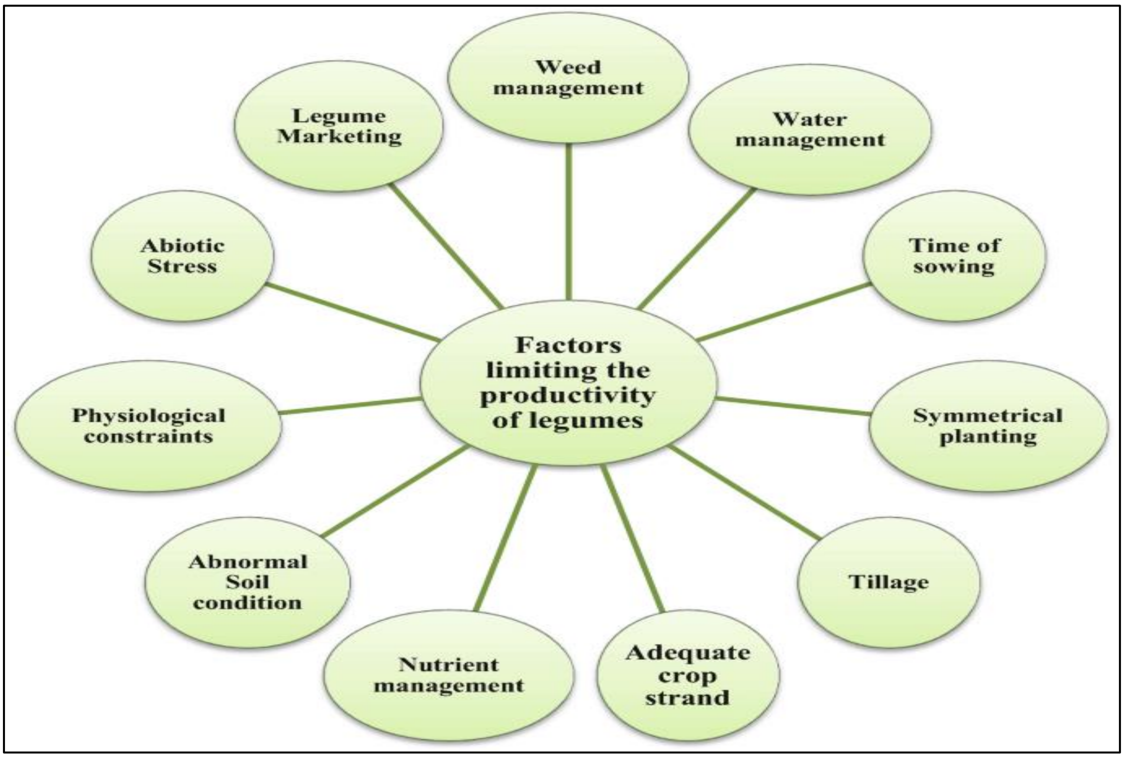

Fig. 2. Factors limiting the productivity of legumes

4. Soil pH: Soil pH affects nutrient availability and microbial activity in the soil. Most legumes prefer a slightly acidic to neutral pH range (6.0-7.5). Acidic or alkaline soils can limit nutrient uptake and hinder the growth of nitrogen-fixing bacteria, reducing the plant's ability to fix atmospheric nitrogen and thus impacting productivity [35].

4.2 Biotic Factors

1. Pests and Diseases: Legumes are susceptible to various pests and diseases that can significantly reduce yield. Common pests include aphids, pod borers, and root-knot nematodes. Diseases such as powdery mildew, rust, bacterial blight, and root rot can cause extensive damage to crops [36]. Effective pest and disease management practices are crucial to protecting legume crops and ensuring high yields.

2. Weeds: Weeds compete with legume crops for resources such as light, water, and nutrients. They can significantly reduce crop yields if not managed properly [37]. Effective weed control measures, including timely weeding and the use of herbicides, are essential to minimize competition and enhance legume productivity.

4.3 Agronomic Factors

1. Seed Quality: The quality of seeds used for planting is a fundamental factor influencing legume productivity. Poor-quality seeds with low germination rates, poor vigour, or susceptibility to diseases can lead to poor stand establishment and reduced yields. Using certified, high-quality seeds is crucial for ensuring good crop performance.

