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ORIGINAL RESEARCH ARTICLE

# Optimizing nitrogen and sulphur nutrition for enhanced yield and yield-attributing traits in groundnut (*Arachis hypogaea* L.)

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**ABSTRACT**

Optimizing nutrient management is pivotal for the proper growth and development of plants to ensure higher productivity. The present study evaluated the effect of different nitrogen-sulphur levels on the growth and yield of groundnut. The experiment comprised six N-S treatment combinations ($F_{1-6}$: N 30, 40 and S 0, 20, 30 kg ha$^{-1}$) with a control ($F_0$: N 0 and S 0 kg ha$^{-1}$) using Randomized Complete Block Design (RCBD) with three replications. The result demonstrated significant yield improvements of groundnut under N and S applications compared to the control. Notably, Binachinabadam-8 ($V_2$) treated with the highest level of N-S ($F_6$, N 40 and S 30 kg ha$^{-1}$) demonstrated the best performance, with enhanced plant height (46.67 cm), number of branches plant$^{-1}$ (8.67), number of pods plant$^{-1}$ (37.67), weight of pods plant$^{-1}$ (27.84 g), number of seeds pod$^{-1}$ (2.10), 100-seed weight (8.67 g), shelling percentage (73.52%), seed yield (1.55 t ha$^{-1}$), stover yield (3.07 t ha$^{-1}$), biological yield (5.36 t ha$^{-1}$) and harvest index (42.66%). Further statistical analyses, such as Pearson correlation analysis, heatmap analysis, and PCA, confirmed trait contributions like number and weight of pods plant$^{-1}$, shelling percentage, 100-seed weight, plant height, and number of branches plant$^{-1}$ for yield variation. The cultivation of Binachinabadam-8 with 40 kg N ha$^{-1}$ (≈87 kg Urea ha$^{-1}$) and 30 kg S ha$^{-1}$ (≈167 kg Gypsum ha$^{-1}$) might offer a promising strategy towards groundnut productivity. The study provides valuable insights for developing nutrient management strategies aimed at sustainable groundnut production in less nutrient soils.



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## INTRODUCTION

Shortage of oilseed production poses a significant risk to global food security, nutritional and economic security, particularly for a developing country like Bangladesh. Each year, Bangladesh needs to import substantial amounts of edible oil, oilseeds and their meal as the national oilseed demand outpaces its domestic production, 1.26 million MT (BBS, 2024). Islam *et al.* (2022) & Shakil (2022) reported that Bangladesh's local supply of edible oil can satisfy at best one-third of its annual consumption, while the rest comes from imports, putting immense pressure on its foreign reserves. For instance, Bangladesh had to expend $3.4 billion in the fiscal year of 2022-23 for this purpose, which was twice as much as that was in three years back ($1.7 billion) (The Daily Star, 2024). Given the situation, groundnut (*Arachis hypogaea* L.) has emerged as a promising oilseed crop in Bangladesh that has historically been cultivated by local farmers in the marginal lands with minimum inputs and care. Groundnut, belonging to the Papilionaceae subfamily within the Leguminosae family, originated in South America and later spread to the rest of the world. With a yearly global production of 50.6 million MT (Statista, 2025), it is the fourth most significant oilseed crop in the world. People in Bangladesh often call it "cheenabadam," which is globally known as the king of vegetable oilseeds as well as the poor man's nut. With a national production of 75.4 thousand MT in 39.1 thousand hectares of land, groundnut ranks as the fourth important oilseed crop in Bangladesh, following rapeseed-mustard, coconut, and soybean, which accounts for around 6.0% of the national oilseed production (BBS, 2024). The significance of oilseeds in Bangladesh is on the rise as the share of vegetable oils in the caloric intake of Bangladeshis is gradually increasing, from 2.33% in 1990 to 2.97% in 2010; it is expected to rise to 3.74% in 2030 and 4.35% in 2050. People consume 20 to 22 grams of edible oil per person per day, most of which (94%) comes of soybean and oil palm, with small contributions from mustard (5%) and groundnut (1%). However, the local production only meets around 5% of the overall annual demand for soybeans; nevertheless, this is mostly used for feed purposes (Bokhtiar *et al*., 2023). Thus, over the decades, Bangladesh has faced a significant shortage of edible oil, as the local production of oilseeds can satisfy only 10% of the national edible oil demand, and the shortfall is met through imports either as crude oil or as oilseeds (USDA, 2022). Consequently, Bangladesh had to import 2.6 million MT of soybeans and 0.7 million MT of soybean oil in 2021-2022. Also, the demand for soybean oil will keep going up, from 1.2 million MT in 2021 to 1.4 million MT in 2030, and 1.7 million MT in 2050. In addition, demand for mustard oil is also expected to rise from 0.15 million MT in 2021 to 0.21 million MT in 2030 and then to 0.40 million MT in 2050. So, the issue of oilseeds and edible oil is going to get no better over time. Conversely, groundnut oil is projected to have a surplus of 0.58 lakh MT by 2050. Therefore, groundnut, with additional efforts on revamping its production, might help make up for the shortfall (Bokhtiar *et al*., 2023).

Groundnut stands apart with its exceptional nutritional value, containing about 38-56% oil, 21-31% protein (Liu & Li, 2023), 14 -30% carbohydrate, 4-18% crude fiber (Sanni *et al*., 2024), also a good source of vitamins (folic acid, β-carotene, thiamine, niacin and tocopherol) (Balasubramanian *et al*., 2023), minerals (phosphorus, sodium, calcium, magnesium, iron, manganese, alluminium, copper, zinc) (Sanni *et al*., 2024), antioxidants and bioactive compounds (resveratrol, phytosterols, phenolic acids and flavonoids) (Balasubramanian *et al*., 2023). Moreover, groundnut oil represents a remarkable quality comprising around 80% unsaturated fatty acids, mostly oleic acid and linoleic acid (Wang *et al*., 2015). Besides, it is also a very useful crop in rotational practice owing to its capability to enrich the soil by fixing atmospheric nitrogen through forming a symbiotic association with nitrogen-fixing bacteria in root nodules and thus contribute to soil fertility enrichment for the subsequent crops (Haneena *et al*., 2021; Sakha *et al*., 2022). Major uses of groundnut include oil extraction, confectionery purposes, such as cakes, biscuits and other bakery products, candies and peanut butter production, etc. In Bangladesh, people usually consume it as roasted "*badam*". Oil cake and stover are used as cattle feed, while the latter also serves fuel purposes.

