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Productivity of Groundnut (*Arachis hypogaea* L.) under different Sowing Times, Nutrient Supply levels and Planting Geometry in Sub-Humid Tropical Environment

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Abstract

Groundnut is a vital oilseed and leguminous crop with significant economic and nutritional benefits, offering a promising option for local farmers. However, optimizing sowing dates, fertility levels, and planting geometry remains a challenge, particularly in the context of climate variability. In order to close this gap, a field experiment on clay loam soil in Medziphema was carried out in 2019 and 2020 to assess the effects of these factors on groundnut productivity. The experiment had three planting geometries (30 cm × 10 cm, 40 cm × 10 cm, and 50 cm × 10 cm), three levels of fertility (75%, 100%, and 125% of the prescribed dose of fertilizers), and two sowing dates (20 June and 10 July). Regardless of planting geometry, the results of a two-year pooled analysis indicated that early sowing (20 June) with 125% RDF generated the maximum oil content (43.50%), shoot dry weight (31.59 g plant^{-1}), and kernel yield (1.57 t ha^{-1}). The maximum shoot dry weight (31.33 g plant^{-1}), kernel yield (1.35 t ha^{-1}), and oil content (42.97%) were observed with a planting geometry of 50 cm × 10 cm. The highest gross (₹57,053.33 ha^{-1}) and net returns (₹34,448.63 ha^{-1}) were achieved with early sowing, 125% RDF, and 40 cm × 10 cm spacing. The highest benefit-cost ratio (2.08) was noted for early sowing which had 100% RDF and 50 cm × 10 cm spacing, highlighting an optimal balance between input costs and economic returns. These findings provide valuable insights for optimizing groundnut cultivation under varying environmental conditions. The study suggests that adjusting sowing dates and fertility management can significantly enhance yield and profitability, offering practical recommendations for farmers and policymakers to improve groundnut production efficiency.

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Introduction

A vital oilseed, food, and pasture crop, groundnuts (*Arachis hypogaea* L.) are widely grown in tropical, subtropical, and warm temperate climates. It belongs to the Fabaceae family and the Papilionaceae subfamily and is commonly known as the poor man's almond, wonder nut, peanut, earthnut, goober pea, monkey nut, pygmy nut, and pig nut. Despite its nut-like appearance, groundnut is a legume with significant economic and nutritional value. It is the world's third largest source of vegetable protein and the fourth most significant source of edible oil. Due to its protein-rich composition, groundnut, when fortified with cereals, has played a crucial role in mitigating protein-energy malnutrition, thus driving its increasing cultivation.[1]

Globally, groundnut production for the 2023-2024 period was estimated at 49.5 million metric tonnes by the USDA. China leads in production, contributing 39% of the global share, followed by India at 12%, with Nigeria and the United States also playing significant roles. India's groundnut production for the 2024-2025 period is projected to reach 7.1 million tons, cultivated over 5.5 million hectares.[2] Major growing states in India include Gujarat, Rajasthan, Tamil Nadu, Andhra Pradesh, Karnataka, and Maharashtra, with 84% of total production occurring during the *kharif* season and 12% during the *rabi* season.[3] In Nagaland, groundnut is cultivated on approximately 1,974 hectares, producing around 2,059 metric tons annually.[4] Notably, average yields in India hover around 1 t/ha, while Northeast (NE) states achieve significantly higher yields of 3-3.5 t/ha due to cooler climatic conditions that limit aflatoxin development, enhancing export opportunities to ASEAN countries.[5]

Despite the favorable climatic conditions in the NEH region, groundnut cultivation in Nagaland faces agronomic challenges, including suboptimal sowing dates, inappropriate planting geometry, and inefficient fertility management. These factors collectively contribute to lower yields, despite the region's potential for higher productivity. In dryland farming, sowing time is usually fixed, but in irrigated conditions, it significantly affects yield. Studies have shown that delayed or early sowing can impact pod development and overall yield due to variations in temperature, moisture availability, and pest pressure.[6] However, specific studies evaluating the optimal sowing dates for groundnut in Nagaland's foothill conditions remain unavailable.

