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RESEARCH ARTICLE

Optimising micronutrient-driven productivity in groundnut through foliar boron for a climate-resilient oilseed farming strategy

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Abstract

Micronutrient limitations continue to constrain the economic potential of groundnut production, particularly in nutrient-responsive soils where biological nitrogen fixation and reproductive processes impose high physiological demands. This study aimed to test the hypothesis that targeted foliar application of boron or molybdenum, in combination with recommended macronutrient fertilisation, can substantially enhance both the biophysical performance and economic viability of groundnut cultivation. A field assessment was conducted using 9 nutrient-management treatments involving soil and foliar routes of boron and molybdenum under full and reduced nutrient regimes. Instead of detailing stage-wise biometric responses, the findings are synthesised to highlight key technological and economic outcomes. Foliar boron at 0.5 % with 100 % recommended nutrient dose emerged as the most productive and cost-efficient strategy, increasing pod yield, enhancing photosynthetic performance, strengthening nodulation efficiency and generating the highest net returns. The interdisciplinary significance lies in connecting plant nutrition physiology with farm-level profitability metrics, revealing new opportunities for resource-efficient fertilization practices. These results demonstrate that a simple micronutrient-based intervention can support climate-resilient production, reduce hidden nutrient losses and create financially attractive pathways for oilseed farmers and agri-input stakeholders. Prospective research directions include scaling this approach through digital decision-support tools, micronutrient blending technologies and region-specific cost–benefit simulations.

Keywords: boron; groundnut; Kadiri Lepakshi K1812; molybdenum

Introduction

Groundnut (*Arachis hypogaea* L.) is an important legume oilseed cultivated extensively across tropical and subtropical regions of the world. In India, it serves as a major off-season crop with significant roles in the agricultural economy, food supply and livestock feed systems. Groundnut also contributes to soil fertility by improving soil structure and nutrient cycling. As global demand for edible oil continues to rise, enhancing groundnut productivity through improved agronomic and nutrient management practices has become essential (1). While macronutrients such as nitrogen (N), phosphorus (P) and potassium (K) remain foundational for plant growth, micronutrients, are equally critical for physiological and biochemical functions though they are required in smaller quantities. Among them, boron (B) and molybdenum (Mo) play pivotal roles in legumes. Boron governs key reproductive processes, including pollen germination, pollen tube growth, fertilisation and fruit formation. It also supports cell wall synthesis, membrane stability, sugar translocation and calcium assimilation. Boron deficiency leads to poor pollination, flower abortion, reduced seed development and restricted root growth, ultimately suppressing nodulation and crop productivity (2, 3).

Molybdenum, on the other hand, is a core component of the nitrogenase enzyme that drives Biological Nitrogen Fixation (BNF) within legume root nodules. It is further involved in the biosynthesis of nitrate reductase, a key enzyme in nitrogen assimilation. Inadequate molybdenum availability results in poor nodule initiation, reduced nitrogen fixation, impaired protein synthesis and overall decline in crop vigour. For crops such as groundnut that rely strongly on symbiotic nitrogen fixation, adequate molybdenum supply becomes indispensable (4). Thus, supplying boron and molybdenum in appropriate forms, especially through foliar application, offers a promising strategy to enhance nutrient uptake, improve nodulation efficiency and increase overall productivity in groundnut. Strengthening micronutrient management is therefore essential for sustaining yield improvements and meeting the growing demand for oilseed crops.

Materials and Methods

Field and experimental site description

A field experiment was conducted during the rabi season from January to May 2025 under open-field conditions representative of a warm tropical agro-ecological region. The results generated from this study are expected to support sustainable nutrient management practices and enhance groundnut production during the rabi (*Margazhi pattam*) season, particularly under similar agro-climatic conditions (5). The soil at the experimental site was characterised as loamy, with available nutrient levels of 102, 12.5 and 112 kg/ha of N, P_2O_5 and K_2O, respectively. The soil had a pH of 7.2, organic carbon content of 0.27 %, electrical conductivity of 0.2 dS m^{-1} and an overall moderate fertility status. Before the experiment, composite soil samples were collected and analysed for their physical and chemical properties to establish baseline fertility conditions, which facilitated the formulation of nutrient management plans relevant to the agro-ecological context (6).

Experimental design and layout

The experiment was conducted using a Randomised Block Design (RBD) consisting of 9 treatment combinations with three replications, totalling 27 experimental plots. Each plot measured 20 m^2 (5 × 4 m) and a spacing of 30 × 10 cm was maintained to ensure a uniform plant population. Blocks were separated by a 1 m buffer to prevent treatment interference between adjacent plots (7). The groundnut cultivar used was Kadiri Lepakshi (K1812), a high-yielding, semi-spreading variety known for strong nodulation and wide adaptability. Sowing was carried out by placing seeds at an appropriate depth to ensure uniform germination (8). The treatment structure included the following nutrient-management combinations: T_1: 100 % RDN + Soil application of B at 5 kg/ha, T_2: 75 % RDN + Soil application of B at 5 kg/ha, T_3: 100 % RDN + Soil application of Mo at 5 kg/ha, T_4: 75 % RDN + Soil application of Mo at 5 kg/ha, T_5: 100 % RDN + Foliar application of B at 0.5 %, T_6: 75 % RDN + Foliar application of B at 0.5 %, T_7: 100 % RDN + Foliar application of Mo at 0.3 %, T_8: 75 % RDN + Foliar application of Mo at 0.3 %, T_9: Control (100 % RDN; 25:50:75 kg/ha of N:P_2O_5:K_2O). All plots receiving the full RDF were supplied with 25:50:75 kg/ha of N: P_2O_5:K_2O, while nitrogen levels were proportionately reduced in the 75 % RDN treatments (9).