In Bangladesh, groundnuts are a well-known crop that can be grown all year round because they are not sensitive to light, but they are mostly planted during the rabi season. However, because of intense crop competition during the rabi season, groundnut farming is shifted to marginal areas with low returns, particularly char fields, from which farmers can only make a small profit because of their low yields. The growing trend of groundnut cultivation in char lands over the years is evidence that, despite its low yields, its ease of cultivation, low farming costs, and high market demand frequently tip the scales in favor of groundnut over other competitive crops like maize, potatoes, sweet potatoes, etc. Hoq *et al*. (2016) reported economic advantages of groundnut over the competitive crops, wheat (~110%) and sesame (~139%) in char lands. However, soil nutrient deficiency along with poor yield performance of traditional varieties has emerged as a major concern in groundnut cultivation in Bangladesh. With improved productivity and profitability through meticulous research and policy interventions, groundnut has a great potential to contribute to the socioeconomic upliftment of the gradually expanding char area of Bangladesh. Adjusted nutrient management as well as the use of high-yielding varieties, therefore, needs to gain serious attention for the accomplishment of the expected yield of groundnut. Gelaye & Luo (2024) highlighted the significant impact of optimum nutrient management alongside genetic advancement on sustainable groundnut production, particularly in resource-limited settings.

Among the group of essential nutrients, nitrogen and sulphur are two of the most important ones for groundnut. Although groundnut being of fixing atmospheric nitrogen (N), additional N fertilization is very crucial in fulfilling of its total N requirement to support enthusiastic vegetative and reproductive development. Due to its high protein content, groundnut usually requires N in greater amounts than any cereal crop. For plants to produce carbohydrate food materials, N is essential for the synthesis and operation of chlorophylls. Furthermore, N plays a crucial function in effective pod filling and raising economic yield by helping to allocate food resources to the reproductive plant sections (Devi *et al*., 2022; Gao *et al*., 2024). Other than proteins and chlorophylls, nitrogen is also a fundamental constituent of many essential phytobiomolecules such as nucleotides, vitamins, hormones, enzymes, alkaloids, etc. (Xie *et al*., 2022). It is also essential for promoting the growth of roots and shoots. Sulfur (S) is increasingly regarded as the fourth essential plant nutrient after NPK (Sharma *et al*., 2024). The S demand for oil crops is comparable to, or occasionally more than, the phosphorus requirement to guarantee excellent output and quality (Sharma *et al*., 2024). The positive impacts of S fertilization in oilseeds have been reported by Kumari *et al.* (2025). Sulphur plays a crucial role in synthesizing three essential amino acids (cysteine, cystine, and methionine) and thus plays a role in protein synthesis in plants. As a constituent of succinyl-CoA, S has a key role in chlorophyll formation and photosynthesis. Thus, through acceleration of the photosynthetic process, S helps in quick cell multiplication and thereby hastens crop growth and development. Veazie *et al.* (2020) reported that chloroplast morphology and functionality were affected by S deficiency in soil. Alongside carbohydrate metabolism, S plays a significant role in the synthesis of glycosides, oils and several constituents involved in the N-fixation. From both qualitative and quantitative perspectives, S stands out with its indisputable role in oil crops like groundnut. S increases oil content of groundnut (Dileep *et al.*, 2021). Jahan *et al.* (2022) reported that farmers practicing chemical fertilization in groundnut obtained greater harvests, overcoming the additional expenses for fertilizers, than those who relied on just the soil supply of nutrients. Li *et al.* (2021) described that N fertilization demonstrated improved plant health, better yields and environmental resistance when compared to the control. Alongside improved nitrogen and Sulphur management, the varietal role in increasing groundnut productivity is also fundamental. The overall groundnut production in Bangladesh in the late 2000s increased by 31% over the last ten years, despite the acreage remaining the same. Deb & Pramanik (2015) attributed the increment of groundnut production to the improvement of yield by 32% by this time. Chemical fertilizers can degrade the environment if they are used excessively, which could reduce agricultural yield. This demonstrates how important it is to optimize fertilizer dosages to maximize productivity while preserving the environment. The impact of nitrogen and sulfur on groundnut yield and yield characteristics has been studied independently in certain literature, but their combined influence is still thought to be understudied. Putting all this into perspective, this study was undertaken to expand understanding on the interactive effect of nitrogen and sulphur on the yield and yield parameters of groundnut varieties. By elucidating the synergistic roles of N and S in groundnut physiology and pod formation, this research seeks to provide an evidence-based foundation for sustainable nutrient management practices in groundnut-based production systems.

## MATERIALS AND METHODS

### Description of the experimental site

The study was carried out at the Agronomy Field Laboratory of Bangladesh Agricultural University (BAU), Mymensingh, during the period from November 2022 to May 2023, situated at 24° 75´ N latitude and 90° 5´ E longitude, with an elevation of 18 meters above the sea level in AEZ-9, Old Brahmaputra Floodplain (UNDP & FAO, 1988). The prevailing sub-tropical monsoon climate of the area is characterized by substantial precipitation from April to October and less precipitation in the rest of the year (Figure 1). Composite samples from the topsoil (0-15cm) of the field were collected before the experiment for the analysis of morphological, chemical and physical features of the soil (Table 1).

### Experimental treatments and design

In this experiment, two factors were evaluated, the first being Factor A: groundnut variety and Factor B: nitrogen-sulphur level and was designed following a Randomized Complete Block Design (RCBD) with three replications. Thus, there was a total of 42 (2×7×3) plots, each 10 $m^2$ (4 m × 2.5 m) in size. The spacing between each block was 1.0 m, and the contiguous plots within a block were 0.5 m apart. The following treatment proprieties were adopted during the experiment.

Experimental treatments

| Factor A: Variety | | Factor B: N-S level (kg $ha^{-1}$) | | Amount |
|---|---|---|---|---|
| 1. BARI Chinabadam-10 | ($V_1$) | 1. $N_0S_0$ | ($F_0$) | N 0 kg $ha^{-1}$ + S 0 kg $ha^{-1}$ |
| 2. Binachinabadam-8 | ($V_2$) | 2. $N_{30}S_0$ | ($F_1$) | N 30 kg $ha^{-1}$ + S 0 kg $ha^{-1}$ |
| | | 3. $N_{30}S_{20}$ | ($F_2$) | N 30 kg $ha^{-1}$ + S 20 kg $ha^{-1}$ |
| | | 4. $N_{30}S_{30}$ | ($F_3$) | N 30 kg $ha^{-1}$ + S 30 kg $ha^{-1}$ |
| | | 5. $N_{40}S_0$ | ($F_4$) | N 40 kg $ha^{-1}$ + S 0 kg $ha^{-1}$ |
| | | 6. $N_{40}S_{20}$ | ($F_5$) | N 40 kg $ha^{-1}$ + S 20 kg $ha^{-1}$ |
| | | 7. $N_{40}S_{30}$ | ($F_6$) | N 40 kg $ha^{-1}$ + S 30 kg $ha^{-1}$ |