2. Plant Density and Spacing: Optimal plant density and spacing are critical for maximizing legume productivity. Overcrowding can lead to competition for resources, while too wide spacing can result in underutilization of available resources. Proper plant spacing ensures adequate light interception, air circulation, and nutrient uptake, promoting healthy plant growth and higher yields.

3. Nutrient Management: As discussed earlier, balanced nutrient management is vital for legume growth. Inadequate or imbalanced fertilization can lead to nutrient deficiencies, poor growth, and reduced yields. Integrated nutrient management practices that combine organic and inorganic fertilizers can enhance soil fertility, improve nutrient availability, and support sustainable legume production.

4.4 Environmental Factors

1. Climate Change: Climate change poses a significant threat to legume productivity. Changes in temperature and precipitation patterns can disrupt growing seasons, increase the incidence of extreme weather events, and alter pest and disease dynamics [38]. Developing climate-resilient legume varieties and adopting sustainable farming practices are essential to mitigate the impacts of climate change on legume production.

2. Soil Erosion and Degradation: Soil erosion and degradation can reduce soil fertility and productivity over time. Legumes, with their relatively shallow root systems, are particularly vulnerable to soil erosion. Conservation practices such as contour farming, terracing, and the use of cover crops can help reduce soil erosion and maintain soil health, supporting sustained legume productivity [39].

The productivity of legumes is influenced by a complex interplay of abiotic, biotic, agronomic, environmental, and socio-economic factors. Addressing these challenges requires an integrated approach that combines improved agronomic practices, effective pest and disease management, sustainable nutrient management, and climate resilience strategies. By understanding and mitigating the factors that limit legume productivity, farmers can enhance their yields, contribute to food security, and support sustainable agricultural development.

5. BENEFITS OF SPACING AND INM FOR ENHANCED GROWTH AND YIELD

Effective spacing and nutrient management are pivotal in maximizing the growth and yield of summer green gram. These agronomic practices ensure optimal resource utilization, improve plant health, and enhance overall productivity. Here, we explore the key benefits of adopting proper spacing and nutrient management strategies for summer green gram cultivation.

5.1 Benefits of Optimal Plant Spacing

1. Improved Light Interception: Optimal plant spacing ensures that each plant receives adequate sunlight, which is crucial for photosynthesis. Proper spacing prevents shading and allows the lower leaves to capture sufficient light, enhancing the plant's photosynthetic efficiency and biomass production.

2. Enhanced Air Circulation: Adequate spacing improves air circulation within the crop canopy. This reduces the humidity levels around the plants, thereby decreasing the incidence of fungal diseases and pest infestations. Better air movement also promotes healthier plant growth by reducing the risk of pathogen spread [40].

3. Reduced Competition for Resources: Properly spaced plants face less competition for essential resources such as water, nutrients, and sunlight. This allows each plant to access a larger share of available resources, leading to better growth, higher biomass accumulation, and improved yield components such as pod number and seed size.

4. Improved Root Development: Sufficient spacing allows the root systems of individual plants to expand freely without interference from neighbouring roots. This enhances the plant's ability to uptake water and nutrients, providing a solid foundation for robust growth and higher productivity.

5. Easier Management Practices: Optimal spacing facilitates easier implementation of agricultural practices such as weeding, irrigation, and pest control. This not only improves the efficiency of these operations but also ensures that the plants receive timely and adequate care, contributing to better growth and yield.

5.2 Benefits of Effective Nutrient Management

1. Balanced Nutrient Supply: Effective nutrient management ensures that plants receive a balanced supply of essential macro and micronutrients. This is critical for various physiological and biochemical processes, including photosynthesis, protein synthesis, and energy transfer, which are vital for plant growth and development.

2. Enhanced Soil Fertility: Integrated nutrient management practices, combining organic and inorganic fertilizers, improve soil fertility. Organic amendments like farmyard manure (FYM) enhance soil structure, increase microbial activity, and improve nutrient retention, while inorganic fertilizers provide readily available nutrients to meet immediate plant needs. The release of organic acids and carbon dioxide gas (CO2) from them also reduces the pH of the soil, which affects the dissolution of minerals and makes its mineral elements more readily available. This is in addition to its ability to hold ions by the humus colloids due to its high surface area.