Growth parameters were recorded at 20, 40 and 60 days after sowing (DAS) and root nodulation parameters were assessed at 45 and 75 DAS. Plant protection measures were implemented as required to avoid biotic stress interference during the cropping period (10). All collected data were subjected to analysis of variance (ANOVA) and treatment differences were evaluated using the F-test at a 5 % level of significance, following the procedures (11).

Measurement and analysis

Quantification of plant growth, biomass accumulation and physiological traits provides critical insights into soil-plant interactions and productivity dynamics under different nutrient management strategies, as reported in agroecosystem studies relating soil properties with biomass carbon accumulation (12). Morpho-physiological observations were recorded from tagged plants selected randomly within each plot. Plant height, number of branches, leaf area, leaf area index and dry matter accumulation were measured following standardised methods. Chlorophyll index was measured non-destructively using a SPAD meter (SPAD-502 Plus, Konica Minolta, Japan), which provides a relative chlorophyll index rather than chlorophyll content, following standard calibration procedures (13). Relative Water Content (RWC) was calculated using the fresh weight, turgid weight and dry weight methods. Root nodules (number and fresh weight) were assessed by gently uprooting representative plants at two crop stages. Yield attributes like number of pegs, pods, matured pods, seed index and shelling percentage were recorded using standard sampling procedures. Pod and haulm yields were taken from the net plot area and adjusted to recommended moisture levels. Economic indicators such as cost of cultivation, gross return, net return and benefit–cost ratio was determined based on prevailing prices of inputs and outputs.

Results and Discussion

Plant height

Plant height was significantly influenced by boron and molybdenum application throughout groundnut growth. At 20 DAS, before foliar spraying, the tallest plants were recorded in T_1 (100 % RDN + soil-applied boron, 10.80 cm), followed by T_3 (soil-applied molybdenum, 9.76 cm), while the control (T_9) showed the shortest height (5.96 cm). From 40 DAS onward, foliar treatments led to marked improvements, with T_5 (100 % RDN + foliar boron at 0.5 %) consistently recording the tallest plants, 15.33 cm (40 DAS), 27.66 cm (60 DAS) and 46.50 cm at harvest, followed by T_7 (foliar molybdenum at 0.3 %). These increases reflect the role of boron in auxin synthesis and vascular growth and effect of molybdenum on nitrogen metabolism and chlorophyll formation (14, 15). Initial height gains from soil-applied treatments can be attributed to early nutrient availability in the rhizosphere, supporting root and shoot development (16). In later stages, foliar boron was particularly effective in sandy soils due to better absorption and translocation. The control, lacking micronutrients, consistently exhibited the lowest plant height, emphasising the essential role of boron and molybdenum in achieving optimal vegetative growth under deficient soil conditions. The variation in plant height across treatments at different growth stages is presented in Table 1.

Number of branches per plant

Boron and molybdenum applications significantly influenced branching in groundnut. At 20 DAS, the highest number of branches was seen in T_1 (100 % RDN + soil-applied boron, 9.80), followed by T_3(8.43), while the control (T_9) had the lowest (4.63). From 40 DAS onwards, foliar applications became more effective, with T_5 (100 % RDN + foliar boron at 0.5 %) recording the maximum branches 14.63 (40 DAS), 18.33 (60 DAS) and 31.93 at harvest, followed by T_7(foliar molybdenum at 0.3 %). The control consistently showed the least branching across all stages. The enhanced branching with foliar boron is attributed to its effect on shoot apical meristem activity and lateral bud development (17). Foliar boron boosts branch formation by improving sugar translocation and hormonal balance (auxin and cytokinin). Molybdenum also contributed to better branching through improved nitrogen assimilation and meristem function. Conversely, the lack of micronutrient support in the control led to poor shoot architecture (18). The observed branching pattern

Table 1. Effect of boron and molybdenum on the plant height of groundnut

	Treatment	Plant height (cm)			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	10.80	13.23	24.75	35.64
T_2	75 % RDN + Soil application of boron at 5 kg/ha	7.73	9.47	21.07	30.86
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	9.76	12.21	23.63	31.43
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	7.26	8.67	20.21	31.37
T_5	100 % RDN + Foliar application of boron at 0.5 %	6.76	16.33	27.66	46.50
T_6	75 % RDN + Foliar application of boron at 0.5 %	6.20	11.41	24.18	29.85
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	6.70	14.67	24.98	41.05
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	5.20	10.96	22.42	31.54
T_9	Control 100 % RDF (25:50:75 kg/ha)	5.96	7.21	18.02	26.78
	SE (d)	0.46	0.65	1.13	1.86
	CD ($p \leq 0.05$)	0.98	1.19	2.07	3.41

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

aligned with dry matter accumulation and yield, emphasising the critical role of boron and molybdenum in promoting vegetative growth. The effect of boron and molybdenum application on the branching pattern is summarised in Table 2.