**Table 1.** Soil properties of the experimental site.

| Soil parameter | Unit | Value |
|---|---|---|
| Soil pH | - | 7.1 |
| Bulk density | g $cc^{-1}$ | 1.37 |
| Soil textural class | - | Silt loam |
| Organic matter | % | 2.15 |
| Total nitrogen | % | 0.11 |
| Available phosphorus | ppm | 19.05 |
| Exchangeable potassium | meq. 100g $soil^{-1}$ | 0.20 |
| Available sulphur | ppm | 18.10 |
| Available zinc | ppm | 1.5 |

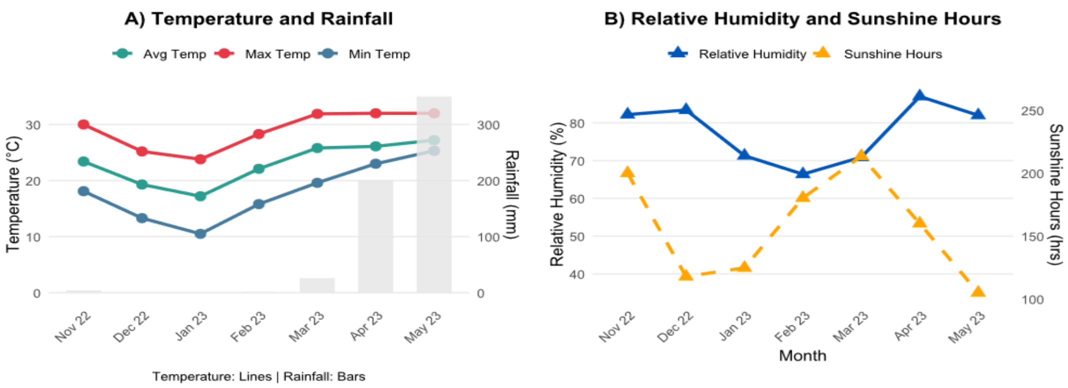


**Figure 1.** *Monthly trends of climatic parameters: average temperature (°C) and rainfall (mm) (A), and average relative humidity (%) and sunshine hours (hrs.) (B) in the experimental site, 2022-2023. (Data source: Bangladesh Meteorological Department).*

### Plot preparation and fertilization

The experimental field was opened with a tractor on November 10, 2022, and left exposed under sunlight for one week. Afterwards, the land underwent several harrowing, ploughing, and cross-ploughing operations, then laddered to ensure fine tilth. After this, the land was properly laid out, subsequently, weeds were eliminated and stubble from the plots as well as soil treatment with Furadan 5G (Carbofuran) @ 15 kg $ha^{-1}$ to prevent damage to the young seedlings from cutworm attack. Finally, drainage channels were introduced around the plots to avoid waterlogging that might otherwise result from abundant rainfall over the study duration. The crop was fertilized with cow dung @ 5 $tonha^{-1}$, TSP 160 kg $ha^{-1}$, MOP 85 kg $ha^{-1}$, and boric acid 10 kg $ha^{-1}$. Nitrogen and sulphur were applied as per the treatments (i. $N_0S_0$ ($F_0$), ii. $N_{30}S_0$ ($F_1$), iii. $N_{30}S_{20}$ ($F_2$), iv. $N_{30}S_{30}$ ($F_3$), v. $N_{40}S_0$ ($F_4$), vi. $N_{40}S_{20}$ ($F_5$), vii. $N_{40}S_{30}$ ($F_6$)) from urea and gypsum, respectively. Half of the urea, along with other fertilizers, was applied basally during the final land preparation, and the rest of the urea was applied by side dressing at 45 days after sowing (DAS) when flowers were initiated.

### Crop establishment and management

Seeds of BARI Chinabadam-10 were collected from Bangladesh Agriculture Research Institute (BARI), Gazipur, Bangladesh, and those of Binachinabadam-8 from Bangladesh Institute of Nuclear Agriculture (BINA), Mymensingh, Bangladesh. On November 20, 2022, the pods were unshelled and treated with Bavistin 250 WP @ 2 g $kg^{-1}$ seed. They were sown in lines with a 30 cm line-to-line spacing and 15 cm seed-to-seed distance, with 3 seeds per hole in well-prepared plots. Gap-filling and thinning operations were performed at 7 DAS to maintain a uniform crop stand in each plot. The plots remained weed-free due to regular surveillance and hand weeding. Three irrigations were provided during the flowering, pegging, and pod development stages of crop growth. Regular inspections were done to monitor the growth and health of the crops. The incidence of whiteflies and ants was observed during the vegetative growth stage. The crop was treated with a single spray of Chlorpyrifos at the recommended dose to combat insect pests, specially whiteflies (*Bemisia tabaci)*, the vector for yellow mosaic virus (YMV), when the early symptoms were noticed.

### Harvesting and data collection

Groundnuts were harvested at the stage when approximately 75% of the pods had attained maturity. After observing maturity indicators like yellowing leaves, leaf spots, and hardened and toughened pods and black tannin coloring within the shell, and the characteristic seed color development, Binachinabadam-8 was harvested on May 7, 2023, and BARI Chinabadam-10 on May 10, 2023. The samples were collected from 1 $m^2$ plots using a 1.0 m × 1.0 m quadrat, avoiding boundary plants. At the time of harvest, the pod contained approximately 35% moisture. After that, the harvested crops were bundled according to treatment and taken to the threshing floor, where the plants and pods were separated. Sun drying of the separated pods and stover was carried out by spreading them on the threshing floor. The seeds were taken out from the pod and sun-dried for 3 to 5 days to obtain the appropriate moisture level of ~8%. Data on plant height (cm), number of branches $plant^{-1}$, number of pods $plant^{-1}$, weight of pods $plant^{-1}$ (g), number of seeds $pod^{-1}$, 100-seed weight (g), seed yield (t $ha^{-1}$), and stover yield (t $ha^{-1}$) were recorded during the harvest. Subsequently, biological yield (t $ha^{-1}$), harvest Index (%), and shelling percentage (%) were calculated.

Biological yield (BY) was the total yield that includes both the pod and stover yield, expressed in t $ha^{-1}$, as follows:

Biological yield = Pod yield + Stover yield

Harvest Index (HI) was calculated by comparing seed yield to biological yield in each plot of groundnuts, expressed as a percentage as follows:

Harvest Index (%)= Seed yield/ Biological yield × 100

Shelling percentage was calculated as the ratio of seed yield to the pod yield of groundnut in each plot, expressed as a percentage as follows:

Shelling percentage (%) = Seed yield/ Pod yield × 100

### Statistical analysis

Data compilation was accomplished with the help of Microsoft Excel, while the entire process of statistical analysis (utilizing the Analysis of Variance (ANOVA) technique), multiple comparison test (utilizing the Least Significant Difference (LSD) test at 5% level of probability) (Gomez & Gomez, 1984). The data visualizations such as bar diagrams, correlation-regression analysis, heatmaps, and principal component analysis (PCA) were carried out with the assistance of the RStudio software (Lun, 2019).

