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INTEGRATED APPROACHES FOR IMPROVING RABI GROUNDNUT (*Arachis hypogaea* L.) PRODUCTIVITY UNDER DIFFERENT SOWING DATES: HIGH-INPUT MANAGEMENT, RHIZOSPHERE MICROBIOME, AND WATER SUSTAINABILITY

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ABSTRACT

Rabi groundnut (*Arachis hypogaea* L.) is an important oilseed crop that is grown widely due to its nutritional, economic, and industrial value. But, sometimes it is limited by the inappropriate sowing time, inefficient nutrient management, less availability of water, and less favorable environmental conditions. Optimization of sowing time in combination with integrated crop management is necessary to improve the rabi groundnut growth, yield, and sustainability. The integrated strategies to enhance the productivity of rabi groundnut through high input management, rhizosphere microbiome, and water sustainability are outlined in the present chapter with respect to various sowing dates. Sowing date plays an important role in crop establishment, phenological development, flowering, and pod formation, temperature, moisture, and interception of solar radiation. Balanced fertilization, better cultivars, precision irrigation, micronutrient application, and integrated nutrient management are high-input management practices that help achieve improved nutrient uptake, physiological efficiency, and productivity. The rhizosphere microbiome has a profound impact on plant growth by enhancing biological nitrogen fixation, nutrient solubilization, production of phytohormones, and stress tolerance. Symbiotic fungi like arbuscular mycorrhizal fungi (AMF) and rhizobium bacteria, plant growth-promoting rhizobacteria (PGPR), help enhance soil fertility, root growth, and tolerance to abiotic stresses. Water Sustainability Practices, such as drip irrigation, mulching, moisture conservation, and efficient irrigation scheduling, can help achieve maximum water-use efficiency and productivity in situations where water is limited. Moreover, the combination of sustainable agronomic management and climate-resilient technologies can enhance soil health, minimize environmental footprint, and promote sustainable agriculture. Hence, the implementation of an integrated management system in appropriate sowing dates can have a significant impact on improving the productivity, profitability, and resource-use efficiency of rabi groundnut production under the changing climatic scenario.

***Keywords*:** Rabi groundnut, sowing dates, rhizosphere microbiome, water-use efficiency, integrated crop management.

Introduction

Groundnut is an oilseed crop that is an important food and economic crop all over the world, especially in tropical and sub-tropical regions (Krishnan *et al*., 2025). Optimal productivity of rabi groundnut requires an integrated approach, considering the complex interactions between high-input management, the groundnut rhizosphere microbiome, and water sustainability, particularly under different sowing dates (Dey *et al*., 2024). The comprehensive approach is essential for improving system productivity and reducing environmental impacts in the groundnut-based cropping systems (Bana *et al*., 2024). This study aims to evaluate the impact of different irrigation methods, such as conventional, time-based automated, and sensor-based automated drip irrigation methods, and different fertigation methods on the growth, physiology, root characteristics, and yield of groundnut (Atharvya *et al*., 2025).

As groundnut is highly sensitive to efficient irrigation and nutrient management, it is important to optimize these aspects to enhance groundnut yield in the rabi season (Sunitha *et al*., 2023). In particular, deficit irrigation of specific cultivars of groundnut, like the Visishta variety, has shown better pod, kernel, and haulm production when grown with seed endophytic bacteria, suggesting that synergistic applications are likely to be effective (Shree *et al*., 2024). An optimum supply of water and nutrients is essential to maximize the performance of groundnut and reduce the losses of water and nutrient resources for sustainable agriculture, by using the resources efficiently and conserving water (Aathithyan *et al*., 2025).

Rabi groundnut production is constrained by several factors, such as insufficient water management practices that affect yield, especially in rain-fed conditions (Gunavathi *et al*., 2024). Drought further aggravates this vulnerability by causing losses of about 6 million tons of groundnut production annually (Eswaran *et al*., 2024; Sivarasan *et al*., 2021), making the need for strong drought mitigation measures like deficit irrigation programs imperative. Through field experiments, it has been shown that deficit irrigation, which involves withholding 80-90% of agronomic evapotranspiration (ET), can significantly increase water productivity, yield, and quality in groundnut crops (Elshamly, 2023; Rathore *et al*., 2021).

Thus, the use of efficient irrigation practices, like drip irrigation, and nutrient management, like smart fertigation, offers a promising approach to improve groundnut productivity and resource use efficiency (RUE), as reported by Aathithyan *et al*. (2025) and Gautam *et al*. (2023). The challenges of uneven fertilizer application and insufficient knowledge of crop management practices are major factors in the reduced productivity of groundnut (Chilwal *et al*. 2025), which can be addressed through these integrated strategies. Implementing critical stage-based irrigation scheduling, especially when groundnut is in the flowering, pegging, and pod filling stages, along with integrated crop management practices, can significantly improve the yield and water use efficiency of groundnut (Naveenkumar *et al*., 2026). Thus, targeted water use, in particular during critical periods of growth such as early vegetative, pegging, and seed formation, is crucial to reduce yield losses in rainfall-prone areas experiencing high variability in rainfall (Ajay *et al*., 2023). In addition, peanut cultivation is facing several issues, such as temperature increase, irregular rainfall, soil degradation, and lack of advanced agricultural technologies in developing nations (Gelaye & Luo, 2024).

Agro-Climatic Requirements of Rabi Groundnut

Rise in temperature, such as an increase of 1.5 °C above the pre-industrial period, has been a major threat to seed yield and quality of groundnut (Gram) during the rabi season, as optimum growth and development of the crop is closely associated with a specific thermal regime (Chilwal *et al*., 2025). In particular, when the temperature is above 32°C, the total biomass and yield are adversely affected, and when the temperature is below the optimum level, sensitivity to fungal attack and seed chemistry changes increase (Puppala *et al*., 2023). The selection of sowing date is critical to be able to avoid extreme temperatures during critical growth stages, and achieve sustainable yield and quality (Elshamly & Nassar, 2024). For example, the flowering and fruit-filling stages are critical ones where water stress has a significant impact, and water availability and moist soils are crucial for optimal development and high yield (Sezen *et al*., 2021). However, frequent periods of drought and inadequate rains at the time of sowing have a great impact on the production of groundnut, thus stressing the importance of soil moisture management (Abukari *et al*., 2024).

Proper availability of macronutrients and micronutrients in suitable proportions is also very important as soil fertility directly affects the productivity of groundnut, and among various macronutrients, deficiency of phosphorus and potassium is most harmful to produce high groundnut yield (Jamir *et al*., 2025). Furthermore, the sowing period has a significant effect on the yield of pods, as the experimental results showed better results for sowing of groundnuts in the 48th and 52nd meteorological weeks (Naik *et al*., 2025a; Naik *et al*., 2025b). This implies that there is a need to synchronize the planting dates with the favourable environmental conditions for achieving optimum productivity and resource use efficiency (RUE) of groundnut crops (Haro & Ovando, 2025). By selecting cultivars suited to various agro-climatic conditions and the expected stress conditions, the ability to produce high yields and reduce the negative effects of stress is further enhanced in the rabi groundnut. Hence, agro-climatic assessments are essential to identify optimal sowing times and choose the genotype with better canopy development, accumulation of biomass, and pod yield potential in different environmental conditions (Paluchani *et al*., 2025).

The maximum temperature has been found to strongly affect pod yield, while the minimum temperature has a strong positive relationship with pod yield (PANDEY, 2023). This underlines the importance of temperature control in groundnut production as any extreme temperature at any stage of the crop's development slows down seed germination, growth, and can result in immature pods (Ijaz *et al*., 2021). In addition, it is very sensitive to soil type, with well drained, sandy loam, rock-free soil required for good root growth and pod setting of the groundnut (Sivasankaran *et al*., 2022). These soil attributes are beneficial for good nutrient assimilation and reduce abiotic stresses, directly affecting plant vigor and yield stability. Groundnut production depends on three factors–genotype, environment, and management practices (G×E×M), which influence the regional characterization and breeding goals for achieving uniform yield (Hajjarpoor *et al*., 2021). The time of sowing and planting density are also important factors in improving groundnut yield and profitability, especially in arid regions (Reager *et al*., 2024).

Such as groundnut, which has been shown to achieve significantly greater yield and higher heat use efficiency when sown in late May or mid-June than when sown earlier or later (Reager *et al*., 2024). In addition, the right sowing date is one of the key factors affecting the growth and yield of groundnut, and the crop response may vary widely depending on the climatic and edaphic conditions of a particular location (Nayak, 2024). Improved management of these factors reduces the negative impact of climate change on the productivity of groundnut, including unpredictable rainfall and increased temperatures (Behera *et al*., 2025).