Planting geometry, which includes row spacing and plant population, is another critical determinant of groundnut productivity. Proper spacing ensures better light interception, root expansion, and nutrient uptake, ultimately enhancing pod development.[7] While research on crop geometry for groundnut has been conducted in other parts of India, its implications under Nagaland's unique agro-climatic conditions remain unexplored.

Fertility management is equally crucial, as groundnut, being a legume, contributes to soil nitrogen fixation, thereby reducing nitrogen fertilizer dependency. However, phosphorus and potassium are essential for improving pod formation, and the application of gypsum has been reported to enhance seedling vigor and soil properties.[8] In many parts of India, nutrient deficiencies have been linked to low groundnut yields, yet no comprehensive studies have evaluated fertility levels specific to the soils and climatic conditions of Nagaland's foothills.

A review of past studies highlights that sowing dates, planting geometry, and fertility management significantly impact groundnut productivity. However, there is a lack of region-specific research focusing on Nagaland's agro-climatic conditions. Given the increasing importance of groundnut cultivation in the state, there is a need for detailed investigation to determine optimal agronomic practices. In order to provide data-driven suggestions for increased productivity and sustainability, this study intends to investigate the impact of planting geometry, sowing dates, and fertility levels on groundnut output in Nagaland's foothills.

Materials and Methods

At the Experimental Research Farm of the School of Agricultural Sciences (SAS), Nagaland University, Medziphema (25°45'09.2"N, 93°51'18.6"E, and 310 m above mean sea level), the study was conducted during the 2019 and 2020 *kharif* seasons. The clay loam soil at the experimental location had an excessive organic carbon content, low levels of accessible phosphate and nitrogen, a medium quantity of available potassium, and an acidic pH of 4.93. The research site is situated in a humid subtropical zone, which experiences an average annual precipitation of 1800 to 2500 mm. The average temperature in the summer is from 21 to 32 degrees Celsius, while it hardly ever falls below 8 degrees in the winter. Three replications and a split-plot design were used in this study. The main plot treatment included two sowing windows: June 20th (D_1) and July 10th (D_2). It also comprised three nutrient supply levels—F_1 - 75% RDF, F_2 - 100% RDF, and F_3 - 125% RDF, where RDF stands for the Recommended Dose of Fertilizer. Additionally, the subplots featured three different planting geometries: 30 cm × 10 cm (S_1), 40 cm × 10 cm (S_2), and 50 cm × 10 cm (S_3). The choice of RDF levels (75%, 100%, and 125%) was based on previous agronomic studies that examined the response of groundnut to different fertilization levels in similar agro-climatic conditions. These levels were selected to assess the optimal nutrient application for maximizing yield while maintaining soil fertility. The spacing choices (30 cm × 10 cm, 40 cm × 10 cm, and 50 cm × 10 cm) were based on recommendations from earlier studies on groundnut, which indicated that row spacing significantly influences light interception, root expansion, and pod development. Groundnut growth is highly sensitive to sowing time. Early or late sowing can impact germination, flowering, and pod filling. Choosing multiple sowing dates helps identify the most suitable time for optimal growth, whereas testing different nutrient levels helps determine the best fertilization strategy for soil fertility improvement and sustainable production. The groundnut variety used was 'ICGS 76,' a high-yielding Virginia bunch variety. Well-decomposed FYM @ 10 t ha^{-1} was uniformly broadcasted over the field and incorporated thoroughly during the final land preparation. The use of varying levels of the recommended dose of fertilizer (RDF) was implemented as per the treatment viz., F1 at 75 % RDF- 15 kg N ha^{-1}+45 kg P ha^{-1}+ 30 kg K ha^{-1}, F_2 at 100% RDF- 20 kg N ha^{-1} + 60kg P ha^{-1}+40 kg K ha^{-1} and F3 at 125% RDF- 25 kg N ha^{-1}+ 75 kg P ha^{-1}+ 50 kg K ha^{-1}. At the time of planting, urea, SSP, and MOP were used to supply nitrogen, phosphorus, and potassium. Sandy loam soil with a pH of 4.85, soil organic carbon (1.21%), available N (253 kg ha^{-1}), available P_2O_5 (18.43 kg ha^{-1}), and available K_2O (142.62 kg ha^{-1}) were the soil characteristics of the experimental site. Healthy, high-quality seeds were selected and sown on 20th June and 10th July as per the treatment, using the suggested seed rate of 75 kg ha^{-1}. Gap filling was performed 10 days after sowing to ensure uniform plant population wherever necessary. Plant protection measures were implemented as required, including integrated pest management (IPM) techniques such as timely application of neem-based bio-pesticides and chemical control when pest incidence exceeded economic thresholds. The major pests observed included aphids, leaf miners, and white grubs, while common fungal diseases like collar rot and late leaf spot were managed using recommended fungicides. These measures ensured minimal pest and disease interference in yield outcomes. Observations were recorded for growth, yield, and yield-related parameters. Soxhlet's ether extraction method was used to determine the kernel's oil content, and the following formula was used to determine the kernel's protein content.