## RESULTS AND DISCUSSION

### Effect of variety on the studied plant parameters of groundnut

Variety exhibited a significant impact on all the plant parameters studied, except no. of seeds $pod^{-1}$ (Table 2). Between the two groundnut varieties, Binachinabadam-8 ($V_2$) demonstrated significant superiority in plant height, number of branches $plant^{-1}$, number of pods $plant^{-1}$, weight of pods $plant^{-1}$, 100-seed weight, shelling percentage, and harvest index (%) than BARI Chinabadam-10 ($V_1$). A non-significant result was obtained in case of number of seeds $pod^{-1}$, however, Binachinabadam-8 ($V_2$) came up with a greater value. One possible factor that could contribute to the increase in yield is the role that sulphur plays in the production of chlorophyll, which in turn speeds up the process of photosynthesis and cell multiplication (Tabassum *et al.*, 2021; Aswini *et al.*, 2024a; Balagangathar *et al.*, 2024b). Nurezannat *et al.*, 2019; Devi, 2019 also reported variations in growth and yield parameters of groundnut across varieties.

**Table 2.** Effect of variety, nitrogen-sulphur level, and interaction effect of variety and nitrogen-sulphur level on the growth parameters and yield attributes of groundnut.

| Factors | Plant height (cm) | No. of branches plant$^{-1}$ | No. of pods plant$^{-1}$ | Pod weight plant$^{-1}$ (g) | No. of seeds pod$^{-1}$ | 100-seed weight (g) | Shelling Percentage (%) | Harvest index (%) |
|---|---|---|---|---|---|---|---|---|
| **Variety** | | | | | | | | |
| $V_1$ | 28.62$^{b}$ | 6.10$^{b}$ | 28.19$^{b}$ | 17.88$^{b}$ | 2.03 | 31.83$^{b}$ | 69.09$^{b}$ | 40.91$^{b}$ |
| $V_2$ | 38.05$^{a}$ | 6.14$^{a}$ | 31.48$^{a}$ | 22.04$^{a}$ | 2.04 | 36.94$^{a}$ | 69.98$^{a}$ | 41.42$^{a}$ |
| **Level of Sig.** | ** | * | * | * | NS | ** | * | * |
| **N-S level** | | | | | | | | |
| $F_0$ | 26.00$^{d}$ | 5.17$^{c}$ | 25.50$^{b}$ | 14.81$^{b}$ | 2.00$^{c}$ | 29.63$^{b}$ | 66.91$^{c}$ | 40.81$^{b}$ |
| $F_1$ | 28.00$^{cd}$ | 5.33$^{bc}$ | 26.17$^{ab}$ | 18.00$^{ab}$ | 2.02$^{bc}$ | 34.15$^{ab}$ | 68.64$^{bc}$ | 41.07$^{a}$ |
| $F_2$ | 34.00$^{a-d}$ | 5.5$^{bc}$ | 29.83$^{ab}$ | 19.35$^{ab}$ | 2.03$^{a-c}$ | 35.05$^{ab}$ | 69.88$^{b}$ | 41.43$^{a}$ |
| $F_3$ | 35.83$^{a-c}$ | 6.50$^{a-c}$ | 30.50$^{ab}$ | 20.97$^{ab}$ | 2.07$^{ab}$ | 35.47$^{a}$ | 69.18$^{bc}$ | 40.70$^{b}$ |
| $F_4$ | 30.17$^{b-d}$ | 5.67$^{bc}$ | 27.33$^{ab}$ | 17.95$^{ab}$ | 2.02$^{bc}$ | 34.35$^{ab}$ | 68.72$^{bc}$ | 41.44$^{a}$ |
| $F_5$ | 37.67$^{ab}$ | 6.83$^{ab}$ | 33.33$^{ab}$ | 23.70$^{a}$ | 2.02$^{bc}$ | 35.88$^{a}$ | 71.00$^{ab}$ | 40.8$^{4b}$ |
| $F_6$ | 41.67$^{a}$ | 7.83$^{a}$ | 36.17$^{a}$ | 24.95$^{a}$ | 2.08$^{a}$ | 36.17$^{a}$ | 72.42$^{a}$ | 41.84$^{a}$ |
| **Level of Sig.** | ** | * | * | * | * | * | ** | * |
| **CV%** | 8.77 | 9.81 | 8.04 | 7.21 | 7.29 | 4.16 | 9.73 | 4.67 |
| **Interaction effect of variety and N-S level** | | | | | | | | |
| V1F0 | 21.67$^{f}$ | 5.00$^{b}$ | 22.00$^{b}$ | 11.46$^{c}$ | 2.00$^{b}$ | 5.00$^{b}$ | 65.30$^{d}$ | 39.77$^{d}$ |
| V1F1 | 23.00$^{f}$ | 5.33$^{b}$ | 22.67$^{ab}$ | 16.83$^{bc}$ | 2.03$^{ab}$ | 5.33$^{b}$ | 67.81$^{cd}$ | 40.37$^{cd}$ |
| V1F2 | 28.33$^{d-f}$ | 5.33$^{b}$ | 30.00$^{ab}$ | 17.52$^{a-c}$ | 2.03$^{ab}$ | 5.33$^{b}$ | 69.98$^{bc}$ | 41.42$^{a-d}$ |
| V1F3 | 31.33$^{b-f}$ | 7.00$^{ab}$ | 31.00$^{ab}$ | 20.56$^{a-c}$ | 2.03$^{ab}$ | 7.00$^{ab}$ | 70.51$^{a-c}$ | 40.68$^{bcd}$ |
| V1F4 | 27.00$^{ef}$ | 6.00$^{b}$ | 25.00$^{ab}$ | 15.56$^{bc}$ | 2.03$^{ab}$ | 6.00$^{b}$ | 67.74$^{cd}$ | 42.09$^{ab}$ |
| V1F5 | 32.33$^{b-f}$ | 7.00$^{ab}$ | 32.00$^{ab}$ | 21.14$^{a-c}$ | 2.00$^{b}$ | 7.00$^{ab}$ | 70.99$^{a-c}$ | 41.01$^{a-d}$ |
| V1F6 | 36.67$^{a-e}$ | 7.00$^{ab}$ | 34.67$^{ab}$ | 22.06$^{a-c}$ | 2.07$^{ab}$ | 7.00$^{ab}$ | 71.31$^{ab}$ | 41.02$^{a-d}$ |
| V2F0 | 30.33$^{c-f}$ | 5.33$^{b}$ | 29.00$^{ab}$ | 18.16$^{a-c}$ | 2.00$^{b}$ | 5.33$^{b}$ | 68.53$^{b-d}$ | 41.86$^{a-c}$ |
| V2F1 | 33.00$^{b-f}$ | 5.33$^{b}$ | 29.67$^{ab}$ | 19.16$^{a-c}$ | 2.00$^{b}$ | 5.33$^{b}$ | 69.47$^{bc}$ | 41.76$^{a-c}$ |
| V2F2 | 39.67$^{a-d}$ | 5.67$^{b}$ | 29.67$^{ab}$ | 21.17$^{a-c}$ | 2.03$^{ab}$ | 5.67$^{b}$ | 69.77$^{bc}$ | 41.43$^{a-d}$ |
| V2F3 | 40.33$^{a-c}$ | 6.00$^{b}$ | 30.00$^{ab}$ | 21.37$^{a-c}$ | 2.10$^{a}$ | 6.00$^{b}$ | 67.85$^{b-d}$ | 40.73$^{b-d}$ |
| V2F4 | 33.33$^{b-f}$ | 5.33$^{b}$ | 29.67$^{ab}$ | 20.34$^{a-c}$ | 2.00$^{b}$ | 5.33$^{b}$ | 69.07$^{bc}$ | 40.79$^{b-d}$ |
| V2F5 | 43.00$^{ab}$ | 6.67$^{ab}$ | 34.67$^{ab}$ | 26.26$^{ab}$ | 2.03$^{ab}$ | 6.67$^{ab}$ | 71.01$^{a-c}$ | 40.67$^{b-d}$ |
| V2F6 | 46.67$^{a}$ | 8.67$^{a}$ | 37.67$^{a}$ | 27.84$^{a}$ | 2.10$^{a}$ | 8.67$^{a}$ | 73.52$^{a}$ | 42.66$^{a}$ |
| **Level of Sig.** | * | * | * | * | * | * | * | * |
| **CV%** | 8.77 | 9.81 | 8.04 | 7.21 | 7.29 | 4.16 | 9.73 | 4.67 |