Effect of Different Sowing Dates on Groundnut Productivity

The sowing period of rabi groundnut is critical for the efficient utilization of the resource for good pod yield, as environmental conditions like temperature and rainfall play an important role in its development (Kumar *et al*., 2024; Liu *et al*., 2023). Studies have revealed that sowing of the crop outside the optimum time, particularly in the second fortnight of February, has resulted in fewer plants, decreased growth characteristics (plant height and dry matter production), and lower yield of pods and haulms (Patoliya *et al*., 2024a, 2024b). On the other hand, early seeding and provision of adequate nutrients yield high kernel production, shoot dry matter, and oil content (Jamir *et al*., 2025). In contrast, experimental data from the South Eastern Ghat Zone show that groundnut sown in the 1st week of December always show better plant stature and a larger number of branches and pods per plant (Das *et al*., 2025).

Seedling emergence and early growth of groundnut are very temperature-dependent, and the optimum soil surface temperatures for emergence are 32°C to 33°C with adequate soil moisture content (Duddigan *et al*., 2023). This very specific range is essential to achieve uniform and rapid germination for strong and even seedling establishment and healthy crop growth. Any deviation from these optimal conditions, like suboptimal temperatures or moisture stress, can result in a delay in emergence, a reduction in the number of stands, and greater vulnerability to early-season stresses, reducing the overall yield potential (Kumar *et al*., 2025). Furthermore, experimental work has consistently shown that the sowing dates have a significant influence on various physiological parameters of groundnut cultivars such as plant height, branching, dry matter accumulation, and pod yield per crop at the time of harvesting (Bhutiya *et al*., 2025).

The interaction of sowing dates and variety selection also affects these parameters, with certain varieties showing better performance when sown in their optimum dates (Baah *et al*., 2025). For example, in Western Maharashtra, it was found that some varieties like JL-776 exhibit superior growth parameters like plant height, dry matter production, etc. when planted in specific meteorological weeks (Yadavrao *et al*., 2023). Likewise, data indicate that sowing at the onset of monsoon is significantly associated with higher pod production as compared with later sowing due to optimal rainfall, soil moisture, and mean temperature during critical growth stages (Yadav, 2022a, 2022b). The extended vegetative growth and improved allocation of assimilates to reproductive structures of these early-seeded crops lead to more pods and higher production (ABE *et al*., 2024). Moreover, November II FN has been recognized as an optimum sowing window for optimal pod yield and can yield similar yields as December I FN in certain agro- climatic growing conditions of groundnut, making it adaptable to slight variations in its late-season sowing schedule (Priya *et al*., 2025).

High-Input Management Practices in Groundnut Cultivation

Balanced fertilization and nutrient scheduling

Appropriate application of macro-and micronutrients is critical to enhance the productivity of groundnut and can play a key role in various processes such as root nodulation, nitrogen fixation, photosynthetic efficiency, and pod filling. Strategic nutrient management (SNM), especially integrated nutrient management (INM), has proven to be an effective practice to significantly improve groundnut growth parameters, yield characteristics, and economic returns under groundnut production conditions (Nayak *et al*., 2023a, 2023b). This is especially important in view of the high nutrient demand of groundnut, particularly for its modern high-yielding varieties, which make intensive demands on soil nutrients (V. & M., 2026). For instance, 50% Recommended Dose of Fertilizer and 10 tonnes Farmyard Manure per hectare has been observed to significantly improve the plant height, number of branches, number of nodules, and hence the pod and haulm yield (Sahoo *et al*., 2023). In contrast, the conventional nutrient management practices may result in significant yield gaps (Praharaj *et al*., 2023). The application of organic amendments like vermicompost further enriches soil with nutrients and microbial activity, ensuring long-term nutrient availability and performance. Actually, studies show that combining organic and inorganic sources of nutrients like 125% RDF with FYM is very advantageous in groundnut pod yield production (Harisudan *et al*., 2024). This way, they use nutrients efficiently and also improve soil health and microbial diversity, which is essential for sustainable agriculture in the long term. Moreover, farmyard manure application at 14.0 t ha^{-1} and 75% of the recommended rate of the fertilizer applied in the root zone has been found to yield better growth and yield in irrigated conditions (Malik *et al*., 2023).

Role of micronutrients and secondary nutrients

In addition to primary nutrients, secondary nutrients and micronutrients like sulfur, calcium, and boron play a key role in numerous physiological functions of groundnut like oil production, pod filling, nitrogen fixation, etc., and require a judicious application (Priyadharshini *et al*., 2025). Adding gypsum (Ca and S) is reported to aid in soil structure and pod development, which enhances yields (Jena, 2024). Similarly, Application of 100% of the recommended dose of Fertilizer along with phosphogypsum at 750 kg ha^{-1} and borax (10 kg ha^{-1}) has been proven to significantly improve plant height, branching, dry matter production, and the number of pods per plant in certain groundnut varieties (Sahana *et al*., 2024). The combination of these also positively affects key yield parameters, including kernel yield, shelling percentage, and oil content, highlighting the need not only for macronutrients, but micronutrients as well, to maximize groundnut production (Shokri *et al*., 2024). Because of the indiscriminate and unbalanced use of fertilizers in conventional agriculture, it is important to adopt ameliorative practices and use nutrients, especially nitrogen, accurately (Nayak *et al*., 2024).

Table 1: Role of Secondary Nutrients and Micronutrients in Plants

Secondary Nutrients

Nutrient	Chemical Form Absorbed by Plants	Major Physiological Functions	Role in Plant Metabolism	Deficiency Symptoms	Excess/Toxicity Symptoms	Important Crops Highly Responsive	Common Fertilizer Sources	Mobility in Plant	Mobility in Soil	Interaction with Other Nutrients
Sulfur (S)	SO_4^{2-} (sulfate)	Essential components of amino acids, cysteine and methionine; protein synthesis; chlorophyll formation; oil synthesis; enzyme activation	Participates in the synthesis of vitamins (biotin, thiamine), coenzymes, and glucosinolates; improves nodulation in legumes	Uniform chlorosis in younger leaves, stunted growth, delayed maturity, thin stems, low oil content	Leaf scorching, reduced growth, induced deficiencies of Mo and Se	Oilseeds, pulses, onion, garlic, crucifers	Gypsum, elemental sulfur, ammonium sulfate, single super phosphate	Low mobility	Moderate mobility	Synergistic with N; antagonistic with Mo at high levels
Calcium (Ca)	Ca^{2+}	Cell wall formation; membrane stability;	Acts as secondary messenger in signaling	Death of growing points, blossom end	Interferes with Mg, K, and micronutrient uptake	Tomato, groundnut, apple, potato,	Lime, gypsum, calcium nitrate	Immobile	Low mobility	Antagonistic with Mg and K; improves B

		root development; cell division; pollen tube growth	pathways; activates enzymes	rot in tomato, tip burn in cabbage, poor root growth		vegetables				utilization
Magnesium (Mg)	Mg^{2+}	Central atom of chlorophyll; enzyme activation; phosphate transfer	Important in photosynthesis, carbohydrate metabolism, and ATP formation	Interveinal chlorosis in older leaves, premature leaf shedding, and reduced photosynthesis	Suppresses Ca and K uptake	Maize, sugarcane, potato, tobacco	Magnesium sulfate, dolomite, magnesium oxide	Mobile	Moderate mobility	Antagonistic with Ca and K

Micronutrients

Micronutrient	Chemical Form Absorbed by Plants	Major Physiological Functions	Specific Biochemical Role	Deficiency Symptoms	Toxicity Symptoms	Crops Sensitive to Deficiency	Soil Conditions Favoring Deficiency	Common Fertilizer Sources	Mobility in Plant	Mobility in Soil	Important Nutrient Interactions
Iron (Fe)	Fe^{2+}, Fe^{3+} chelates	Chlorophyll synthesis, respiration, and photosynthesis	Component of cytochromes, ferredoxin, and enzymes involved in electron transport	Interveinal chlorosis of young leaves, bleaching, and reduced growth	Bronzing, tiny brown spots, root blackening	Rice, citrus, soybean, groundnut	Alkaline and calcareous soils	Ferrous sulfate, Fe-EDTA chelates	Immobile	Low mobility	Excess P reduces Fe availability
Zinc (Zn)	Zn^{2+}	Enzyme activation, auxin synthesis, protein metabolism	Component of carbonic anhydrase, dehydrogenases, and RNA polymerase	Khaira disease in rice, little leaf, stunted growth, interveinal chlorosis	Chlorosis and reduced root growth	Rice, maize, wheat, citrus	High pH soils, sandy soils, and high phosphorus soils	Zinc sulfate, Zn-EDTA, zinc oxide	Moderately mobile	Low mobility	Antagonistic with P and Cu
Manganese (Mn)	Mn^{2+}	Photosynthesis, enzyme activation, nitrogen metabolism	Essential for water splitting in photosystem II	Interveinal chlorosis with brown spots, gray speck in oats	Brown spots and crinkled leaves	Cereals, legumes, sugar beet	Organic soils, alkaline soils	Manganese sulfate, Mn chelates	Low mobility	Moderate mobility	Excess Fe reduces Mn uptake
Copper (Cu)	Cu^{2+}	Lignin synthesis, reproductive growth, and enzyme activity	Part of the oxidases, plastocyanin, and electron transport proteins	Dieback of shoots, chlorosis, poor grain formation	Reduced root growth, leaf chlorosis	Wheat, citrus, onion	Organic soils, sandy soils	Copper sulfate, Cu-EDTA	Immobile	Low mobility	Excess Zn and P may induce Cu deficiency
Boron (B)	H_3BO_3, BO_3^{3-}	Cell wall formation, sugar transport, pollination, and seed development	Important in membrane integrity and carbohydrate transport	Death of growing points, hollow stem, fruit cracking, poor seed set	Leaf burn, chlorosis, necrosis	Cauliflower, sunflower, groundnut, sugar beet	Sandy soils, drought conditions, and high pH soils	Borax, boric acid	Immobile	Moderate mobility	Closely associated with Ca metabolism
Molybdenum (Mo)	MoO_4^{2-}	Nitrogen fixation and nitrate reduction	Component of nitrate reductase and nitrogenase enzymes	Whiptail in cauliflower, nitrogen deficiency-like	Rare; may induce Cu deficiency	Legumes, cauliflower	Acidic soils	Sodium molybdate, ammonium molybdat	Mobile	High mobility	Synergistic with N; antagonistic with S