Protein content (%) = % N content × 6.25.

Based on the current market pricing for the produce and experiment inputs, an economic analysis was carried out. A split-plot design and the Analysis of Variance (ANOVA) technique, as described by Gomez and Gomez[9] were used to statistically analyse the data gathered from each study. To identify significant changes between treatments, the criterion of statistical significance was chosen at $p < 0.05$.

Results

Growth and Yield Attributes

The growth attributes, viz. plant dry weight, shoot dry weight of groundnut were significantly influenced by sowing dates, fertility level and planting geometry. Maximum height (32.59 cm) was under treatment D_1F_3, combination of June 20 sowing along with 125% of RDF while D_1F_2 (32.43 cm) was statistically at par with D_1F_3. The least plant height was exhibited by D_2F_1 (27.38 cm). These differences were statistically significant ($p < 0.05$), suggesting that early sowing and higher fertility levels positively impact plant height, potentially due to extended vegetative growth and improved nutrient availability. Prior studies also reported comparable results of maximum plant height with early sowing.[10]

Effect of planting geometry irrespective of sowing dates and fertility levels showed that plant height was significantly highest (31.70 cm) with wider spacing at 50 cm x 10 cm and was statistically similar (30.93 cm) with spacing of 40 cm × 10 cm. The likely reason for this could be reduced competition for light and nutrients in wider spacing, allowing for better root expansion and shoot elongation.[11] It was also reported that a spacing of 35 cm × 20 cm resulted in higher yields compared to closer spacing of 20 cm × 15 cm.[12] However, the physiological basis for this requires further investigation, particularly regarding root development and light interception.

Groundnut sown on June 20 along with application of 125% of RDF showed the highest shoot dry weight of 31.59 g plant^{-1} at harvest. This growth was statistically significant ($p < 0.05$), reinforcing that early sowing results in better growth due to a longer vegetative period and enhanced resource utilization. Among the different planting geometries, S_3 (50 cm × 10 cm) resulted in the highest shoot dry weight (31.33 g plant^{-1}). This indicates that wider spacing optimally supports biomass accumulation, likely due to better access to light, reduced intra-plant competition, and improved nutrient uptake. Similar results also reported the highest dry matter accumulation in black gram under wider spacing.[13]

Fertility levels and sowing dates have a major impact on peanut yield characteristics. The D2F1 pairing had the lowest pod count per plant, while the D1F3 pairing had the highest pod count per plant. This suggests that early sowing, combined with higher fertility levels, provides optimal growing conditions, including prolonged reproductive phases and adequate nutrient supply. Early sowing of peanuts in southeastern Turkey led to higher pod yields, pod numbers, and oil content compared to late sowing, regardless of cultivar.[14] Among the different geometries, S_3 (50 cm × 10 cm) generated more numbers of pods plant^{-1} (18.70) whereas S_1 had the lowest (16.40) for the pooled mean value. This may be due to the reduced inter-plant competition in wider spacing, enabling better resource partitioning towards pod development. Closer spacing leads to higher competition for nutrients and moisture, which affected plant growth and pod filling whereas wider spacing ensured better access to nutrients and moisture per plant but requires efficient weed management.[15]

Pooled mean value of 1000-seed weight was statistically not significant due to different sowing windows, fertility levels and spacing. Highest value of 389.09 g with respect to 1000-seed weight was observed with D_1F_3. D1F3 had the most statistically significant shelling (67.44%), whereas D2F1 had the least, with a pooled value of 64.82%. This could be due to early sowing facilitating improved seed filling and pod maturity under favorable environmental conditions.