Here, different letters within the same column differ significantly.

### Effect of nitrogen-sulphur level on the studied plant parameters of groundnut

All the plant parameters studied were affected significantly by nitrogen-sulphur level (Table 2). Results demonstrated a progressive increase in the values of plant parameters with increasing nitrogen-sulphur level. Consequently, $N_{40}S_{30}$ ($F_6$) produced the best results, while control treatment, $N_0S_0$ ($F_0$), produced the least. N40S20 (F5), N30S30 (F3), and N30S20 (F2) demonstrated statistically non-significant differences in most of the parameters examined, indicating the impact of sulphur on groundnut, even though the greatest improvements in the growth parameters and yield attributes of groundnut were noted at the highest level of nitrogen and sulphur. Meena *et al.* (2011) also reported that applications of N 40 kg ha$^{-1}$ significantly improved the growth characteristics (dry matter accumulation, chlorophyll content, nodules plant$^{-1}$) and yield traits (number of pods plant$^{-1}$, and number of seeds pod$^{-1}$) of groundnut, which conforms to the findings from this experiment. However, a further increase in N dose to 60 kg ha$^{-1}$ marked no statistical superiority. The application of 34 kg N ha$^{-1}$ (maximum level) recorded the highest performance in growth and yield traits of groundnut (Balagangathar *et al.*, 2024a). Applied N augments photosynthesis and thereby improves source size, which in return results in greater plant height and dry matter accumulation (Palsande *et al.*, 2019; Chakraborty *et al.*, 2019). Likewise, a progressive improvement in groundnut growth and yield parameters with an increasing level of S was previously reported by Nurezannat *et al.* (2019) (S up to 60 kg ha$^{-1}$), Balagangathar *et al.*, (2024a) (S up to 60 kg ha$^{-1}$), Bhadiyatar *et al.* (2022) (S up to 45 kg ha$^{-1}$), Dileep *et al.* (2021) (S up to 40 kg ha$^{-1}$), where they found the maximum S level producing the best results. One possible factor that could contribute to the increase in yield is the role that sulphur plays in the production of chlorophyll, which in turn speeds up the process of photosynthesis and cell multiplication (Aswini *et al.*, 2024b; Balagangathar *et al.*, 2024b).

### Interaction effect of variety and nitrogen-sulfur level on the studied plant parameters of groundnut

Results revealed a significant impact of the interaction effect of groundnut variety and nitrogen-sulphur level on all the plant parameters studied, *viz.* plant height, number of branches plant$^{-1}$, number of pods plant$^{-1}$, weight of pods plant$^{-1}$, number of seeds pod$^{-1}$, 100-seed weight, shelling percentage and harvest index (%) (Table 2). Binachinabadam-8 ($V_2$), when applied with $N_{40}S_{30}$ ($F_6$), outperformed the remaining combinations; however, BARI Chinabadam-10 ($V_1$) treated with $N_{40}S_{30}$ ($F_6$) produced statistically similar results. Conversely, the lowest performance in the growth parameters and yield attributes was obtained from BARI Chinabadam-10 ($V_1$) treated with $N_0S_0$ ($F_0$), showing no significant difference with that obtained from Binachinabadam-8 ($V_2$) treated with the same level of N-S, apart from in harvest index. According to Balagangathar *et al.* (2024a) and Nurezannat *et al.* (2019), who revealed a strong interactive influence of variety and sulphur level on the growth and yield characteristics of groundnut, this is in agreement with the findings of those researchers.

## Effect of variety on groundnut yield

Binachinabadam-8 ($V_2$, 1.33 t ha$^{-1}$) produced significantly higher seed yield (SY) than BARI Chinabadam-10 ($V_1$, 1.26 t ha$^{-1}$), but the varietal effect on groundnut stover yield (StY) was found to be non-significant (Figure 2A). However, Binachinabadam-8 ($V_2$, 2.71 t ha$^{-1}$) registered a greater stover yield than BARI Chinabadam-10 ($V_1$, 2.67 t ha$^{-1}$). Overall, significantly greater biological yield (BY) was obtained from Binachinabadam-8 ($V_2$, 4.63 t ha$^{-1}$) compared to BARI Chinabadam-10 ($V_1$, 4.52 t ha$^{-1}$). Differences in the genetic composition of the varieties may be the cause of this disparity in yield performance. This supports the findings of Nurezannat *et al.* (2019), who found that groundnut yield is significantly influenced by variety.