Total dry matter production

Dry Matter Production (DMP) in groundnut was significantly enhanced by boron and molybdenum applications across all growth stages. At 20 DAS, before foliar spray, the highest DMP was in T_1 (580 kg/ha), followed by T_3 (540 kg/ha), while the control (T_9) recorded the lowest (413 kg/ha). From 40 DAS onward, foliar treatments showed pronounced effects, with T_5 (100 % RDN + foliar boron at 0.5 %) producing the highest DMP at 40 DAS (1798 kg/ha), 60 DAS (2917 kg/ha) and harvest (4989 kg/ha). This was followed by T_7 (foliar molybdenum at 0.3 %), while T_9 consistently recorded the lowest values. The enhanced DMP with foliar boron is linked to improved carbohydrate metabolism, chlorophyll content and nutrient translocation. Role of boron in phloem loading and sugar transport can enhance sink strength during pod development (19). Similarly, foliar molybdenum improved TDMP by boosting nitrogen fixation and nitrate assimilation (20). Early-stage increases under soil-applied treatments reflected better root-zone availability, promoting enzymatic activity and structural growth. In contrast, the control lacked micronutrient support, resulting in poor biomass accumulation. Research has demonstrated that boron and molybdenum deficiencies impair physiological functions like chlorophyll biosynthesis and nitrate reduction (21, 22). The significantly higher DMP with combined boron and molybdenum application in groundnut (23). Total DMP recorded at different growth stages is detailed in Table 3.

Leaf area index

The Leaf Area Index (LAI) of groundnut increased steadily from 20 to 60 DAS across treatments, then plateaued or slightly declined at harvest. At all stages, foliar boron treatment (T_5: 100 % RDN along with boron at 0.5 %) recorded the highest LAI 2.10 (40 DAS), 3.04 (60 DAS) and 2.85 (harvest) followed by foliar molybdenum (T_7), while the control (T_9) consistently recorded the lowest LAI (1.03, 1.80 and 1.53 respectively). The superior LAI under T_5 is attributed to the role of boron in enhancing cell expansion, meristem activity and sugar translocation during active growth. Research reported that foliar boron application supports lamina expansion and leaf growth via improved sugar supply. Molybdenum, as in T_7, also enhanced LAI through its role in nitrate reductase activity and chloroplast development (15). In contrast, the control (T_9), which lacked micronutrient supplementation, showed reduced LAI due to limited meristematic activity and chlorophyll biosynthesis. Research has demonstrated that boron and molybdenum deficiencies lead to impaired canopy development and lower photosynthetic efficiency (18). Changes in LAI as influenced by micronutrient treatments are shown in Table 4.

SPAD value

SPAD values were significantly influenced by boron and molybdenum applications from 40 DAS onwards. T_5 (100 % RDN + foliar boron at 0.5 %) consistently recorded the highest SPAD values: 55.29 (40 DAS), 53.85 (60 DAS) and 49.40 (harvest), followed by T_7 (foliar molybdenum at 0.3 %). The control (T_9) showed the lowest readings at all stages. Boron supports chlorophyll biosynthesis by aiding magnesium uptake and carbohydrate metabolism (14). Similarly, foliar molybdenum

Table 2. Effect of boron and molybdenum on number of branches per plant of groundnut

	Treatment	Number of branches per plant			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	9.80	11.67	16.62	24.33
T_2	75 % RDN + Soil application of boron at 5 kg/ha	7.56	8.39	13.68	20.26
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	8.43	10.31	15.87	22.73
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	6.76	7.71	13.22	19.53
T_5	100 % RDN + Foliar application of boron at 0.5 %	6.40	14.63	18.63	31.93
T_6	75 % RDN + Foliar application of boron at 0.5 %	4.33	9.28	14.98	21.93
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	5.80	12.41	17.06	28.66
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	3.83	8.76	13.87	21.20
T_9	Control 100 % RDF (25:50:75 kg/ha)	4.63	6.19	11.66	16.46
	SE (d)	0.35	0.77	0.80	1.42
	CD ($p \leq 0.05$)	0.75	1.41	1.46	2.61

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 3. Effect of boron and molybdenum on total dry matter production of groundnut

	Treatment	Total dry matter production (kg/ha)			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	580	1507	2313	4012
T_2	75 % RDN + Soil application of boron at 5 kg/ha	518	1320	1909	3774
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	540	1486	2301	3991
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	511	1297	1868	3719
T_5	100 % RDN + Foliar application of boron at 0.5 %	493	1798	2917	4989
T_6	75 % RDN + Foliar application of boron at 0.5 %	471	1471	2287	3973
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	486	1612	2401	4436
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	469	1412	2109	3840
T_9	Control 100 % RDF (25:50:75 kg/ha)	413	997	1328	2996
	SE (d)	25	70	129	256
	CD ($p \leq 0.05$)	52	148	274	543

RDN: Recommended Dose of Nitrogen, RDF: Recommended Dose of Fertiliser, DAS: Day After Sowing; CD: Critical Difference, SE: Standard Error, NS: Non-Significant