In terms of shelling percentage, treatment S3 (50 cm × 10 cm) showed the highest value of 67.31%. Higher shelling percentage under wider spacing can be attributed to the optimal spacing that reduces intra-plant competition and enhances pod development,[16] observed that, when compared to more constrained spacings like 30 cm × 10 cm and 22.5 cm × 10 cm, a planting spacing of 30 cm × 15 cm produced the greatest number of pods per plant, pod weight, and shelling %.

Yield and Quality Attributes

Variations in seed and stover yield were significant with the date of sowing and fertility levels in groundnut. The pooled mean data showed that the D1F3 treatment had the greatest seed yield (1.57 t ha^{-1}) and stover yield (2.61 t ha^{-1}), while the D_2F_1 treatment had the lowest seed yield (1.01 t ha^{-1}). The biological yield was also highest for early sowing combined with high fertility, D_1F_3 reaching 4.18 t ha^{-1} in pooled mean data while D_1F_2 4.07 t ha^{-1} was found to be at par. These results indicate that early sowing (D_1) with high fertility levels (F_3) provides optimal conditions for growth, resulting in greater seed and stover yields, and consequently a higher overall biological yield. This may be due to the extended growing season and better nutrient availability enhancing plant development and productivity. The results are also in compliance with the recent studies on groundnut cultivation that emphasize the importance of sowing date and fertilizer levels on seed yield wherein sowing at the onset of the monsoon resulted in significantly higher pod yields compared to later dates, with an average yield increase of 13.4% over sowing 10 days later.[17]

S3 (50 cm × 10 cm) had the highest pooled seed output of 1.35 t ha^{-1}, indicating that planting geometry had a substantial impact on yield. On the other hand, S_1 (30 cm x 10 cm) produced the least amount of seed overall (1.17 t ha^{-1}). In a similar vein, S_1 had the lowest stover production (2.06 t ha^{-1}), whereas S_3 had the greatest pooled output (2.48 t ha^{-1}). This pattern was also seen in the biological yield, where S_3

recorded the greatest pooled yield of 3.83 t ha^{-1}, followed by S_1 with the lowest pooled yield of 3.22 t ha^{-1} and S_2 with a close par value of 3.69 t ha^{-1}. These results can be attributed to the optimal spacing in S_3, which reduces intra-plant competition for resources, leading to better growth and higher yields in comparison to the denser spacing of S_1.

The data indicated that the sowing date and fertility levels exerted a substantial impact on the amount of protein and the highest amount of protein was documented in D_1F_3 with value of 21.90% in pooled value, while the least pooled value was noted in D_2F_1 with 17.03%. This variation may be attributed to increased nitrogen availability under higher fertility levels, promoting enhanced protein synthesis. Among the planting geometries, S_3 (50 cm × 10 cm) showed the greatest amount of protein, with a pooled value of 20.60% while S_1 (30 cm × 10 cm) showed the lowest protein content (18.51%) in pooled data and the results suggests that wider planting geometry (S_3) enhances protein content in groundnut due to reduced plant competition, allowing for better nutrient uptake and more optimal growth conditions. The increased spacing in S_3 likely leads to higher biomass and better seed development, contributing to higher protein levels. Conversely, the closer spacing in S_1 results in increased competition for nutrients and resources, leading to lower protein content in the seeds. This suggests that reduced plant competition allows for greater nitrogen assimilation, which is crucial for protein biosynthesis.