				symptoms				e			
Chlorine (Cl)	Cl^-	Osmotic regulation, stomatal movement, and photosynthesis	Involved in oxygen evolution during photosynthesis	Wilting, chlorosis, and reduced root growth	Leaf burn, reduced growth, salinity injury	Wheat, barley, coconut	Highly leached soils	Potassium chloride, calcium chloride	Mobile	High mobility	Excess Cl may suppress nitrate uptake
Nickel (Ni)	Ni^{2+}	Urease enzyme activation, nitrogen metabolism	Essential for urea breakdown and seed viability	Leaf tip necrosis, poor seed germination, and urea toxicity symptoms	Chlorosis and inhibited root growth	Legumes, pecan, soybean	Highly weathered soils	Nickel sulfate	Mobile	Moderate mobility	Linked with Fe and Zn metabolism

Detailed Functional Importance of Secondary Nutrients

Nutrient	Role in Photosynthesis	Role in Protein Synthesis	Role in Enzyme Activation	Role in Stress Tolerance	Role in Yield and Quality
Sulfur	Helps chlorophyll formation	An essential constituent of sulfur-containing amino acids	Activates several enzymes	Enhances tolerance against cold and drought	Improves oil content, flavor, and protein quality
Calcium	Maintains chloroplast membrane integrity	Indirect role through cellular stability	Activates ATPase and signaling enzymes	Improves tolerance to salinity and diseases	Enhances fruit firmness and shelf life
Magnesium	Central component of the chlorophyll molecule	Involved in amino acid synthesis	Activates enzymes related to energy transfer	Reduces oxidative stress	Improves grain filling and sugar accumulation

Detailed Functional Importance of Micronutrients

Micronutrient	Role in Photosynthesis	Role in Respiration	Role in Nitrogen Metabolism	Role in Reproductive Growth	Role in Disease Resistance
Iron	Essential in chlorophyll synthesis and electron transport	Cytochrome component	Helps nitrate and sulfate reduction	Supports pollen viability	Enhances antioxidant defense
Zinc	Regulates chlorophyll production	Supports enzyme systems	Required for protein synthesis	Improves flowering and seed formation	Improves resistance against pathogens
Manganese	Water splitting in photosynthesis	Activates respiratory enzymes	Aids nitrate assimilation	Enhances seed development	Strengthens lignin formation
Copper	Electron transport in photosynthesis	Component of oxidase enzymes	Indirect role in protein synthesis	Improves grain and fruit quality	Increases disease resistance
Boron	Maintains chloroplast function	Indirect role through sugar transport	Facilitates nitrogen utilization	Essential for pollination and fruit set	Maintains cell wall integrity
Molybdenum	Indirect role through nitrogen metabolism	Supports nitrate reduction	Essential for nitrogenase activity	Improves pod and seed formation	Enhances legume nodulation
Chlorine	Essential for oxygen evolution	Maintains ionic balance	Influences nitrate transport	Improves turgor for reproductive organs	Reduces certain fungal diseases
Nickel	Indirect role through the urease function	Supports metabolic enzymes	Essential for urea metabolism	Improves seed vigor	Maintains metabolic balance

Critical Deficiency Symptoms in Major Crops

Nutrient	Rice	Wheat	Maize	Groundnut	Tomato	Citrus
Sulfur	Pale young leaves	Reduced tillering	Yellowing	Poor nodulation	Reduced fruit quality	Pale foliage
Calcium	Poor root growth	Weak stems	Tip burn	Empty pods	Blossom end rot	Fruit cracking
Magnesium	Interveinal chlorosis	Leaf striping	Yellow margins	Premature leaf fall	Reduced photosynthesis	Leaf yellowing
Iron	Bronzing and chlorosis	Yellow young leaves	Whitening	Chlorosis	Pale leaves	Iron chlorosis
Zinc	Khaira disease	Stunted plants	White bud	Reduced peg formation	Small leaves	Rosetting
Boron	Sterility	Poor grain filling	Reduced cob size	Hollow heart	Fruit cracking	Gum pockets
Copper	Poor panicle formation	Dieback	Twisted leaves	Reduced growth	Poor flowering	Twig dieback

Molybdenum	Poor nitrogen use	Chlorosis	Reduced growth	Ineffective nodules	Leaf distortion	Rare symptoms

Use of improved varieties and quality seed

The first step towards maximum productivity is to select high-yielding and disease-resistant genetically improved varieties of groundnut, which are carefully designed to maximize yield potential and adapt to agroclimatic conditions. These include varieties that are resistant to major diseases and pests, and varieties that are suited to specific sowing dates and input regimes to ensure good establishment and development of the crop. Moreover, the realised productivity and groundnut quality rely on the interactions between the inherent genetic capabilities of the cultivar used and the environment and management. Hence, the development of high genetic potential cultivars of crops such as groundnut varieties 'HNG-10' and 'Binachinabadam-8', which have exhibited better growth, yield, and quality traits in the INM approach, is significant for sustainable intensification (Kumari *et al*., 2026; Zakaria *et al*., 2025). Also, quality planting seed of these improved varieties ensures a high percentage of germination, robust seedling growth, and uniformity required to ensure maximum plant stand and yield. In addition, it has been reported that the use of combined nutrient management strategies (together with conventional chemical fertilizer and organic farming) can also provide further advantage to these improved varieties as they can help to optimize nutrient availability and soil health (Gorai *et al*., 2024).

Plant population and spacing management

Agronomic parameters like optimum plant density and spatial arrangement of plants play a significant role in the overall yield and resource use efficiency in groundnut production, which directly influences light interception, nutrient uptake, and intra-plant competition. However, although high densities could reduce the area of the root growth (Kumar *et al*., 2024), the right planting density can significantly impact the PUE of the plant, such as 330,000 plants per hectare for Spanish/Valencia cultivars. But, low plant stands can lead to low resource utilisation and yield, creating the need to balance the number of plants to ensure maximum yield of groundnut (Tran, 2025). The studies indicated that a planting rate of 25:25 × 10 cm in groundnut was significant in improving the yield of pods, which was achieved by an increase in the number of kernels per pod, test weight, pod shelling percentage, and pods per plant compared with planting rates of 30 × 10 cm and 15:15 × 10 cm (Nisani *et al*., 2023). This plant geometry allows for the most efficient capture of resources and minimizes the competition between plants, with greater photosynthetic efficiency and biomass allocation to reproductive organs.