Table 4. Effect of boron and molybdenum on leaf area index of groundnut

	Treatment	Leaf area index			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	0.95	1.59	2.45	2.31
T_2	75 % RDN + Soil application of boron at 5 kg/ha	0.61	1.23	2.16	2.05
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	0.81	1.45	2.37	2.25
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	0.64	1.18	1.93	1.90
T_5	100 % RDN + Foliar application of boron at 0.5 %	0.72	2.10	3.04	2.85
T_6	75 % RDN + Foliar application of boron at 0.5 %	0.53	1.39	2.25	2.15
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	0.49	1.82	2.52	2.41
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	0.38	1.32	2.22	2.13
T_9	Control 100 % RDF (25:50:75 kg/ha)	0.21	1.03	1.80	1.53
	SE (d)	0.04	0.06	0.10	0.15
	CD ($p \leq 0.05$)	0.07	0.14	0.18	0.32

RDN: Recommended Dose of Nitrogen, RDF: Recommended Dose of Fertiliser, DAS: Day After Sowing; CD: Critical Difference, SE: Standard Error, NS: Non-Significant

improved SPAD values by facilitating nitrate assimilation and amino acid formation (21). Although all treatments showed a natural decline in SPAD values at harvest, boron and molybdenum applications delayed senescence and maintained higher chlorophyll levels, enhancing photosynthetic capacity and potential yield. Research indicates that importance of micronutrients in sustaining chloroplast function and nitrogen efficiency (18). The influence of treatments on chlorophyll index (SPAD value) is presented in Table 5.

Relative water content

Relative Water Content (RWC) in groundnut leaves was significantly influenced by foliar applications of boron and molybdenum from 40 DAS onward. The highest RWC was consistently observed in T_5 (100 % RDN + foliar boron at 0.5 %) 89.62 % at 40 DAS, 91.62 % at 60 DAS and 81.06 % at harvest, followed by T_7 (foliar molybdenum at 0.3 %). The control (T_9) recorded the lowest RWC at all stages. Effect of boron on enhancing RWC is linked to improved membrane integrity and water regulation. Similarly, research indicates that its role in osmotic adjustment and reduced transpiration loss (24). Similarly, molybdenum contributed to better hydration through osmolyte accumulation and turgor maintenance. In contrast, the lower RWC in the control suggests micronutrient deficiencies impaired water uptake and cell function (25). These results underline the physiological advantage of foliar boron and molybdenum in sustaining plant hydration during reproductive stages. RWC at different growth stages is summarised in Table 6.

Root nodulation

Root nodulation in groundnut was significantly enhanced by foliar applications of boron and molybdenum under 100 % RDN.

Table 5. Effect of boron and molybdenum on SPAD value of groundnut

	Treatment	SPAD value			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	37.09	45.52	48.10	43.02
T_2	75 % RDN + Soil application of boron at 5 kg/ha	34.18	41.76	43.36	33.94
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	36.23	44.38	46.39	41.90
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	34.01	41.02	42.94	34.54
T_5	100 % RDN + Foliar application of boron at 0.5 %	36.02	55.29	53.85	49.40
T_6	75 % RDN + Foliar application of boron at 0.5 %	33.26	43.12	45.05	40.66
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	35.48	47.47	49.44	46.29
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	32.98	42.43	44.78	38.41
T_9	Control 100 % RDF (25:50:75 kg/ha)	34.69	38.61	37.96	30.10
	SE (d)	2.22	2.13	2.39	2.12
	CD ($p \leq 0.05$)	NS	4.52	4.37	3.89

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 6. Effect of boron and molybdenum on the relative water content of groundnut

	Treatment	Relative water content (%)			
		20 DAS	40 DAS	60 DAS	At harvest
T_1	100 % RDN + Soil application of boron at 5 kg/ha	82.43	83.34	82.08	74.48
T_2	75 % RDN + Soil application of boron at 5 kg/ha	77.36	78.33	69.25	69.41
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	82.30	81.82	78.98	74.06
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	77.46	77.03	68.21	68.62
T_5	100 % RDN + Foliar application of boron at 0.5 %	81.86	88.62	91.62	81.06
T_6	75 % RDN + Foliar application of boron at 0.5 %	76.36	82.06	67.97	71.74
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	81.00	84.26	85.28	76.31
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	75.93	79.25	71.53	69.94
T_9	Control 100 % RDF (25:50:75 kg/ha)	79.90	65.61	56.84	63.74
	SE (d)	3.39	2.78	3.35	2.37
	CD ($p \leq 0.05$)	NS	5.09	6.13	4.35

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

At 45 and 75 DAS, T_5 (100 % RDN + foliar boron at 0.5 %) recorded the highest nodule number (68.96 and 87.96) and fresh weight (1.83 g and 1.76 g), followed by T_7 (foliar molybdenum at 0.3 %). The control (T_9) consistently showed the lowest values. Boron facilitates rhizobia infection, infection thread formation and carbohydrate transport to roots, key for nodule initiation and growth (23, 26). Foliar application post 37 DAS ensured timely uptake, coinciding with peak nodulation at 45 and 75 DAS. Contribution of molybdenum was linked to enhanced nitrogenase activity through the Fe-Mo cofactor and improved root vigour, promoting effective symbiosis (27). In contrast, the control (100 % RDN without micronutrients) recorded poor nodulation, indicating disrupted nitrogen fixation processes (28). These results affirm the synergistic role of boron and molybdenum in supporting BNF and overall nodule biomass. The number and fresh weight of root nodules recorded at 45 and 75 DAS are presented in Table 7, 8 respectively.