3. Increased Nitrogen Fixation: Adequate nutrient management, especially with the application of phosphorus and molybdenum, enhances nodulation and nitrogen fixation in green gram. This reduces the need for synthetic nitrogen fertilizers and improves soil health by enriching it with biologically fixed nitrogen.

4. Improved Yield Attributes: Balanced fertilization positively impacts key yield attributes such as pod number, seed size, and seed weight [41]. Proper nutrient supply during critical growth stages ensures that plants develop more pods per plant, produce larger seeds, and achieve higher overall yield.

5. Enhanced Stress Resistance: Nutrients like potassium and micronutrients such as zinc and boron improve the plant's resistance to environmental stresses such as drought, high temperatures, and diseases [42]. Healthy, well-nourished plants are better equipped to withstand adverse conditions, ensuring stable yields even under suboptimal growing conditions.

5.3 Combined Benefits of Spacing and Nutrient Management

1. Synergistic Effects on Growth: When optimal spacing and effective nutrient management are combined, the benefits are synergistic. Proper spacing allows for better nutrient uptake and utilization, while balanced fertilization supports vigorous growth [24]. Together, these practices enhance overall plant health, leading to higher biomass production and better yield attributes.

2. Maximized Resource Use Efficiency: Combining appropriate spacing with effective nutrient management maximizes the use efficiency of water, light, and nutrients. This ensures that plants make the best use of available resources, leading to more sustainable and efficient crop production.

3. Higher Economic Returns: The combined approach leads to higher yields and better quality produce, which translates into increased economic returns for farmers. Improved productivity and reduced input costs through efficient resource use enhance profitability and support sustainable farming livelihoods.

4. Sustainable Agriculture: Adopting optimal spacing and nutrient management practices contributes to sustainable agriculture by improving soil health, reducing dependency on chemical fertilizers, and promoting environmentally friendly farming practices. This helps in maintaining long-term soil fertility and productivity, ensuring the sustainability of green gram cultivation [25-26].

The benefits of proper spacing and nutrient management for the enhanced growth and yield of summer green gram are manifold. These practices improve resource utilization, enhance plant health, increase yield components, and contribute to higher economic returns. By adopting these agronomic strategies, farmers can achieve more sustainable and productive green gram cultivation, supporting food security and agricultural sustainability [43-44]. Continued research and extension efforts are necessary to refine these practices and adapt them to varying agro-ecological conditions, ensuring that farmers can reap the full benefits of optimized spacing and nutrient management.

6. CONCLUSION

The comprehensive review underscores the pivotal role of optimizing plant spacing and nutrient management in enhancing the growth and yield of summer green gram. Effective implementation of these agronomic practices is essential for maximizing the productivity and sustainability of green gram cultivation. Proper plant spacing is crucial for maximizing light interception, air circulation, and root development. Adequate spacing reduces competition for water, nutrients, and sunlight, allowing each plant to thrive. This practice also facilitates better management of agricultural operations such as weeding, irrigation, and pest control, contributing to healthier plants and higher yields. Balanced nutrient management ensures that green gram plants receive essential macro and micronutrients for optimal growth. Integrating organic and inorganic fertilizers enhances soil fertility, improves soil structure, and increases microbial activity. Adequate nutrient supply supports vigorous plant growth, enhances nitrogen fixation, and boosts yield attributes such as pod number, seed size, and overall productivity. The combination of optimal spacing and effective nutrient management results in synergistic benefits, leading to higher biomass production and improved yield components. This integrated approach maximizes resource use efficiency, ensuring sustainable and productive green gram cultivation. It also leads to higher economic returns due to increased yields and better-quality produce, while reducing input costs through efficient resource utilization. Adopting these agronomic strategies supports sustainable agriculture by improving soil health, reducing reliance on chemical fertilizers, and promoting environmentally friendly practices. Enhanced productivity and profitability from these practices contribute to the economic well-being of farmers and ensure long-term agricultural sustainability. Continued research and extension efforts are crucial for refining these practices and adapting them to diverse agro-ecological conditions. Providing farmers with access to quality inputs, training, and knowledge about best practices will further enhance the adoption and effectiveness of optimized spacing and nutrient management. In conclusion, the optimization of plant spacing and nutrient management is vital for achieving higher growth and yield of summer green gram. These practices not only enhance productivity and profitability but also contribute to sustainable agricultural development, ensuring the long-term viability of green gram cultivation and supporting global food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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