Treatment D1F3 gave maximum oil content 43.50% in pooled value, while the least was noted in D_2F_1 40.51%. The variation in oil content can be attributed to several factors, including sowing date, fertility levels, and yearly environmental conditions. The timing of sowing affects plant growth and oil production by influencing exposure to optimal conditions such as temperature and sunlight. The timing of sowing affects plant growth and oil production by influencing exposure to optimal conditions such as temperature and sunlight. Different sowing dates can thus result in varying oil accumulation in seeds. Soil fertility plays a crucial role as well, with higher fertility levels generally supporting better plant health and increased oil content due to better nutrient availability. Additionally, yearly variations in weather and environmental conditions can significantly impact crop yields and oil content.

With a pooled score of 42.97%, the planting geometry of 50 cm × 10 cm had the greatest amount of oil, whereas S1 had the least amount of oil (41.31%). These variations reflect how each planting geometry affects resource distribution among plants and responds to annual environmental factors, ultimately impacting oil production efficiency.

Economics

The cost of cultivation remained uniform across all treatments under planting geometry F_3 (125% RDF) at ₹29,205.58 ha^{-1}, irrespective of sowing date and spacing. This consistency is attributed to the higher and standardized input costs associated with 125% RDF, particularly fertilizers, which contribute significantly to overall expenses. Since fertilizer quantity directly influences costs, it remains unchanged across different treatments under F_3, aligning with previous research findings.[18,19]

Among the treatments, $D_1F_3S_2$ (early sowing on June 20th with 125% RDF and 40 cm × 10 cm spacing) recorded the highest gross returns of ₹57,053.33 ha^{-1}, whereas $D_2F_3S_1$ (late sowing on July 10th with 125% RDF and 30 cm × 10 cm spacing) yielded the lowest at ₹35,936.67 ha^{-1}. These variations highlight the influence of sowing date, fertilizer levels, and planting geometry on crop performance. Early sowing with optimal nutrient availability (D_1F_3) generally promotes better growth and yield, leading to higher returns.

The highest net returns of ₹34,448.63 ha^{-1} were also observed in $D_2F_3S_1$, reinforcing the advantage of early sowing combined with adequate fertilization. This combination enhanced crop growth and productivity, ultimately maximizing profitability.

Regarding the Benefit-Cost (B:C) ratio, the highest value (2.08) was recorded in $D_1F_2S_3$ (June 20th sowing with 100% RDF and 50 cm × 10 cm spacing), reflecting an optimal balance between input costs and revenue. In contrast, $D^2F_3S_1$ had the lowest B:C ratio (1.23) due to higher cultivation costs that were not sufficiently offset by returns, thereby reducing overall profitability.

Table 1: Impact of different sowing dates, fertility levels and planting geometry on growth parameters and yield attributes of groundnut crop

Treatment	Plant height (cm)	Shoot dry weight (g/plant)	Mature pod/ plant	Test weight (g)	Shelling (%)
Date of sowing and fertility levels					
D_1F_1	30.54	30.31	17.90	387.36	66.03
D_1F_2	32.43	31.43	19.04	384.48	66.90
D_1F_3	32.59	31.59	19.22	389.09	67.44
D_2F_1	27.38	27.38	16.12	384.18	64.82
D_2F_2	29.78	29.78	17.59	385.95	65.16
D_2F_3	30.21	30.21	17.56	384.15	65.92
SEm±	0.35	0.26	0.20	2.61	0.25
CD at 5%	1.03	0.77	0.59	NS	0.75
Planting geometry					
S_1	28.83	28.46	16.4	388.03	64.43
S_2	30.93	30.56	18.61	386.08	66.39
S_3	31.70	31.33	18.70	383.50	67.31
SEm±	0.22	0.21	0.15	1.49	0.16
CD at 5%	0.62	0.59	0.43	NS	0.46

*NS - Non-significant

Table 2: Impact of different sowing dates, fertility levels and planting geometry on kernel yield, oil and protein content of groundnut crop