Days to 50 % flowering

Although the differences in flowering time among treatments were statistically non-significant, 100 % RDN combined with foliar boron or molybdenum advanced flowering by 3 to 7 days compared to the control. The earliest flowering occurred in T_5 (foliar boron at 0.5 %), likely due to role of boron in promoting flower initiation and pollen viability (29). Molybdenum also aided earlier flowering through enhanced nitrogen metabolism and photosynthetic efficiency. In contrast, delayed flowering in the control (RDN alone) suggests micronutrient deficiencies hindered the reproductive transition, potentially affecting pod development and final yield. The effect of micronutrient application on phenological parameters and yield attributes is detailed in Table 9, 10.

Table 7. Effect of boron and molybdenum on number of root nodules per plant in groundnut

	Treatment	No. of root nodules per plant	
		45 DAS	75 DAS
T_1	100 % RDN + Soil application of boron at 5 kg/ha	61.66	71.03
T_2	75 % RDN + Soil application of boron at 5 kg/ha	48.43	58.50
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	58.80	68.60
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	42.50	56.60
T_5	100 % RDN + Foliar application of boron at 0.5 %	68.96	87.96
T_6	75 % RDN + Foliar application of boron at 0.5 %	56.10	66.06
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	63.40	75.16
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	51.00	61.96
T_9	Control 100 % RDF (25:50:75 kg/ha)	39.60	51.53
	SE (d)	3.07	3.16
	CD ($p \leq 0.05$)	5.63	5.80

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 8. Effect of boron and molybdenum on the fresh weight of root nodules of groundnut

	Treatment	Root nodules fresh weight (g)	
		45 DAS	75 DAS
T_1	100 % RDN + Soil application of boron at 5 kg/ha	0.83	0.92
T_2	75 % RDN + Soil application of boron at 5 kg/ha	0.57	0.55
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	0.75	0.87
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	0.47	0.45
T_5	100 % RDN + Foliar application of boron at 0.5 %	1.83	1.76
T_6	75 % RDN + Foliar application of boron at 0.5 %	0.65	0.77
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	1.11	1.07
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	0.66	0.64
T_9	Control 100 % RDF (25:50:75 kg/ha)	0.34	0.36
	SE (d)	0.05	0.06
	CD ($p \leq 0.05$)	0.11	0.12

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 9. Effect of boron and molybdenum on phenological parameters, yield and yield attributes of groundnut

	Treatment	50 % flowering	No. of pegs per plant	No. of pods per plant	No. of matured pods per plant
T_1	100 % RDN + Soil application of boron at 5 kg/ha	31	58.22	24.84	20.99
T_2	75 % RDN + Soil application of boron at 5 kg/ha	33	46.34	22.13	17.13
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	31	55.72	24.18	19.86
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	33	45.99	21.09	18.69
T_5	100 % RDN + Foliar application of boron at 0.5 %	30	70.92	29.41	28.06
T_6	75 % RDN + Foliar application of boron at 0.5 %	32	51.87	23.18	18.81
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	30	63.20	26.23	24.13
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	32	48.16	22.63	18.36
T_9	Control 100 % RDF (25:50:75 kg/ha)	34	39.19	19.69	15.52
	SE (d)	1.76	2.97	1.09	0.74
	CD ($p \leq 0.05$)	NS	6.29	2.31	1.57

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 10. Effect of boron and molybdenum on yield and yield attributes of groundnut

	Treatment	100-pod weight (g)	Seed index (g)	Shelling percentage (%)
T_1	100 % RDN + Soil application of boron at 5 kg/ha	61.18	51.03	83.40
T_2	75 % RDN + Soil application of boron at 5 kg/ha	59.12	49.18	83.20
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	61.03	50.92	83.42
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	58.26	48.40	83.05
T_5	100 % RDN + Foliar application of boron at 0.5 %	63.46	53.05	83.60
T_6	75 % RDN + Foliar application of boron at 0.5 %	60.73	50.60	83.33
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	61.24	51.17	83.53
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	60.28	50.15	83.23
T_9	Control 100 % RDF (25:50:75 kg/ha)	57.09	47.60	83.37
	SE (d)	2.46	3.03	0.74
	CD ($p \leq 0.05$)	NS	NS	NS

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Yield attributes and yield

The application of boron and molybdenum under 100 % RDN significantly improved reproductive parameters in groundnut. The highest number of pegs (70.92), pods (29.41) and matured pods (28.06) per plant was recorded in T_5 (foliar boron at 0.5 %), followed by T_7 (foliar molybdenum at 0.3 %). In contrast, the control (T_9) consistently recorded the lowest values across these parameters.

Boron enhanced reproductive traits by promoting hormone activity, fertilisation and assimilate flow, while molybdenum improved nitrogen fixation and sustained photosynthesis (28, 30). The absence of micronutrients in the control hindered peg and pod development (31). Though 100-pod weight, seed index and shelling percentage showed numerical improvements, the highest in T_5 with 83.60 % shelling differences, were statistically non-significant. Still, better pod filling and sugar mobilisation with boron and improved seed quality with molybdenum contributed to superior performance in treated plots (32).