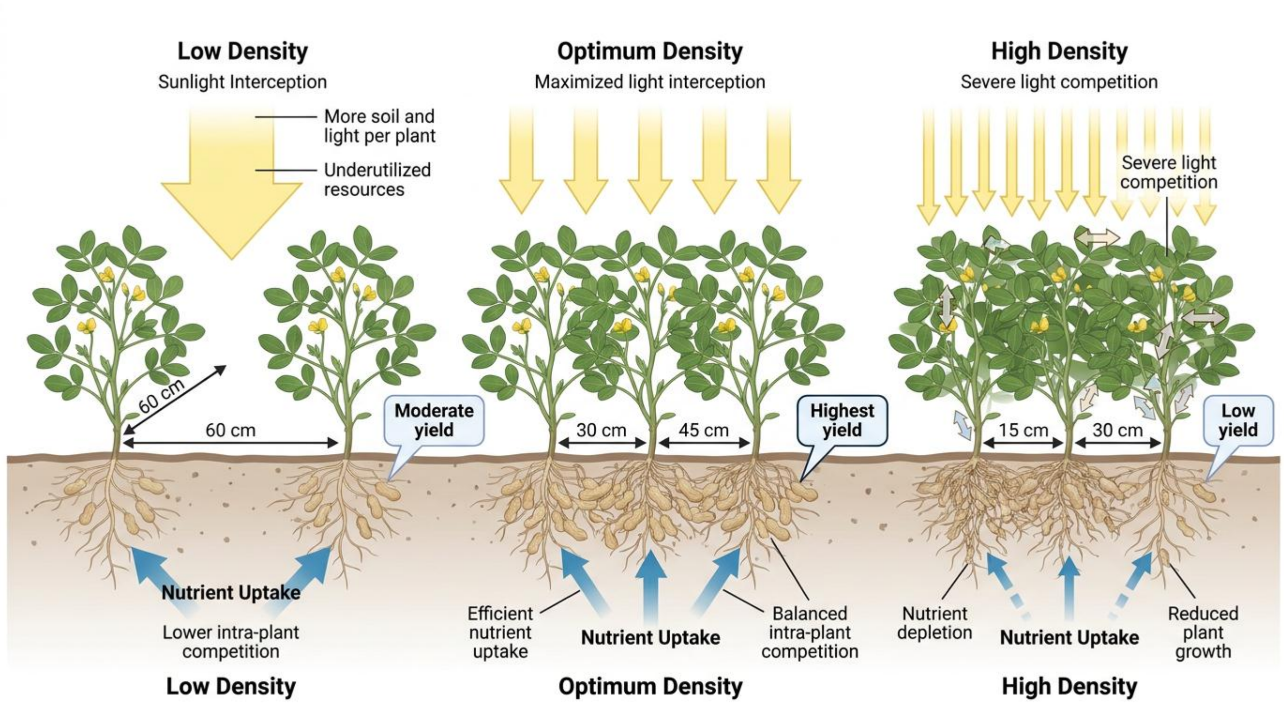

Fig. 1 : The diagram indicates the impact of plant density on sunlight interception, nutrient absorption, and groundnut production, highlighting that the balance of plant density leads to efficient use of resources, optimal competition, and

the highest yield. Low density, on the other hand, will not use the available resources to the fullest, whereas high density will cause intense competition for light and nutrients, which will reduce plant growth and yield.

These planting geometries and seed priming techniques can be synergic when combined to enhance germination, seedling vigour, and growth parameters like plant height and leaf area index (LAI), as further studies revealed (Karunakaran *et al*., 2023). These integrated approaches include optimum plant density, seed treatment, and, in total, are expected to achieve maximum yield and efficient use of resources in groundnut. In addition, plant density is also significant in the management of weeds like broadleaf weeds and grass weeds, and high density typically leads to high control of weed species due to competition between plants and weeds (Shittu *et al*., 2025). The interaction of various planting densities and row configurations and their effects on the yield of groundnut has also been demonstrated, and it was observed that 30 × 10 gave a higher yield than 45 × 10, particularly under higher input management. This highlights the importance of a suitable spatial layout for improved resource management and to minimize competition between plants, especially when combined with nutrient management (Desmae *et al*., 2022).

Integrated Nutrient Management (INM)

Organic and inorganic nutrient sources

The synergistic use of both organic and inorganic fertilizers is essential for sustainable groundnut production as it provides soil with essential macro and micro elements to improve soil physicochemical properties and microbial activity, both of which are important for long-term soil health and nutrient cycling (Ibrahim *et al*., 2021). The results demonstrated that the integrated approach of using bio-fertilizers and organic amendments such as farmyard manure or press mud, along with fertilizers, resulted in a significant advantage in growth, yield attributes, and economic returns of groundnut compared to either organic or inorganic fertilizers being used alone (Babu *et al*., 2024; Paramasivan *et al*., 2024; Warsi *et al*., 2024). For example, the use of vermicompost as an organic nutrient source with seed treatment using microbial inoculants can enhance the pod yield as well as the uptake of nutrients, particularly in the case of BFT (Gaikwad *et al*., 2025). Additionally, 75% application of recommended fertilizer along with 2 t ha^{-1} of vermicompost also showed significant improvement in the growth parameters, yield attributes, and total pod and haulm yield in groundnut (Patel *et al*., 2024). The judicious use of organic manures (Farmyard manure, neem cake) along with biofertilizers like Rhizobium and phosphate-solubilizing bacteria still further augment yield parameters by improving nutrient availability and establishing a healthy rhizosphere microbiome (Sharma & Moinuddin, 2025).

Biofertilizers and nutrient-use efficiency

Biofertilizers, especially the nitrogen-fixing bacteria such as Rhizobium, and phosphate-solubilizing bacteria, are of great significance in increasing nutrient acquisition and minimizing the need for chemical fertilizers, leading to better nutrient-use efficiency in groundnut production (Gaikwad *et al*., 2025). Incorporating rhizobial inoculant along with vermicompost has been demonstrated to work synergistically in improving nitrogen fixation, nutrient availability, and plant growth, which resulted in higher nodulation, pod production, and growth of plants (Nahar, 2025). It is evident in studies that have been conducted in which the use of biofertilizers along with the integrated nutrient management has been done, which has led to higher yields of groundnut and better microbial activity as compared to conventional methods of chemical fertilizer application (Palai *et al*., 2026; Paramesh *et al*., 2023). Application of beneficial microbes (VAM fungi and different plant growth-promoting bacteria) singly or in combination with organic amendments (vermicompost and farmyard manure) significantly enhances the growth and yield parameters and nutrient assimilation in groundnut (Arachis pintoi, Donga & Mathukia, 2021; Priyansha *et al*., 2024). In particular, biochar-based rhizobium inoculants have been found to increase nodulation, root weight, shoot weight, nut yield, soil nutrient uptake, soil nitrification, and decrease soil denitrification, resulting in better uptake of N and growth of plants (Shikha *et al*., 2023).

Impact on soil fertility and crop productivity

The integration of biofertilizers and organic amendments is comprehensive, and it has a significant impact on soil fertility by increasing the content of organic matter, improving soil structure, and promoting soil health, which results in better nutrient cycling. This integrated approach helps in minimizing the negative impacts of synthetic fertilizers, such as reducing nutrient leaching, preventing groundwater pollution, and reducing greenhouse gas emissions (Yadav & Yadav, 2024). Furthermore, the use of bio-fertilizers is an essential method for maintaining and improving soil health in sustainable agriculture by promoting nutrient balance and biodiversity, which is crucial for soil health (Shaaban *et al*., 2025). Additionally, it has the potential to tackle the issue of nutrient-poor soils that are found in many areas where groundnut is grown, providing a greener way to produce groundnut than with chemical fertilizers (Chuong, 2025). In particular, biofertilizers such as Rhizobium sp. with vesicular arbuscular mycorrhizal fungi and sufficient phosphorus application have been observed to produce a significant increase in the growth, pod yield, and oil content of groundnut compared with individual application of biofertilizers and phosphorus (Baburao & Singh, 2024). Moreover, the combined application of bio-fertilizers and soil amendments such as farmyard manure has been demonstrated to greatly improve nodulation and growth characteristics such as plant biomass, shoot length, and root length in groundnut (Ghosh *et al*., 2023). The symbiotic associations created by these inoculants, like the nitrogen fixation capacity of Rhizobium and increased nutrient uptake of mycorrhizal fungi, all contribute to enhancing nutrient availability and plant physiological activities (Bajaj, 2021; Godar *et al*., 2023).

Rhizosphere Microbiome and Plant–Microbe Interactions

Role of rhizosphere microorganisms in groundnut growth

The rhizosphere ecosystem is a small region of soil rich in microorganisms that is greatly affected by root exudates, and these microorganisms play an important role in plant health, plant defense, and nutrient cycling around the rhizosphere of groundnut (Arachis pintoi) (Shittu *et al*., 2025). These microorganisms, such as bacteria, fungi, and archaea, interact with the plant in complex ways and affect its ability to acquire nutrients, resist disease, and withstand stress (Wang *et al*., 2024; Xu *et al*., 2023). For instance, plant growth-promoting rhizobacteria are reported to promote plant growth by improving nutrient availability through nitrogen fixation, phosphate solubilization, and modulation of phytohormones, besides reducing phytopathogens (Eswaran *et al*., 2023; Vasant *et al*., 2023). The peanut rhizosphere microbial community is significantly altered during the growth and development of the crop from pre-sowing till post-harvest, which affects the uptake of nutrients by the plant and the productivity of the crop (Hinsu *et al*., 2021).