## Effect of nitrogen-sulphur level on groundnut yield

The nitrogen-sulfur level demonstrated a significant contribution to the SY, StY and BY of groundnut (Figure 2B). The highest SY (1.54 t ha$^{-1}$) was obtained from $N_{40}S_{30}$ ($F_6$) and the lowest (1.12 t ha$^{-1}$) from $N_0S_0$ ($F_0$), where the latter showed statistical similarity with that (1.18 t ha$^{-1}$) from $N_{30}S_0$ ($F_1$). Similarly, the greatest StY (3.10 t ha$^{-1}$) was also recorded from $N_{40}S_{30}$ ($F_6$) and the lowest (2.46 t ha$^{-1}$) from $N_0S_0$ ($F_0$), where the latter was statistically similar to that from $N_{30}S_0$ ($F_1$, 2.49 t ha$^{-1}$) and $N_{40}S_0$ ($F_4$, 2.54 t ha$^{-1}$). Consequently, $N_{40}S_{30}$ ($F_6$) registered the greatest BY (5.33 t ha$^{-1}$), as well as $N_0S_0$ ($F_0$) produced the lowest (4.16 t ha$^{-1}$), having statistical similarity with that from $N_{30}S_0$ ($F_1$, 4.22 t ha$^{-1}$). The best yield performance of $N_{40}S_{30}$ ($F_6$) were ascribed to its superiority in all the growth parameters and yield attributes studied, and vice versa in the case of $N_0S_0$ ($F_0$). This agrees with the findings of Meena *et al.* (2011), who earlier reported maximum groundnut yield at N 40 kg ha$^{-1}$ contrasted to the control or even a greater dose as high as N 60 kg ha$^{-1}$, resulting from significant improvement in the growth characteristics and yield attributes. At N 34 kg ha$^{-1}$, Balagangathar *et al.* (2024b) achieved the maximum groundnut pod, kernel, and haulm production. They ascribed this to N's function in promoting the synthesis of amino acids and chlorophyll, which results in a higher biomass buildup and its transfer to the reproductive portions. Xia *et al.* (2021) reported an efficient translocation of N from leaves to the pods of groundnut at a N fertilization rate of 40-60 kg ha$^{-1}$. In case of S, the best yield performance of groundnut, as reported by Dileep *et al.* (2021); Hoang *et al.* (2021), was revealed at doses of S (30-40 kg ha$^{-1}$) similar to this experiment. However, Balagangathar *et al.* (2024a) reported that at a greater dose of S, 60 kg ha$^{-1}$, which might be due to the low initial S availability status of the soil. At the highest level used, N 50 and S 40 kg ha$^{-1}$, Devi *et al.* (2022) reported the maximum pod and haulm production of groundnuts, which was statistically comparable to that of N 40 and S 40 kg ha$^{-1}$.

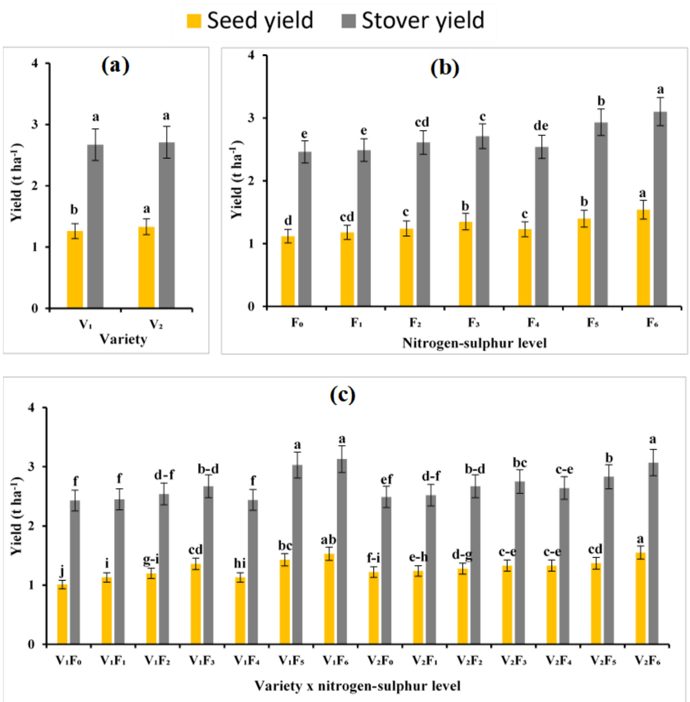


**Figure 2.** *Effect of variety (a), nitrogen-sulphur level (b), interaction effect of variety and nitrogen-sulphur (c) on seed yield and stover yield of groundnut.*

## Interaction effect of variety and nitrogen-sulphur level on groundnut yield

The interaction effect of variety and nitrogen-sulphur level on the seed, stover and biological yields of groundnut was significant (Figure 2C). The highest seed yield was obtained from $V_2F_6$ (1.55 t ha$^{-1}$), which was statistically at per with that from $V_1F_6$ (1.53 t ha$^{-1}$), while the lowest one was obtained from $V_1F_0$ (1.01 t ha$^{-1}$). The stover yield was maximum from $V_1F_6$ (3.13 t ha$^{-1}$), which was statistically similar to those from $V_2F_6$ (3.07 t ha$^{-1}$) and $V_1F_5$ (3.03 t ha$^{-1}$). Besides, the minimum stover yield was obtained from $V_1F_0$ (2.43 t ha$^{-1}$), having statistical similarity with those from $V_1F_4$ (2.44 t ha$^{-1}$), $V_1F_1$ (2.45 t ha$^{-1}$), $V_2F_0$ (2.49 t ha$^{-1}$), $V_2F_1$ (2.52 t ha$^{-1}$) and $V_1F_2$ (2.54 t ha$^{-1}$). Likewise, the highest biological yield was obtained from $V_2F_6$ (5.36 t ha$^{-1}$) and the lowest from $V_1F_0$ (4.04 t ha$^{-1}$), which showed statistical similarity with that from $V_1F_1$ (4.11 t ha$^{-1}$). This aligns with the findings of Nurezannat *et al.* (2019), who reported that the interactive effect of variety and sulphur level was significant on groundnut yield.

## Correlation analysis

A correlation analysis was conducted to investigate the magnitude and direction of linear associations between various growth parameters, yield attributes, and yield in groundnut, in response to varying N-S levels across different varieties (Figure 3). As the correlogram depicted, both seed and stover yields of groundnut had significant, strong positive correlations with the yield traits viz. number of pods plant$^{-1}$, pod weight plant$^{-1}$, 100 seed weight and shelling percentage, implying that these parameters are the strongest yield predictors across treatments. Growth parameters viz. plant height and number of branches plant$^{-1}$ also demonstrated significant, strong positive correlations with both seed and stover yields, which implies that increased vegetative growth supported greater reproductive development. Besides, these growth parameters and yield attributes also showed strong interrelationships among themselves, which underscores their collective contribution to groundnut productivity (Waghmode *et al.*, 2017; Devi *et al.*, 2022; Zhang *et al.*, 2024). On the other hand, their low reactivity to different N-S levels among cultivars resulted in weak or non-significant relationships between harvest index and number of seeds per pod, reflecting their minimal contribution to reproductive development. The findings recommend that important factors in varietal selection and N-S management be evaluated to maximize groundnut yield (Dileep *et al.*, 2021; Hoang *et al.*, 2021; Aswini *et al.*, 2024a).