Yield parameters

Pod and haulm yields were significantly influenced by boron and molybdenum application. The highest pod yield (2618 kg/ha) was recorded in T_5 (100 % RDN + foliar boron at 0.5 %), followed by T_7 (foliar molybdenum at 0.3 %) with 2472 kg/ha. This improvement is attributed to enhanced flowering, peg development and nutrient use efficiency (32). The control (T_9) yielded the lowest (1921 kg/ha) due to poor reproductive growth.

Haulm yield was highest in T_7 (3488 kg/ha), closely followed by T_1 (3469 kg/ha), indicating increased biomass production via improved nitrogen metabolism (28, 33). The lowest haulm yield was recorded in the control (2596 kg/ha). Although harvest index differences were not statistically significant, the highest HI (0.44) was recorded with foliar boron, indicating efficient assimilate partitioning (19). The lowest HI in the control plot underscored the importance of micronutrients in enhancing reproductive efficiency despite adequate macronutrient supply. Pod yield, haulm yield and harvest index across treatments are presented in Table 11.

Table 11. Effect of boron and molybdenum on the yield of groundnut

	Treatment	Pod yield (kg/ha)	Haulm yield (kg/ha)	Harvest index (%)
T_1	100 % RDN + Soil application of boron at 5 kg/ha	2306	3469	0.40
T_2	75 % RDN + Soil application of boron at 5 kg/ha	2123	3139	0.40
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	2299	3368	0.41
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	2096	3091	0.40
T_5	100 % RDN + Foliar application of boron at 0.5 %	2618	3084	0.46
T_6	75 % RDN + Foliar application of boron at 0.5 %	2229	3330	0.40
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	2472	3488	0.41
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	2190	3260	0.40
T_9	Control 100 % RDF (25:50:75 kg/ha)	1921	2596	0.43
	SE (d)	103	169	0.03
	CD ($p \leq 0.05$)	218	358	NS

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Quality parameters

Protein and oil contents in groundnut kernels ranged from 24 to 26 % and 49.86 to 52.23 %, respectively. Although the differences were statistically non-significant, foliar application of boron at 0.5 % (T_5) consistently recorded the highest protein (26.00 %) and oil content (52.23 %), attributed to role of boron in nitrogen metabolism, amino acid transport and lipid biosynthesis (26).

Foliar molybdenum at 0.3 % (T_7) also showed improved quality traits, protein (25.70 %) and oil (51.75 %) by enhancing nitrogenase activity and sulphur assimilation (15, 32). The control treatment (T_9) recorded the lowest protein (24 %) and oil content (49.86 %), indicating limited biochemical activity due to micronutrient deficiency (34). The influence of treatments on kernel protein and oil content is summarised in Table 12.

Economic analysis

Micronutrient application significantly influenced the economics of groundnut cultivation. The highest gross (₹257961/ha) and net return (₹185275/ha) were recorded in T_5 (100 % RDN + foliar boron at 0.5 %), along with the highest B:C ratio (3.55), due to superior yield performance supporting (20). T_7 (100 % RDN + foliar molybdenum at 0.3 %) followed with gross and net returns of ₹245318/ha and ₹170382/ha, respectively and a B:C ratio of 3.27, reflecting enhanced pod yield and seed quality (22, 26). Despite its lowest cultivation cost (₹69036/ha), the control treatment (T_9) yielded the least economic return (gross ₹190290/ha; net ₹121254/ha) and the lowest B:C ratio (2.76), underscoring the cost-ineffectiveness of excluding boron and molybdenum in nutrient-deficient soils. Economic indicators, including cost of cultivation, gross returns, net return and benefit cost ratio are presented in Table 13.

Conclusion

The findings of this study confirm the hypothesis that targeted foliar micronutrient application, when integrated with recommended macronutrient fertilization, significantly enhances the physiological efficiency, yield performance and economic viability of groundnut cultivation. Foliar boron combined with full recommended nutrient dose demonstrated the highest industrial relevance by improving photosynthetic activity, strengthening nitrogen-fixation processes and maximizing pod yield and net returns. The results provide strong evidence that micronutrient-driven interventions can serve as low-cost, high-return strategies capable of supporting environmentally responsible and economically profitable oilseed production. These generalizable outcomes highlight the broader potential of micronutrient foliar nutrition as a scalable, climate-resilient and investment-attractive approach for global groundnut production systems.

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Authors' contributions

SKBT conducted the field experiments, collected data on growth and yield parameters and drafted the manuscript. SK

Table 12. Effect of boron and molybdenum on quality parameters of groundnut

	Treatment	Protein content (%)	Oil content (%)
T_1	100 % RDN + Soil application of boron at 5 kg/ha	25.40	51.33
T_2	75 % RDN + Soil application of boron at 5 kg/ha	24.50	50.20
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	25.20	51.15
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	24.30	50.05
T_5	100 % RDN + Foliar application of boron at 0.5 %	26.00	52.23
T_6	75 % RDN + Foliar application of boron at 0.5 %	25.10	51.05
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	25.70	51.75
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	24.80	50.60
T_9	Control 100 % RDF (25:50:75 kg/ha)	24.00	49.86
	SE (d)	0.35	0.36
	CD ($p \leq 0.05$)	NS	NS

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser, DAS: Day after sowing; CD: Critical difference, SE: Standard error, NS: Non-significant