Symbiotic nitrogen fixation and Rhizobium association

One of the main symbiotic associations in groundnut is with the nitrogen-fixing bacteria of the genus Bradyrhizobium, which initiate nodules on the root of the plant, which fix nitrogen from the atmosphere into a form usable for the plant (Mitra *et al*., 2025). This complex process greatly reduces the use of synthetic nitrogen fertilizers, which in turn helps reduce the environmental impact and promote sustainable farming practices (Dey *et al*., 2024; Krishnan *et al*., 2025). The use of Rhizobium inoculants has always been proven to increase the yield of groundnut (Lathyrus siliquaeallis L.), particularly in nitrogen-deficient soils, and therefore plays an important role in increasing the production of the crop and nitrogen fixation (ABEBE *et al*., 2026). Grain protein content can be increased by up to 28% and yield by 15% after inoculation with Bradyrhizobium japonicum, as shown in studies, which has been attributed to increased nitrogen absorption and biomass growth (Pradhan *et al*., 2025). In addition to nitrogen fixation, these microbial communities are affected by several parameters, such as nutrient availability, temperature, water content, soil structure, soil pH, and host plant genetic traits and root exudates (Hossain *et al*., 2023).

Plant growth-promoting rhizobacteria (PGPR) and mycorrhizae

They play a crucial role in the peanut plant's core microbiome, participating in nutrient cycling and overall plant health, with some genera like *Sphingomicrobium*, *Actinoplanes*, and *Pseudomonas* spp. of the Pseudomonadaceae family being beneficial. In addition to these, other plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi contribute to plant growth and abiotic and biotic stress tolerance through their metabolic functions, such as inducing host plant defense mechanisms and better water metabolism (Eswaran *et al*., 2024; Kang *et al*., 2023; Li *et al*., 2023). Fertilization, crop species, plant diversity above the ground, and variance of the microclimate due to the canopy and root exudates each modulate this dynamic rhizosphere microbiome, influencing the composition of the microbial community and its functional attributes (Dong *et al*., 2022). To improve agricultural productivity, the genetic and biochemical mechanisms underlying these symbiotic associations need to be better understood, with an emphasis on the groundnut plant's ability to enhance nodulation efficiency and reduce its reliance on rhizobia. The complex relationship between the groundnut plant and its associated microbiome, including rhizobia and plant growth-promoting rhizobacteria, underscores the need for a deeper understanding of the genetic and biochemical mechanisms underlying these symbiotic associations, with a particular focus on how the groundnut plant contributes to its symbiotic efficiency and decreases its dependency on rhizobia (Godar *et al*., 2023). This knowledge is essential for designing specific inoculation protocols to make the most of these microbial alliances for improving nutrient efficiency and stress tolerance in groundnut production (Bigattón *et al*., 2024; Liang *et al*., 2024).

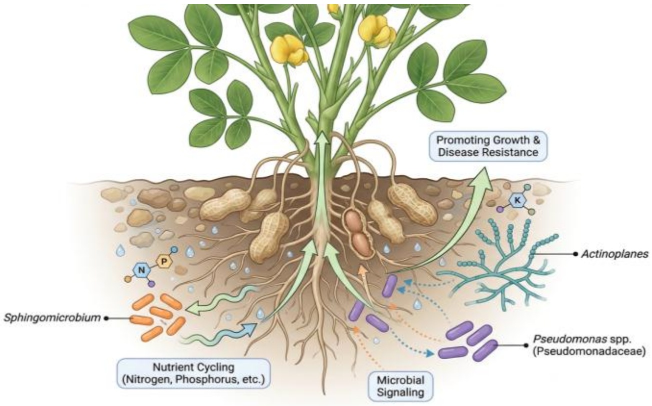

Fig. 2 : The diagram illustrates the interactions between groundnut roots and beneficial rhizosphere microorganisms involved in nutrient cycling, microbial signaling, and plant growth promotion. Microbes such as *Pseudomonas*, *Actinoplanes*, and *Sphingomicrobium* enhance nutrient availability, improve disease resistance, and support overall plant health and productivity.

Microbial interactions under different sowing environments

Due to alterations in sowing dates, the colonization pattern and soil microbial activities in the groundnut rhizosphere would also vary. Different planting times, for example, may also lead to different temperature and moisture conditions, which can influence the composition and activity of nitrogen-fixing bacteria and phosphate-solubilizing microorganisms, thus impacting nutrient availability and performance of the plants (Wang *et al*., 2021). Moreover, different soil types (acidic, neutral, and saline-alkali soils) have differential regulatory effects on peanut growth and bacterial communities, affecting yield and the abundance of beneficial bacteria species, such as Bradyrhizobium and Streptomyces (Lan *et al*., 2025). It has been demonstrated that applying specific intercropping patterns increases soil N availability by altering the soil microbiome and its activities (Qiao *et al*., 2024). Arbuscular mycorrhizal fungi play an important role in this beneficial microbial community; they provide enhanced photosynthesis in the host plant, improve root morphology and nutrient and water uptake, and reduce abiotic stress (Agyekum *et al*., 2023; Liu *et al*., 2023). Moreover, intercropping systems have been shown to trigger a 'cry for help' mechanism in the rhizosphere microbiome, whereby stress plants attract beneficial rhizosphere microorganisms such as Pseudomonas spp. under stressful conditions through intercrop root-root communication through the secretion of flavonoids from peanut roots (Wang *et al*., 2025).

Water Management and Sustainability in Rabi Groundnut

Irrigation scheduling and critical growth stages

Water is the most limiting factor for achieving the maximum yield of rabi groundnut, and the requirement is specifically the amount and timing of irrigation during critical phenological stages, which greatly affects the physiological processes and nutrient uptake. This will ensure water availability during the period of peak plant requirement for greater photosynthetic efficiency and biomass accumulation. Groundnut is considered drought-tolerant, but the water stress during critical growth stages like flowering and pod formation leads to a significant reduction in growth parameters such as shoot dry weight, number of nodules, and harvest index (Elshamly, 2023). However, drought resistance of peanut can be improved through appropriate water management practices, such as inoculating the rhizosphere with arbuscular mycorrhizal fungi, which can improve physiological parameters and microbial stability in the peanut rhizosphere (Du *et al*., 2026). In addition to inoculation, strategies such as deficit irrigation that can help reduce the amount of water needed to achieve full irrigation requirements are found to maintain the yield of groundnut in limited water supply conditions (Chi & Dong, 2024).

Water-use efficiency in groundnut cultivation

The adoption of modern water-saving innovations and practices, like precision irrigation and intercropping systems, has the potential to significantly boost water use efficiency in groundnut farming (Qiu *et al*., 2025). For example, by intercropping between non-phytosiderophore-producing plants and graminaceous plants, the rhizosphere iron and zinc availability would be improved, and hence would improve the nutrient acquisition ability (Homulle *et al*., 2021). Furthermore, certain intercropping patterns, such as finding the best strip width in maize/peanut systems, have been demonstrated to enhance crop productivity and water use efficiency, fostering water-smart agriculture in water-stressed areas (Sun *et al*. 2025). Besides, the use of automated drip watering and low-cost smart drip fertigation systems is a potential avenue to optimize water and nutrient supply, thereby improving the growth, physiology, root properties, and yield of groundnut, while reducing the resource wastage (Aathithyan *et al*., 2025).

Moisture conservation practices and mulching

Mulching, especially when using organic or synthetic sources, is an important practice to minimize water loss due to evaporation from the soil surface, to regulate soil temperature, and to reduce weed population, thus improving the overall water use efficiency of rabi groundnut cultivation. This is an effective technique for saving soil moisture and also enhancing soil health and microbial activity, which play a key role in nutrient cycling and plant growth (Sivarasan *et al*., 2021). Different mulching methods, such as straw, plastic mulch, and living mulch, could greatly affect the hydrothermal regime of soils, thereby affecting the decomposition rates of organic matter and the release of nutrients. In groundnut, optimal mulching coupled with stress-reducing chemicals has been observed to effectively improve the growth, yield, physiological attributes, and water use efficiency (Gajera *et al*., 2024). Moreover, the adoption of a strategy of strategic use of the critical stage-based irrigation scheduling in the context of a well-coordinated crop management system can potentially sustainably intensify groundnut production, particularly in water-limited regions, by providing water during critical stages of crop growth (Naveenkumar *et al*., 2026).

Drip irrigation and precision water management

Drip irrigation, by providing direct water to the root zone, reduces evaporative loss and runoff from the crop, which improves water use efficiency and reduces environmental impacts in groundnut production (Elshamly & Nassar, 2024). This is also the most precise application of water, which can be achieved by fertigation, adding fertilizers to the irrigation system, and then delivering specific nutrients to the plant roots (Aathithyan *et al*., 2025). In fact, smart fertigation systems ensure optimal uptake of nutrients and microbial population, thereby enhancing soil health and the productivity of groundnut (Aathithyan *et al*., 2025). Selecting groundnut varieties with greater drought tolerance and efficient root architecture (Gelaye *et al*., 2025; Gelaye & Luo, 2024) is another crucial water management aspect that can enhance water use efficiency. These choices of cultivars, along with other agronomic practices such as conservation agriculture and raised bed planting, play a significant role in boosting productivity and sustainable groundnut production in water-limited areas (Chilwal *et al*., 2025; Sisodia & Sharma, 2023). Furthermore, adopting mulching methods such as plastic films and straw can further improve soil moisture holding capacity and soil temperature regulation, which are essential to ensure good crop growth and productivity in dryland farming systems (Li *et al*., 2025; Zhao *et al*., 2024).