Treatment	Seed yield (t/ha)	Stover yield (t/ha)	Biological yield (t/ha)	Protein content (%)	Oil content (%)
Date of sowing and fertility levels					
D_1F_1	1.22	2.35	3.57	19.35	42.19
D_1F_2	1.53	2.54	4.07	21.36	43.15
D_1F_3	1.57	2.61	4.18	21.90	43.50
D_2F_1	1.01	1.99	3.00	17.03	40.51
D_2F_2	1.15	2.15	3.31	18.64	41.49
D_2F_3	1.18	2.17	3.35	19.1	41.90
SEm±	0.01	0.03	0.04	0.26	0.15
CD at 5%	0.04	0.10	0.12	0.78	0.44
Planting geometry					
S_1	1.17	2.06	3.22	18.51	41.31
S_2	1.32	2.38	3.69	19.58	42.09
S_3	1.35	2.48	3.83	20.60	42.97
SEm±	0.01	0.02	0.02	0.21	0.09
CD at 5%	0.03	0.06	0.06	0.61	0.26

Table 3: Economic of groundnut crop under different sowing dates, fertility levels and planting geometry

Date of sowing and fertility levels x Planting geometry	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	Benefit: cost ratio
D1F1S1	25149.0	40283.3	19617.6	1.6
D1F1S2	25149.0	43433.3	20828.6	1.7
D1F1S3	25149.0	46016.7	21487.8	1.8
D1F2S1	27177.1	50976.7	30310.9	1.9
D1F2S2	27177.1	54840.0	32235.3	2.0
D1F2S3	27177.1	56646.7	32117.8	2.1
D1F3S1	29205.6	50893.3	30227.6	1.7
D1F3S2	29205.6	57053.3	34448.6	2.0
D1F3S3	29205.6	56236.7	31707.8	1.9
D2F1S1	25149.0	36026.7	15360.9	1.4
D2F1S2	25149.0	37683.3	15078.6	1.5
D2F1S3	25149.0	37060.0	12531.1	1.5
D2F2S1	27177.1	36136.7	15470.9	1.3
D2F2S2	27177.1	44053.3	21448.6	1.6
D2F2S3	27177.1	45273.3	20744.4	1.7
D2F3S1	29205.6	35936.7	15270.9	1.2
D2F3S2	29205.6	44220.0	21615.3	1.5
D2F3S3	29205.6	45336.7	20807.8	1.6

Discussion

These findings emphasize the critical role of optimal sowing time, planting geometry, and nutrient application in maximizing groundnut growth and yield. Early sowing aligns key growth phases with favorable environmental conditions, such as optimal temperature and soil moisture, which are essential for improved germination, root establishment, and vegetative growth. This observation aligns with previous studies that have demonstrated how early sowing promotes better plant vigor and development by reducing exposure to late-season drought and high temperatures that can hinder crop performance.

Furthermore, the benefits of wider spacing (50 cm × 10 cm) were evident in promoting superior plant growth. Adequate spacing minimizes interplant competition for essential resources like sunlight, nutrients, and water, thereby fostering better root development, canopy expansion, and photosynthetic efficiency. In contrast, closer spacing leads to increased competition, restricting plant access to these resources and ultimately limiting growth and biomass accumulation. However, while this study establishes the yield advantage of wider spacing, it does not delve into the physiological mechanisms behind this observation. Future research should examine how factors such as light interception, root architecture, and soil nutrient dynamics vary across different spacing treatments.

Early sowing not only extends the growing period but also enhances biomass accumulation by allowing plants to fully exploit the available resources. The extended vegetative and reproductive phases enable higher nutrient uptake and allocation toward key structural components, such as shoots and pods, thereby contributing to increased dry matter production. The synergistic effect of early sowing and optimal spacing was particularly evident in maximizing groundnut biomass, as plants had both the time and space to grow without constraints.