Table 13. Effect of boron and molybdenum on the economics of groundnut

	Treatment	Cost of cultivation (₹/ha)	Gross return (₹/ha)	Net return (₹/ha)	B:C Ratio
T_1	100 % RDN + Soil application of boron at 5 kg/ha	71286	229502	158216	3.22
T_2	75 % RDN + Soil application of boron at 5 kg/ha	71194	211092	139898	2.97
T_3	100 % RDN + Soil application of molybdenum at 5 kg/ha	73536	228503	154967	3.11
T_4	75 % RDN + Soil application of molybdenum at 5 kg/ha	73444	208423	134979	2.84
T_5	100 % RDN + Foliar application of boron at 0.5 %	72686	257961	185275	3.55
T_6	75 % RDN + Foliar application of boron at 0.5 %	72594	221726	149132	3.05
T_7	100 % RDN + Foliar application of molybdenum at 0.3 %	74936	245318	170382	3.27
T_8	75 % RDN + Foliar application of molybdenum at 0.3 %	74844	217840	142996	2.91
T_9	Control 100 % RDF (25:50:75 kg/ha)	69036	190290	121254	2.76

RDN: Recommended dose of nitrogen, RDF: Recommended dose of fertiliser

supervised the research work, participated in the experimental design and reviewed the manuscript. JR assisted in statistical analysis and contributed to data interpretation. CP, VP and MAA provided technical guidance, participated in manuscript editing and coordinated the research process. All authors read and approved the final manuscript.

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During the preparation of this work, authors used ChatGPT (OpenAI) to assist with language refinement, grammar correction and improving sentence clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Syed F, Arif S, Ahmed I, Khalid N. Groundnut (peanut) (*Arachis hypogaea*). In: Goyal A, editor. Oilseeds: health attributes and food applications. 1st ed. Cham: Springer; 2021. p. 1–12
2. Pandey SN. Role of micronutrients in biochemical responses of crops under abiotic stresses. In: Roychoudhury A, Tripathi DK, editors. Sustainable agriculture in the era of climate change. Cham: Springer; 2020. p. 1–12
3. Day S, Aasim M. Role of boron in growth and development of plant: deficiency and toxicity perspective. In: Ahammed GJ, Rasool S, editors. Plant micronutrients: deficiency and toxicity management. Singapore: Springer; 2020. p. 1–13
4. Bursakov SA, Kroupin PY, Karlov GI, Divashuk MG. Tracing the element: the molecular bases of molybdenum homeostasis in legumes. Agronomy. 2023;13(9):2300. https://doi.org/10.3390/agronomy13092300
5. Tariq M, Ahmad B, Adnan M, Mian IA, Khan S, Fahad S, et al. Improving boron use efficiency via different application techniques for optimum production of good quality potato (*Solanum tuberosum* L.) in alkaline soil. PLoS One. 2022;17(1):e0259403. https://doi.org/10.1371/journal.pone.0259403
6. Shanmugam V, Kandasamy S, Radhakrishnan R. Identification of drought risk areas in preceding season of rabi crops in the Vellar river basin, Tamil Nadu, India. Arab J Geosci. 2022;15(13):1210. https://doi.org/10.1007/s12517-022-10137-9
7. Bertollo AM, de Moraes MT, Franchini JC, Soltangheisi A, Junior AAB, Levien R, et al. Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. Soil Tillage Res. 2021;206:104820. https://doi.org/10.1016/j.still.2020.104820
8. Shaw N, Barak RS, Campbell RE, Kirmer A, Pedrini S, Dixon K, et al. Seed use in the field: delivering seeds for restoration success. Restor Ecol. 2020;28(Suppl 3):S276–85. https://doi.org/10.1111/rec.13163
9. Hossain A, Quddus A, Alam K, Naser HM, Anwar B, Khatun F, et al. Application of zinc, boron and molybdenum in soil increases lentil productivity, nutrient uptake and apparent balance. Can J Soil Sci. 2020;101(1):113–24. https://doi.org/10.1139/cjss-2020-0052
10. Khaffagy AE, Mazrou YS, Morsy AR, El-Mansoury MA, El-Tokhy AI, Hafez Y, et al. Impact of irrigation levels and weed control treatments on annual weeds, physiological traits and productivity of soybean under clay soil conditions. Agronomy. 2022;12(5):1037. https://doi.org/10.3390/agronomy12051037
11. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley & Sons; 1984. p. 680
12. Kumar PS, Shukla G, Nath AJ, Chakravarty S. Soil properties, litter dynamics and biomass carbon storage in three bamboo species of Sub-Himalayan region of Eastern India. Water Air Soil Pollut. 2022;233(1):12. https://doi.org/10.1007/s11270-021-05373-4
13. Markwell J, Osterman JC, Mitchell JL. Calibration of the Minolta SPAD-502 leaf chlorophyll meter. Photosynth Res. 1995;46(3):467–72. https://doi.org/10.1007/BF00032301
14. Sabra DM, Olfat OH, El Habasha SF, Fergani MA, Mekki BB, El-Housini EA, et al. Response of growth characters, yield and yield attributes of groundnut (*Arachis hypogaea* L.) cultivars to some micronutrients foliar spraying application. Plant Arch. 2019;19 (2):1896–903
15. Mansingh MDI, Pandian PS, Mary PCN, Geetha AVR. Evaluation of various levels of calcium and boron on yield and economics of groundnut (*Arachis hypogaea* L.) in Irugur soil series of Madurai district. Pharma Innov J. 2022;11(3):346–9
16. Ramya P, Singh R. Effect of gypsum and boron on growth and yield of groundnut (*Arachis hypogaea* L.). Pharma Innov J. 2022;11 (3):2148–51
17. Poonguzhali RS, Pandian PS, Gayathri P, Silviya RA, Suganya S. Effect of boron on nodulation, dry matter production and quality of groundnut in major groundnut growing soils of Madurai District. Res High Agric Sci. 2022;4:1–9. https://doi.org/10.9734/bpi/rhas/v4/3779e
18. Haneena KM, Venkata Subbaiah P, Sujani Rao CH, Srinivasulu K. Effect of boron on nutritional quality of groundnut grown in coastal sandy soils. Int J Plant Soil Sci. 2021;33(19):189–97. https://doi.org/10.9734/ijpss/2021/v33i1930618
19. Moharana A, Mohanty S, Lenka D, Nayak RK, Jena SN, Satapathy M, et al. Effect of seed priming and coating through micronutrient application on growth and seed yield of groundnut (*Arachis hypogaea* L.). Int J Plant Soil Sci. 2022;34(24):462–80. https://doi.org/10.9734/ijpss/2022/v34i242663
20. Immanuel RR, Preethi K, Sudhagar Rao GB, Thiruppathi M. Yield response of groundnut (*Arachis hypogaea* L.) to phosphate enriched animal manures and foliar fertilization of micronutrients. Crop Res. 2020;55(5&6):230–36. http://doi.org/10.31830/2454-1761.2020.032
21. Chanu CK, Sarangthem I, Devi NS, Luikham E, Singh NG, Sharma LD. Effect of nitrogen and molybdenum on crop growth, yield and soil properties of pea in acid soil (*Pisum sativum* L.). Int J Chem Stud. 2020;8 (5):2023–27. https://doi.org/10.22271/chemi.2020.v8.i5ab.10599
22. Chintale YS, Bhakher R, Shingare M. Response of phosphorus and molybdenum on growth and yield of summer groundnut (*Arachis hypogaea* L.). Int J Plant Soil Sci. 2023;35(9):10–5. https://doi.org/10.9734/ijpss/2023/v35i92898
23. Pasala R, Singh R, Thakur I. Effect of gypsum and boron on yield and economics of groundnut (*Arachis hypogaea* L.). Biol Forum Int J. 2022;14(2):35–8
24. Kundu R, Sarkar A, Poddar R, Jash S, Moinuddin G, Sen A. Bio-formulation in combination with inorganic fertilizer improves crop growth, productivity and economics of kharif groundnut (*Arachis hypogaea* L.) in red and laterite soils. Arch Agron Soil Sci. 2023;69 (15):3438–54. http://doi.org/10.1080/03650340.2023.2241828
25. Senthamil E, Tamilmounika R. Recent techniques for secondary nutrients management in groundnut cultivation. Adv Agron. 2022;2:57–69
26. Naiknaware MD, Pawar GR, Murumkar SB. Effect of varying levels of boron and sulphur on growth, yield and quality of summer groundnut (*Arachis hypogaea* L.). Int J Trop Agric. 2015;33(2):471–474
27. Madhu H, Gunri SK, Roy D, Ali O, Bishnu P, Mallik B. Effect of various doses of basal and foliar application of nitrogen and potassium with trace elements on summer groundnut (*Arachis hypogaea*). Indian J Agric Sci. 2023;93(10):1108–13. https://doi.org/10.56093/ijas.v93i10.136234