Weed, Pest, and Disease Management

Major weeds affecting rabi groundnut

Having access to information on weed species and their control is of major importance to reduce yield losses during rabi groundnut production because competition for resources can be a major constraint on crop growth. There is a significant weed competition problem in groundnut, especially at the early growth stages, because of its slow initial growth rate (Vishnu *et al*., 2025). This competition can result in a significant loss of crop yield, ranging from 17% to 85% of applied nutrients, mostly due to weeds taking more than 50% of the nutrients supplied (Rabari *et al*., 2024).

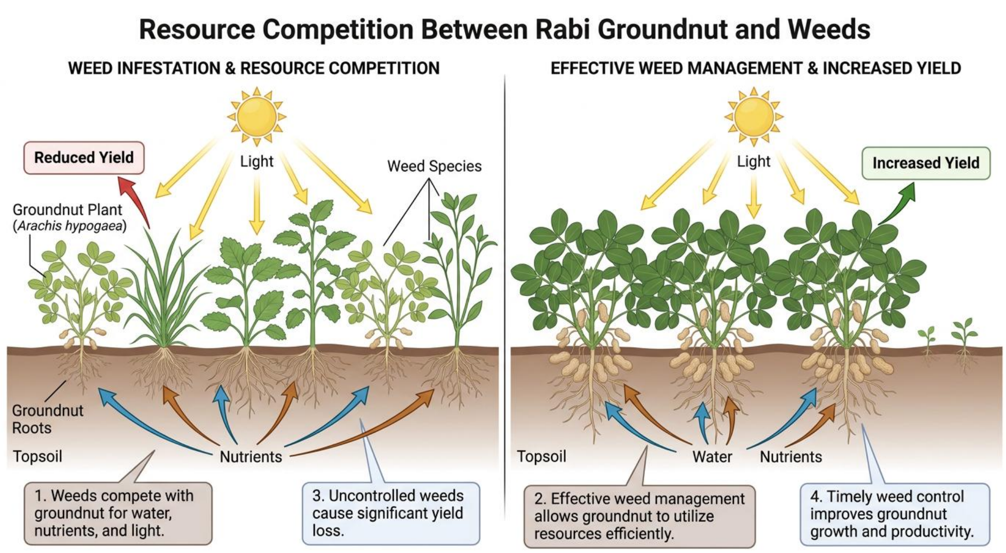

Fig. 3 : The diagram illustrates the competition between weeds and rabi groundnut plants for essential resources such as light, water, and nutrients, which can significantly reduce crop growth and yield under unmanaged conditions. It also highlights that effective and timely weed management improves resource utilization, enhances plant development, and ultimately increases groundnut productivity.

Hence, the adoption of integrated weed management (IWM) strategies, which involve cultural, mechanical, and chemical management, is critical to improve groundnut productivity and resource use. For example, pre-emergence herbicides followed by proper hand weeding have shown a good control of weed population and resulted in higher yield of groundnut ("Integrated Crop Management for Climate Resilience in Rainfed Groundnut (Arachis Hypogaea) Cultivation," 2021; Sunitha *et al*., 2023). Weed infestation can contribute to yield loss in groundnut ranging between 15 to 40%, making such integrated approaches very crucial in groundnut production (Hussain *et al*., 2023). Weed management during the critical crop-weed competition period (40-60 days after sowing) is most critical to maximize the yield of groundnut (Swetha *et al*., 2022; Tripathi & Singh, 2022) as weed-free plots yielded significantly higher than the untreated plots.

Integrated pest and disease management strategies

To ensure sustainable production of groundnut, effective integrated pest and disease management is essential to the crop due to its susceptibility to a host of pathogens and pests that can affect yield and quality (Pujar *et al*., 2025). Such strategies may be implemented through a combination of multiple management approaches, including the use of host plant resistance, biological control agents, cultural management, and judicious use of chemicals to limit economic loss and reliance on synthetic pesticides (Charitha *et al*., 2024). In the case of soil-borne diseases, for example, the use of disease-resistant cultivars and bio-controlling agents has been effective in improving the yield of groundnut and controlling the incidence of diseases (Umesh *et al*., 2025). Additionally, pre-emergence and post-emergence herbicides (with the occasional inclusion of manual weeds) constitute a viable weed control program for the entire season, leading to increased crop productivity (Narwal & Yenagi, 2026; Ravi *et al*., 2024; Srinivasan *et al*., 2024). Such integrated practices involving various methods of weed control are especially crucial because, during its early stages of growth, groundnut is highly susceptible to weed competition, which can result in significant yield loss (Nivetha *et al*., 2022; Priyanka *et al*., 2023). In fact, mixtures of pre-mix post-emergence herbicides, like imazethapyr + imazamox, propaquizafop + imazethapyr, or quizalofop-p-ethyl + imazethapyr, have proven effective in controlling a wide range of weeds and in maximizing the economic return in groundnut production (Kalyani *et al*., 2024). However, specific post-emergence herbicides like metamifop 8% + imazethapyr 4% + imazomox 3% ME are very effective in reducing weed density and dry weight of weeds, which further helps in improving cropping performance (Kumar *et al*., 2025). Additionally, a specific combination of the herbicides pendimethalin and imazethapyr with quizalofop ethyl applied as a single tank mix at a specific growth stage is a very effective weed control strategy, which boosted the economic yield and money returns of groundnut cultivation, especially in labour-limited conditions (Ravi *et al*., 2023).

Biological and eco-friendly control measures

These measures focus on methods that do not use synthetic chemicals or pesticides, such as the use of natural enemies and biopesticides, to control pests and diseases, thus minimizing the impact on the environment from traditional chemical controls. For instance, modules for IPM that include seed treatments (fungicide-based, like Carbendazim + Mancozeb) and need-based spraying of insecticides (Dimethoate) have proven to be highly effective for the control of major insect pests and diseases in groundnut (Gawade *et al*., 2025). The use of microbial inoculants, especially those that improve the systemic resistance of the plant or act directly as pathogen inhibitors in the plant, is a potential opportunity to strengthen the plants' natural defenses and lower disease pressure in groundnut. Furthermore, the use of biopesticides based on botanical extracts or microbial metabolites is an alternative where it is possible to manage a variety of pest complexes sustainably, thus reducing contamination of the environment and promoting biodiversity in agroecosystems. Integrated pest management (IPM) involves choosing appropriate varieties, sanitation, and timing of planting to ensure long-term sustainability of groundnut production (Maheshala *et al*., 2022). In addition, an optimum sowing date strategy can help reduce the incidence of pests and diseases as it will avoid peak predator and pathogen activity, which will help support crop resilience. Likewise, the use of certain herbicide schedules like pendimethalin followed by quizalofop-p-ethyl has been found to be significantly more effective than the traditional hand weeding practices in terms of controlling weed population and enhancing the production of groundnut (Pattanayak *et al*., 2025).

Physiological and Biochemical Responses under Different Sowing Dates

Photosynthesis and chlorophyll dynamics

A negative effect of delayed sowing on the photosynthetic efficiency and chlorophyll content has been observed, which in turn affects the groundnut's ability to accumulate biomass and yield pods, especially under high-temperature conditions. On the other hand, favourable sowing dates coincide with favourable environmental conditions, thus favouring high photo-synthetic rates and maintaining a high chlorophyll integrity, essential for achieving maximum crop yields. This optimization of sowing windows becomes critical because groundnut is a high-energy crop that has a high nutrient demand, and nutrient uptake rate is directly related to the productivity of the crop and the inherent fertility of the soil (Nayak, 2024). The optimal conditions, however, are being threatened by global climate change, which is causing unpredictable temperature variations and changes in rainfall patterns, affecting groundnut growth and yield (Chilwal *et al*., 2025; Reager *et al*., 2024). To further complicate these problems, late or early sowing, which puts stress on crop plants, is used to simulate the effects of climate change, which exacerbates these problems and brings the plant to heat stress and consequently reduces the productivity (Shahin *et al*., 2023). This highlights the importance of agro-meteorological assessments to find the best sowing window that could make the most of favorable thermal and radiation conditions, increasing resource-use efficiency and overall production (Paluchani *et al*., 2025). The responses of groundnut to sowing date and physiological characteristics, such as photosynthetic capacity and chlorophyll content of the crop, play an important role in harnessing the sun's energy to produce biomass, which makes precise timing essential for realizing yield potential. In addition, changes in sowing dates may considerably influence the nutrient acquisition and utilization efficiency, which in turn will affect the overall nutrient status of the plant and the productivity. This requires a comprehensive knowledge of the effects of different sowing dates on the absorption and allocation of macro- and micronutrients in crops under different soil and climatic conditions. Sowing dates, for example, are optimised to prevent a high temperature during critical growth stages, which causes degradation of chlorophyll and decreases light absorption and photosynthetic rate (Kumar *et al*., 2023).