## Regression analysis

A regression analysis was undertaken to elucidate the degree and direction of associations of seed yield with key growth parameters and yield attributes of groundnut under varying N-S levels across two varieties (Figure 4). Among the traits evaluated, number of pods plant$^{-1}$ stood as the most influential yield determinant of groundnut, showed the strongest positive linear relationship with seed yield ($R^2$ = 0.85). Likewise, pod weight plant$^{-1}$ and shelling percentage also marked their outstanding roles in enhancing seed yield, as depicted through strong positive associations with seed yield ($R^2$ = 0.76 each). However, 100 seed weight and number of branches plant$^{-1}$ demonstrated moderate positive associations ($R^2$ = 0.64 each), while plant height showed the weakest yet significant association ($R^2$ = 0.61) among the parameters studied. The findings underscored the differential role of key growth parameters and yield attributes in enhancing groundnut yield under varying N-S levels across varieties (Hoang *et al.*, 2021; Balagangathar *et al.*, 2024a). Among the traits, number of pods plant$^{-1}$, followed by pod weight plant$^{-1}$ and shelling percentage, reported the most critical contribution to yield variation across treatments. These crucial growth factors and yield characteristics should be given top priority in strategic decisions regarding N-S management and groundnut variety selection to achieve increased productivity (Dileep *et al.*, 2021; Xia *et al.*, 2021; Bhadiyatar *et al.*, 2022).

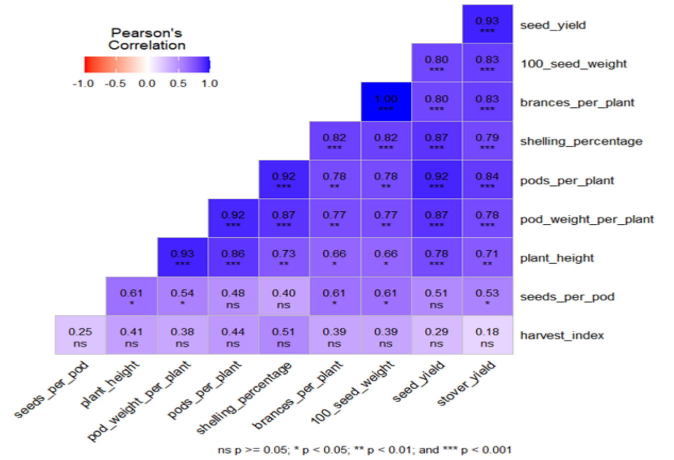


**Figure 3.** *Pearson correlation analysis of growth parameters, yield attributes and yield of groundnut in response to varying N-S levels across varieties.*

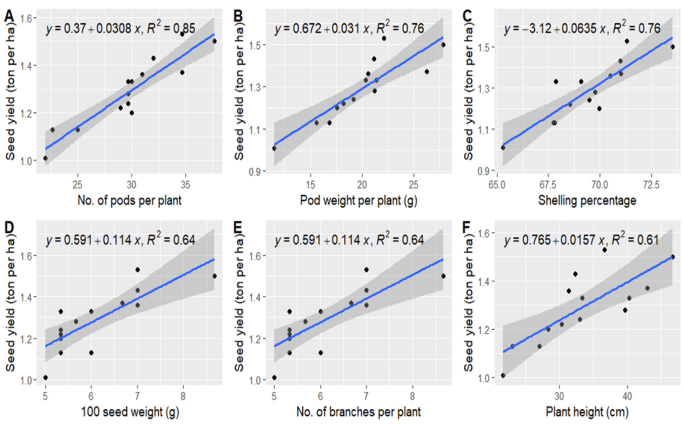


**Figure 4.** *Regression analysis of the impact of growth parameters and yield attributes (A. Number of pods per plant, B. Pod weight per plant, C. Shelling percentage, D. 100 seed weight, E. Number of branches per plant, and E. Plant height) on the seed yield of groundnut in the light of the effect of various nitrogen-sulphur levels on groundnut varieties.*

## Principal component analysis

A scree plot was prepared prior to drawing the PCA bi-plot to visualize the relative importance of the principal components in explaining the variability in groundnut production (Figure 5A). The scree plot revealed that the first principal component (PC1) accounts for 73.3% of the total variance present in the dataset, followed by the second principal component (PC2) with 9.3%, making these two components collectively accumulate the majority (82.6%) of the meaningful variation resulting from employing varying N-S levels on groundnut varieties. PCA was done to sort out the traits that best describe the impact of N-S level on the growth and yield of groundnut varieties. The bi-plot consisting of the first two principal components along with the loadings of variables is presented in Figure 5B where the x-axis represents PC1 and the y-axis represents PC2. As the PCA Bi-plot revealed, traits like shelling percentage (SP), plant height (PH), number of pods plant$^{-1}$ (PPP), pod weight plant$^{-1}$ (PWPP), hundred seed weight (HSW), number of branches plant$^{-1}$ (BPP), number of seeds pod$^{-1}$ (SPP), seed yield (SY), and stover yield (StY) were aligned towards the positive PC1 direction, meaning that they were positively correlated with PC1. The close alignment of these factors indicated a positive correlation among them. Consequently, treatments placed in this direction represented greater values in these factors and vice versa. However, as seen by its steep upward trajectory, the harvest index (HI) was more heavily loaded on the PC2 axis and did not form a cluster with the others, indicating that it did not correlate with them. Possibly because of its high PC1 trait scores from using high levels of N and S (F6) on the superior-performing variety (V2), V2F6 stood out from the other treatment combinations and demonstrated a substantial influence of PC1 (Hoang *et al.*, 2021; Xia *et al.*, 2021; Aswini *et al.*, 2024b). In contrast, treatments on the left, like V1F0 and V1F1, indicated low scores in PC1 traits, possibly due to the application of low N-S levels (F0 and F1, respectively) on the lower-performing variety (V1), resulting in reduced growth and yield performance.

## Heatmap analysis

A heatmap analysis was performed to investigate the traits that best demonstrate the impact of varying nitrogen-sulphur levels