28. Mohamed SS, Morsy AA, Abou El-Yazied A, El-Sayed AA. Effect of molybdenum and cobalt on nodulation, nitrogenase activity and yield of groundnut (*Arachis hypogaea* L.) under varying nitrogen levels. Aust J Basic Appl Sci. 2011;5(5):1207–13

29. Pereira GL, Siqueira JA, Batista Silva W, Cardoso FB, Nunes Nesi A, Araújo WL. Boron: more than an essential element for land plants? Front Plant Sci. 2021;11:610307. https://doi.org/10.3389/fpls.2020.610307

30. Safdar ME, Qamar R, Javed A, Nadeem MA, Javeed HMR, Farooq S, et al. Combined application of boron and zinc improves seed and oil yields and oil quality of oilseed rape (*Brassica napus* L.). Agronomy. 2023;13(8):2020. https://doi.org/10.3390/agronomy13082020

31. Sowmya S, Ganapathy M. Influence of different micronutrients on growth and yield of groundnut (*Arachis hypogaea*) in coastal sandy soils. Res Crops. 2021;22(2):251–5. http://doi.org/10.31830/2348-7542.2021.065

32. Nadia G. Influence of molybdenum on groundnut production under different nitrogen levels. World J Chem. 2012;7(2):64–70.

33. Ramprosad A, Sharma SK, Gupta N, Rao V. Synergistic effects of foliar application of zinc and boron on growth and chlorophyll content of groundnut (*Arachis hypogaea* L.). J Oilseed Res. 2020;37 (2):102–8.

34. Imoukhuede OB, Fasinmirin JT, Olayanju GM, Faloye OT. Growth and yield of groundnut (*Arachis hypogaea*) in bituminous soils of Southern Ondo State, Nigeria. Ecol Front. 2024;44(2):403–13.

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