Stress tolerance mechanisms

The differential need for water at different stages of development of groundnut, especially during the mid-pod filling stage when high photosynthesis is essential for pod development, is a manifestation of the physiological basis of drought tolerance (Puppala *et al*., 2023). Indeed, sowing time is a key adaptation strategy to counteract the negative impacts of extreme temperature, and better pod production was recorded in moderate sowing dates than early or late sowing (Liu *et al*., 2023). The strategy to plant at optimal times guarantees that the plants spend more time in their most sensitive stages of the crop cycle, such as flowering and pod filling, during conditions of sufficient moisture and favourable temperatures, promoting yield stability (Naik *et al*., 2025). Furthermore, genotypes with stable performance in terms of amount of chlorophyll and good pod production under water stress are considered to be physiologically resilient, which is essential for sustained productivity under environmental variability (Adja *et al*., 2025). Genetic susceptibility to drought, coupled with environmental conditions like temperature and water availability, requires a holistic approach to optimize sowing dates according to the physiological needs of the particular cultivar of groundnut. For example, high temperatures above 45 °C and low temperatures below 15 °C will greatly reduce germination and growth of the plants, showing a narrow thermal window for optimal plant growth (Ijaz *et al*., 2021).

Nutrient uptake and partitioning

The exact sowing time also plays a crucial role in the effective absorption and distribution of essential nutrients through the rhizosphere, and research has shown that the later sowing time is related to higher soil temperatures, which can result in greater uptake of phosphorus from the root zone (Abaza *et al*., 2023). This phenomenon is due to higher microbial activity at the higher temperature, which helps to mineralize and mobilize phosphorus and make it more assimilable by plants (Kadirimangalam *et al*., 2022). The complex nature of the rhizosphere dynamics and the availability of nutrients with sowing date, however, demands further research to find the best strategy for groundnut nutrient acquisition. In addition, the sowing date's relationship with nutrient uptake is found for other important macronutrients, including nitrogen and potassium, which impact their availability and their efficiency in utilization, especially under different soil moisture conditions. Furthermore, the rhizosphere microbiome is highly dynamic in response to sowing time, and therefore can affect the nutrient cycle and its uptake by the crops, so there is a need for a holistic understanding of these intricate biotic relationships to enhance nutrient use efficiency in groundnut cultivation. Such a dynamic interplay highlights the need to take into account microbial community response to environmental cues associated with varying sowing windows in order to optimize nutrient delivery to the plant to the greatest extent possible. For this reason, an abiotic-biotic approach should be taken to optimise sowing dates to obtain the highest productivity and most efficient use of resources for groundnut. This holistic approach may contribute to the creation of specific agronomic practices that, besides fostering yield, can also contribute to sustainable agricultural systems. These comprehensive approaches are especially important for adapting to the effects of climate change, which can impact the timing of agricultural activities and consequently, the performance of agricultural operations (Jamir *et al*., 2025; Tlatlaa *et al*., 2023).

Yield Attributes and Quality Parameters

Pod formation and kernel development

Reduced row spacing has been reported to enhance pod formation by inducing better vegetative growth and movement of photosynthate to developing pods and enhancing the availability of phosphorus for robust root development (Bajya & Sharma, 2024; Jamir *et al*., 2025). This improvement is frequently seen when higher rates of phosphorus application are used, which directly affects the phosphorus availability in the soil and the improvement of the nutritional quality of the soil, providing an optimum soil condition for groundnut growth and development (Kumar *et al*., 2024). Pod formation and other yield parameters, such as number of pods per plant, kernel number per pod, and test weight, were significantly affected by higher levels of phosphorus application (at 60 kg ha^{-1}) along with foliar application of 0.5% of $ZnSO_4$ (Minz *et al*., 2024). On the other hand, phosphorus deficiencies can cause decreased photosynthetic activity and less efficient pod setting, which affects final yield (Salama, 2024). This highlights its important and essential function in leguminous crops, as phosphorus is highly required for energy transfer molecules, which are important for nitrogen fixation, and also for other physiological processes (Murtaza *et al*., 2022). Moreover, plant growth regulators like indole acetic acid and gibberellic acid were found to synergistically interact with phosphorus availability to further stimulate reproductive development and ultimately yield of pods (Karunakaran *et al*., 2023).

Shelling percentage and oil content

Gypsum application has been reported to improve the availability of calcium and its role in kernel development and oil production, which led to an increase in shelling percentage and oil content (Shokri *et al*., 2024). The use of integrated nutrient management (INM) practices, in which inorganic and organic nutrient sources are combined with micronutrient sources such as boron (inorganic) and press mud or farmyard manure (organic) is very effective in increasing these quality parameters, which include better supply of nutrients and the improvement of the physicochemical characteristics of the soil (Jena, 2024; Warsi *et al*., 2024). Importantly, the amount of calcium obtained from gypsum application is directly related to higher kernel yields, better pod filling, and lower empty pods, and is an essential requirement for groundnut productivity (Malla & Wagle, 2021). Specifically, it has been shown that the use of gypsum, especially at 225 kg ha^{-1}, results in significant improvement in pod yield, haulm yield, and kernel yield (Brar & Manhas, 2023). According to further study, application of 50% gypsum at 50% basal and 50% at 45 days after sowing in association with 100% RDF gave the maximum pod and haulm yields and revealed that timely availability of calcium along with comprehensive nutrient management was very crucial for groundnut quality (Priyadharshini *et al*., 2025). The specific gypsum formulation that provides the key calcium and sulfur nutrients, as well as extra nutrients such as phosphorus and zinc, is also responsible for better pod filling and yield (Dhumgond *et al*., 2023; Parmar *et al*., 2025).

Influence of integrated management on quality traits

Integrated nutrient management, which includes 75% STCR and Rhizobium, humic acid, and poultry manure, has been shown to have a significant effect on pod yield as well as haulm yield, due to improvement in soil physicochemical properties and availability of nutrients over time (Paramasivan *et al*., 2023, 2024). The same is true for the combination of 100% Recommended Dose of Fertilizer, Phosphogypsum at 750 kg ha^{-1} and Borax at 10 kg ha^{-1}, which significantly improved plant height, branching, dry matter production, and total and filled pods plant^{-1} (Sahana *et al*., 2024). The integrated approaches involve optimizing the use of fertilizers along with organic amendments, leading to a substantial enhancement of pod yield and other yield parameters like pod weight and shelling percentage (Kumari *et al*., 2026; Veeranna *et al*., 2023). Furthermore, it has been observed that balanced use of nitrogenous, potassic, and enriched organic manures along with micronutrients like zinc and boron has been found to be more effective in optimizing yield attributes like number of pods per plant and shelling percentage (Vidhya *et al*., 2024). Ca applied at 165 kg ha^{-1} (as gypsum) has been reported to significantly enhance pod production, number of filled pods, and hundred seed weight by 9%, 77%, and 46%, respectively, in different seasons than the control (Malla *et al*., 2021). Co-application of gypsum with farmyard manure has been reported to enhance peanut yield and quality parameters such as crude protein and oil content by 67% and 65%, respectively, in different seasons than the control (Latif *et al*., 2021). Moreover, it has been reported that the growth parameters (SPL), kernel yield attributes, and yield of maize were significantly increased when 75% of the fertilizer dose was applied along with 2 t ha^{-1} of vermicompost, which also led to a significantly higher protein content in the kernels (Patel *et al*., 2024).

Role of Sustainable and Climate-Resilient Practices

The adoption of practices like zero tillage and residue management is identified as one of the key strategies that will help in improving soil health, water holding capacity, and nutrient cycling, which would lead to sustainable groundnut production under varying climatic conditions. These practices often lead to increased water infiltration and reduced evaporation, which are critical for maintaining adequate soil moisture during dry spells, directly impacting groundnut growth and yield (Swathi *et al*., 2024). Moreover, the use of polyhalite fertilizers as multi-nutrient sources can be used to solve the issue of deficiency of potassium, calcium, magnesium, and sulphur in these conservation systems, which can increase yield and soil health (Gopinath *et al*., 2024). Moreover, the effect of organic amendments and bio-fertilizers like Rhizobium and phosphate-solubilizing bacteria was found to be synergistic in enhancing soil fertility and nutrient use efficiency, which would enhance the resilience of groundnut plants and increase the productivity (Sharma & Moinuddin, 2025).