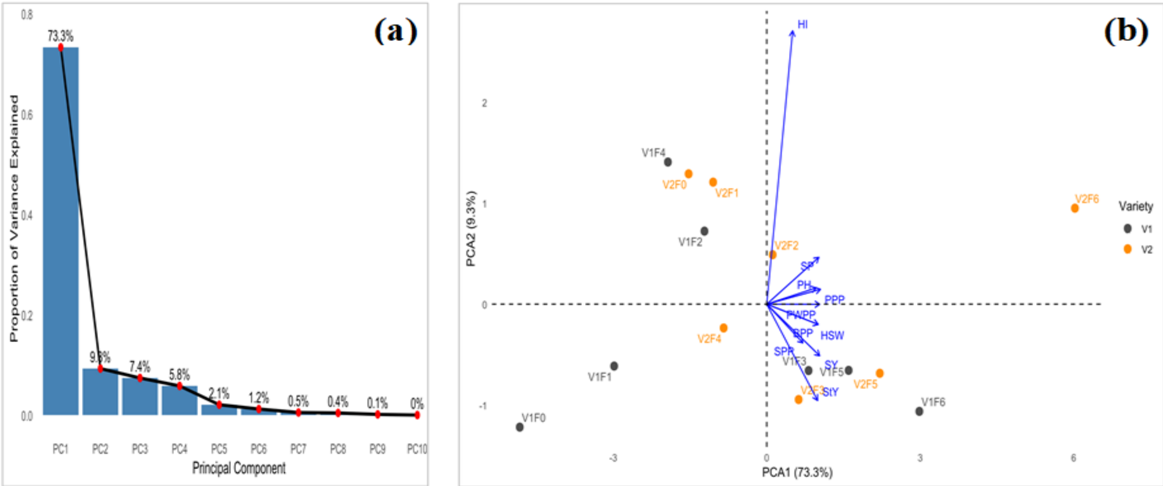


*Figure 5. Scree plot of the principal components (a) and PCA Bi-plot showing the first two principal components (PC1 and PC2) for the effect of varying N-S levels (b) on growth parameters, yield attributes and yield of groundnut varieties. Here, the black and yellow dots represent 14 treatment combinations, consisting of two varieties and seven nitrogen-sulphur levels. V1 = BARI Chinabadam-10, V2 = Binachinabadam-8, PH = Plant height, BPP = Number of branches per plant, PPP = Number of pods per plant, PWPP = Pod weight per plant, SPP = Number of seeds per pod, HSW = Hundred seed weight, SP = Shelling percentage, HI = Harvest index, SY = Seed yield, StY = Stover yield.*

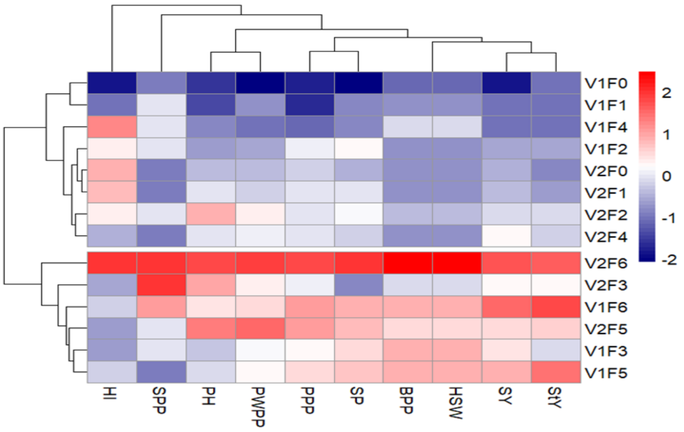


*Figure 6. Heatmap analysis of growth parameters, yield attributes and yield of groundnut in response to varying N-S levels across varieties. V1 = BARI Chinabadam-10, V2 = Binachinabadam-8, PH = Plant height, BPP = Number of branches plant$^{-1}$, PPP = Number of pods plant$^{-1}$, PWPP = Pod weight plant$^{-1}$, SPP = Number of seeds pod$^{-1}$, HSW = Hundred seed weight, SP = Shelling percentage, HI = Harvest index, SY = Seed yield, StY = Stover yield.*

on the yield of groundnut varieties, where the horizontal axis represents growth parameters and yield traits, and the vertical axis represents different treatment combinations (Figure 6). The treatment combinations were grouped into two distinct clusters using hierarchical clustering of standardized trait data. The lower cluster, which is represented by red hues and includes treatments with higher N-S doses, performed better than the upper cluster, which is represented by blue hues and includes treatments with lower N-S doses. Consequently, the most intense red bands across all growth parameters and yield attributes matched V2F6's maximum yield performance. V1F6, V2F5, and V1F5 all recorded yield and trait performance that was comparable to V2F6's. On the other hand, the poor trait performance of V1F0, V1F1, V1F2, V1F4, V2F0 and V2F1 was reflected in their poor yield performance. To sum up, the heatmap findings confirmed the superiority of elevated N-S levels (especially F6) in enhancing the growth and yield parameters of groundnut towards yield maximization in groundnut varieties (especially V2); meanwhile, which also validated the PCA findings.

## Conclusions

The present study explored the effect of different doses of nitrogen and sulphur levels on plant growth parameters, yield traits and yield of groundnut varieties. The result revealed that variety and nitrogen-sulphur level had a significant impact in which Binachinabadam-8 performed better than BARI Chinabadam-10 in all the growth parameters and yield attributes except number of seeds pod$^{-1}$, ultimately producing significantly better seed (1.33 t ha$^{-1}$ and 1.26 t ha$^{-1}$, respectively) and biological (4.63 t ha$^{-1}$ and 4.52 t ha$^{-1}$, respectively) yields. In case of nitrogen-sulphur level, N 40 kg ha$^{-1}$ + S 30 kg ha$^{-1}$ ($F_6$) recorded the best performance, in plant growth parameters, yield attributes, as well as seed (1.54 t ha$^{-1}$), stover (3.10 t ha$^{-1}$) and biological (4.64 t ha$^{-1}$) yields. Meanwhile, nitrogen-sulphur level, N 40 kg ha$^{-1}$ + S 30 kg ha$^{-1}$ ($F_6$) recorded the best performance, and vice-versa for N 0 kg ha$^{-1}$ + S 0 kg ha$^{-1}$ ($F_0$), in plant growth parameters, yield attributes, as well as seed (1.54 t ha$^{-1}$ and 1.12 t ha$^{-1}$, respectively), stover (3.10 t ha$^{-1}$ and 2.46 t ha$^{-1}$, respectively) and biological (4.64 t ha$^{-1}$ and 3.58 t ha$^{-1}$, respectively) yields. With interaction between variety and nitrogen-sulphur level, $V_2F_6$ interaction (application of 40 kg nitrogen and 30 kg sulphur) performed well with the highest traits performance in Binachinabadam-8 than BARI Chinabadam-10. So, the application of 40 kg nitrogen (= 87 kg Urea ha$^{-1}$) and 30 kg sulphur (= 167 kg Gypsum ha$^{-1}$) along with other fertilizers at recommended doses might be practiced on Binachinabadam-8 to optimize groundnut yield.

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## DECLARATIONS

### Author's contribution

Conceptualization, Methodology, Data curation, Formal analysis, Resources, Visualization, Writing- original draft: G.Z.; Conceptualization, Data curation, Formal analysis, Methodology, Writing-original draft: M.A.H.; Project administration, Funding acquisition, Investigation, Supervision, Writing- review & editing: M.B.; Formal analysis, Resources, Validation, Writing- review & editing: M.H.M. and M.H.M.; Project administration, Funding acquisition, Supervision, Conceptualization, Investigation, Writing-original draft: A.K.H. All authors have read and agreed to the published version of the manuscript.

**Conflicts of interest:** The authors declare no conflict of interest.

**Ethics approval:** This study did not involve any animal or human participant and thus ethical approval was not applicable.

**Consent for publication:** All co-authors gave their consent to publish.

**Data availability:** The data that support the findings of this study are available on request from the corresponding author.

**Supplementary data:** No supplementary data is available for the paper.

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