The study also emphasises how fertility levels affect yield and growth characteristics. Nutrient availability was greatly increased by applying 125% of the suggested dosage of fertilisers (RDF), which therefore improved plant vigour, pod development, and seed quality. Wider spacing likely facilitated better nutrient utilization, as individual plants had greater access to soil nutrients without excessive competition. However, the discussion lacks an exploration of the potential long-term effects of high-input fertilizer strategies on soil fertility and sustainability. Continuous application of high fertilizer doses can lead to nutrient imbalances, soil degradation, or increased production costs, raising concerns about long-term viability. Future studies should investigate whether the observed benefits of high fertilizer inputs can be sustained over multiple growing seasons without detrimental environmental impacts.

In terms of economic feasibility, while the study presents a benefit-cost (B:C) ratio analysis, it does not discuss the affordability and practicality of increased fertilizer inputs for smallholder farmers. High-input strategies may not always be economically viable, particularly in resource-constrained farming systems. Further research should include a comparative profitability analysis of different fertility levels across multiple seasons and cropping systems to provide clearer recommendations for farmers. Additionally, integrating farmer perspectives on input affordability, accessibility, and risk management would enhance the study's applicability.

The study's results indicate that early sowing, coupled with higher fertility levels and optimal spacing, creates favorable conditions for maximizing pod development, shelling percentage, and seed quality. Early sowing likely improved pod formation due to better environmental conditions during flowering and seed filling. However, the lowest pod count observed under the late sowing (D2) and low fertility (F1) treatment suggests that delayed sowing reduces the available growing period, restricting nutrient uptake and allocation during critical growth stages. Similarly, while wider spacing (S_3) led to increased pod yields, the physiological mechanisms underlying this response remain unexplored. Did the increased light penetration enhance photosynthesis and assimilate partitioning? Did reduced root competition improve water and nutrient absorption? These questions warrant further investigation.

The impact of agronomic practices on seed quality, particularly protein and oil content, was also evident in this study. The observed variations in seed composition can be attributed to differences in sowing time, fertility levels, and spacing, all of which influence nutrient assimilation and metabolic activity. Early sowing likely provided an extended period of optimal temperature and light conditions, enhancing enzymatic activity and protein synthesis. In a similar vein, greater fertility raised the availability of nutrients, especially nitrogen, which is essential for the synthesis of amino acids and proteins, leading to an increase in protein content. However, the study does not elaborate on the biochemical pathways through which these fertility levels influenced oil accumulation. Did increased nitrogen availability enhance chlorophyll content and overall photosynthetic capacity, leading to higher oil synthesis? Future studies should examine the physiological and biochemical mechanisms driving these responses.

Moreover, the role of planting geometry in determining seed composition needs further clarification. The study reports that wider spacing improved protein and oil content, but it does not explain why. A possible explanation is that reduced competition under wider spacing allowed for better resource allocation toward reproductive structures, leading to improved seed quality. Additionally, increased exposure to sunlight under wider spacing may have enhanced photosynthetic efficiency, promoting lipid biosynthesis in developing seeds. Investigating the relationship between canopy structure, light interception, and seed composition could provide deeper insights into this phenomenon.

Conclusion

The experimental results suggest that adopting a sowing date of June 20th, along with 125% RDF and a planting geometry of 50 cm × 10 cm, optimizes the growth and productivity of groundnut in the sub-humid tropical environment of Nagaland. However, while this strategy appears effective, it is important to consider potential trade-offs, such as increased input costs and sustainability concerns associated with higher fertilizer application. Additionally, these findings are based on a specific regional context, and their applicability to other agro-climatic zones requires further investigation. The study also has certain limitations, including climatic variability, potential measurement errors, and the need for multi-season trials to validate long-term consistency. Further research is necessary to refine these recommendations and develop a more sustainable and regionally adaptable groundnut cultivation strategy.

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Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Author Contributions

- **Zulutemjen Jamir:** Data collection, formal analysis, writing—original draft.
- **Lanunola Tzudir:** Supervision, project administration, validation, writing—review and editing.
- **Shivani Kumari:** Manuscript writing and revision.
- **Virosano Solo:** Field experiment execution, data collection, literature review.
- **Sibino Dolie:** Data processing, writing—review & editing.
- **Debika Nongmaithem, Rekha Yadav, Noyingthung Kikon, Merentoshi Mollier:** Advisory and manuscript finalization.

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