Strategically using adaptive varieties and optimized cropping calendars to reduce the effects of erratic weather patterns and longer dry spells and to ensure regular crops (Nayak *et al*., 2024). Furthermore, judicious nutrient management is crucial for groundnut productivity under different climatic conditions, which involves using the right doses and timing of macro and micronutrients (Kabilan *et al*., 2025; Maria *et al*., 2025). This comprehensive strategy combines both genetic and agronomic strategies to ensure the stability and improvement of groundnut yields while reducing environmental impacts. These systems also include the addition of integrated organic nutrient management strategies, which, besides increasing growth and yield, also improve soil organic matter and nutrient levels in post-harvest soils (Gaikwad *et al*., 2025; Yasmin, 2022). Climate-resilient groundnut varieties, especially drought-tolerant varieties, are important in boosting agricultural production and household incomes and are important tools for adapting to climate change (Tabe-Ojong *et al*., 2023).

Long-term sustainability of agriculture is key to soil health and carbon sequestration, which includes methods that increase SOC and enhance microbial activity (Timilsina *et al*., 2025). Conservation agriculture practices like mulching and minimal tillage are effective in improving soil quality and resilience to support sustainable crop production, which involves promoting biological, physical, and chemical properties of the soil (Omomowo & Babalola, 2021). In particular, farmyard manure and legume-cover cropping offer great potential to boost soil organic carbon, a measure of soil health and fertility (Bana *et al*., 2024). Additionally, biochar inoculants with rhizobiums have been reported to affect the functional microbes population, thereby enhancing the N uptake and soil nitrification while reducing denitrification, which ultimately led to improved plant growth and nut yield (Shikha *et al*., 2023). These practices, along with agroforestry and integrated nutrient management, also help in carbon sequestration and enhancing soil health (Paramesh *et al*., 2023).

Economic Analysis and Farmer Profitability

Under integrated management systems, the cost of cultivation may often show a positive marginal contribution to the returns, especially as opposed to conventional cultivation systems, where the returns from marginal increments in the use of synthetic inputs are reduced. This can be done by enhancing soil fertility and carbon sequestration by implementing integrated nutrient management practices that involve adding biochar to the soil, organic amendments, and site-specific nutrient application (Suresh, 2025). For example, the use of pigeonpea biomass as a nutrient source can help minimize inorganic fertilizer use and associated production costs, contributing to sustainable production (Yeboah *et al*., 2021). Furthermore, CSA practices such as adopting plant varieties with resilience to climate change and optimized nutrient management techniques have proven to be highly effective in increasing farm productivity and farm income, improving technical and resource use efficiency, and increasing resilience against climate change (Ma & Rahut, 2024).

Benefit-cost ratio and net returns are very important measures of the economic viability of these sustainable agricultural interventions, as they directly show the economic performance of farmers and their profitability. The implementation of climate-smart agricultural technologies is consistently found to have a positive impact on farmers' economic performance, including improved farm productivity, income, and resilience (Zheng *et al*., 2024). Meta-analyses show that CSA can generate yield gains of 20-38 % in stressed conditions due to climate change, with an increase of soil carbon sequestration of 1.2-1.5 Mg C ha^{-1} yr^{-1} (Devarajan *et al*., 2026). These practices have the potential to reduce climate change impacts and increase the resilience and sustainability of agricultural systems (Çokkızgın *et al*., 2025). In particular, agroforestry systems are able to sequester carbon and improve soil organic matter levels, promoting overall farm sustainability and diversification (Comolli *et al*., 2024; Osorio-Marín *et al*., 2024).

Integrated farming systems that skillfully integrate different components (crop rotation, intercropping, conservation tillage, etc.) are essential to improve resource-use efficiency and sustainability by optimizing the use of water, nutrients, and solar energy, thereby increasing the ecological stability and lowering the environmental impact. The strategic incorporation of biological, inorganic, and organic nutrient sources to achieve sustainable crop production and enhance soil ecology, through optimizing nutrient delivery and improving soil organic matter and water retention, is crucial (Zerssa *et al*., 2023). This holistic approach leads to a significant decrease in the environmental impact of agricultural operations and also enhances the productivity and sustainability of agricultural systems and ecosystems (Goufo *et al*., 2026; Kabato *et al*., 2025). In addition, the full implementation of CSA practices, such as sustainable land and water management, climate-resilient cropping systems, and integrated soil fertility management, has been found to boost the productivity of farms by 28-45% and the income of farmers by 35-52% (Harsela, 2026).

Recent Advances and Future Research Directions

Precision agriculture involves advanced technologies such as remote sensing, artificial intelligence, and machine learning in order to effectively manage the inputs in groundnut and enhance yield prediction, thus enabling precise site-specific management (Safdar *et al*., 2024). Such technologies can enable better control over input application (e.g., water and nutrients), thereby enhancing resource use efficiency and minimizing environmental footprints (Mushtaq *et al*., 2025). The technology is a precision farming technology of an advanced level, and should be further studied with respect to its effectiveness and economic viability in different agro-ecological zones, particularly with respect to its scalability and applicability to smallholder farmers. There is a need to invest in further investigations of integrated farming systems like agroforests and conservation tillage to understand how they can enhance the efficiency of resource use and improve resilience in various farming contexts (Maqbool *et al*., 2025; Singh *et al*., 2023). This means comprehension of the relationship between above-ground and below-ground biodiversity and their role in maintaining soil health and productivity, and understanding the cumulative effects (Saikanth *et al*., 2023; Scordia *et al*., 2025). In developing countries, where climate variability is increasingly a problem in the face of a warming climate, peanut production and food security can be optimized through the development of peanut varieties with higher drought tolerance and drought resistance (Gelaye & Luo, 2024).

This is because the rhizosphere is the most vital microbial environment, which can be manipulated through microbiome engineering and bio-stimulants, to improve plant vigor and stress tolerance (Chi & Dong, 2024). They have the potential to greatly enhance plant uptake, resistance to disease, and productivity, which requires additional studies of these methods to evaluate their practicality and scalability. Moreover, understanding the genetic basis of disease and pest resistance in common diseases and pests is important for the production of resistance and tolerance in groundnut to meet the challenge of climate change through advanced molecular breeding techniques (Pei *et al*., 2026; Sabitha *et al*., 2025). Finally, further development of precision farming technologies, especially those for specialty crops such as groundnut, is important to adapt them for efficient cultivation, user-friendliness, and cost-effectiveness for their adoption by farmers in general (Khoddamzadeh *et al*., 2026; Pierre, 2024).

With AI, remote sensing, and digital agriculture applications, there is a greater possibility of providing real-time information for decision making, optimizing resources, and forecasting groundnut yield with greater accuracy (Akintuyi, 2024; Pugh *et al*., 2024). The innovations, alongside the inclusion of devices belonging to the Internet of Things (IoT), enable the detailed monitoring of environmental parameters and plant physiological responses, allowing dynamic adjustments of cultivation practices (Alazzai *et al*., 2024). Furthermore, the establishment of strong, stable root systems (with deep rooting and efficient xylem design) is essential for better water and nutrient uptake, particularly during drought, and is key to developing groundnut climate adaptation (Gelaye *et al*., 2025). Genetic innovations like marker-assisted selection, genomic selection, and targeted gene editing help to develop climate-resilient groundnut varieties that are improved for drought resistance and nutritional quality (Abady *et al*., 2024; Yu & Chen, 2024). Additionally, the molecular targets and quantitative trait loci (QTL) associated with drought stress tolerance and efficient phenotyping through the use of phenomics and artificial intelligence (AI) are crucial to speeding up the development of climate-resilient groundnut genotypes (Rajpal *et al*., 2023).

Conclusion

Optimization of rabi groundnut (*Arachis hypogaea* L.) productivity demands the use of suitable agronomic, biological, and water management practices in different sowing environments. Optimum sowing dates, well-balanced nutrient application, better cultivars, precision irrigation, enhancing the rhizosphere microbiome, and sustainable soil management are all important for improving crop growth, nutrient uptake, pod development, and overall yield. Rhizosphere microorganisms like beneficial rhizosphere bacteria (including Rhizobium and plant growth-promoting rhizobacteria, PGPR) and fungi (mycorrhizal fungi) are important in various aspects; their beneficial role in improving nutrient availability, biological nitrogen fixation, and stress tolerance is important for sustainable crop production. Sowing time is important because the crop should be at the right growth stage when the optimal temperature, moisture, and solar radiation levels are available for the most efficient use of the plant's resources. The right sowing time also reduces abiotic stresses and enhances WUE, which is crucial for coping with a changing climate and water scarcity. Other practices that can be undertaken to maintain productivity include drip irrigation, mulching, integrated nutrient management, and conservation tillage practices that also help to maintain soil health and environmental quality. Future research focus can be directed towards developing the groundnut production system resilient to climate change, engineering techniques to enhance the microbiome of groundnut, precision agriculture strategies, and advanced water-saving technologies for improving the productivity, profitability, and sustainability of rabi groundnut production in different agro-ecological regions.

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