NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 43, 2026
www.incda-fundulea.ro; doi.org/10.59665/rar4393 First Online: August, 2026. DII 2067-5720 RAR 2026-159

Synergistic Effect of Nitrogen and Boron Sources on Cotton Growth and Productivity under Heavy Clay Soils

Hossam S. El-Beltagi[1*], Mohsen Mohamed Mohamed Sharaf[2], Adel A. Rezk[1], Mohamed Fathi El-Nady[3], Mohamed M. El-Mogy[4], Metwaly Mahfouz Salem Metwaly[3], Hosny Hamed Kesba[4], Kholoud A. El-Naqma[5], Lamy Hamed[6], Azza A. El-Hendawy[2]

[1]Agricultural Biotechnology Department, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

[2]Agronomy Research Division, Cotton Research Institute, Agricultural Research Center, Giza, Egypt

[3]Department of Agricultural Botany, Faculty of Agriculture, Kafrelsheikh University, Kafr El-sheikh, 33516, Egypt

[4]Department of Arid Land Agriculture, College of Agriculture and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

[5]Soil & Water and Environment Research Institute, Agriculture Research Center, Giza, 12619, Egypt

[6]Department of Environment and Agricultural Natural Resources, College of Agricultural and Food Sciences, King Faisal University, Al-Ahsa 31982, Saudi Arabia

[*]Corresponding author. E-mail: helbeltagi@kfu.edu.sa

ABSTRACT

Cotton is a cornerstone of Egypt's agriculture, but its productivity in heavy clay soils is severely constrained by the immobilization of essential nutrients, especially nitrogen (N) and micronutrients such as boron (B). Therefore, the present study aimed to evaluation nitrogen sources including urea (130 kg/fedd.), ammonium sulfate (285.7 kg/fedd.) and ammonium nitrate (179.1 kg/fedd.) alone and in combination with boron sources including boric acid (0.68 g/L), sodium borate (0.55 g/L), and potassium borate (1.2 g/L) as foliar application on cotton grown under heavy clay soil conditions over two growing seasons (2024 and 2025). The trials were conducted using a split-plot design. Results demonstrated that ammonium nitrate and ammonium sulfate significantly enhanced vegetative growth (plant height and number of fruiting branches), chlorophyll content (a, b and total), productivity traits (number of open bolls and boll weight), yield components (seed index and seed cotton yield), as well as nutrient content (N, P, K) compared to urea. Furthermore, foliar application of boron sources significantly improved all evaluated growth and yield parameters. The most significant improvements in plant height, fruiting branch number, boll weight, and seed cotton yield were consistently recorded with the combined application of potassium borate and ammonium nitrate in both seasons. This combination considers as a strategy provides an effective approach for optimizing cotton production in heavy clay soils.

Keywords: ammonium nitrate, ammonium sulfate, boric acid, potassium borate, sodium borate, seed cotton yield.

INTRODUCTION

Cotton (*Gossypium barbadense* L.) is the most widely used natural fiber crop and a key component of Egypt's agricultural and industrial sectors, often called "white gold" due to its role in producing fiber, oil, and employment. In the 2023/2024 season, global cotton cultivation covered about 30.98 million hectares with an average yield of 1.34 t/ha and total production of about 41.46 million tons, while in Egypt it occupied about 0.11 million hectares with an average yield of 0.96 t/ha and total production of about 0.11 million tons (USDA, 2024). Cotton growth and productivity are strongly influenced by environmental conditions, with nitrogen being the most critical limiting nutrient (Khan et al., 2017; El-Beltagi et al., 2024a). In heavy clay soils, nitrogen and micronutrients such as boron may become fixed and less available, making careful fertilization essential. Therefore, improving cotton yield and fiber quality requires an integrated fertilization approach that includes balanced applications of N, P, and K along with micronutrients, applied in split doses

Received 7 April 2026; accepted 16 August 2026.

based on soil and plant analysis (Wright et al., 2003; Khan et al., 2017).

In dense clay soils, nitrogen fertilizers such as urea, ammonium sulfate (AS), and ammonium nitrate (AN) can improve cotton productivity, but their efficiency depends on soil properties and application methods. Ammonium sulfate is particularly beneficial because it supplies both nitrogen and sulfur and remains a relatively low-cost fertilizer. Ammonium nitrate provides readily available nitrogen; however, its use requires careful irrigation management to avoid losses. Its ammonium (NH_4^+) form is retained by clay particles, reducing leaching, while its nitrate (NO_3^-) form is quickly available for plant uptake but is highly susceptible to leaching and denitrification under waterlogged conditions. Therefore, due to its dual nitrogen forms, ammonium nitrate behaves differently in heavy clay soils compared to lighter soils, making proper timing and application essential (Qin et al., 2025).

Foliar application of boron in clay soils improves the efficiency of nitrogen use by enhancing nutrient uptake, root development, and overall plant productivity. Boron works with nitrogen to increase its utilization in dense soils where nutrient mobility is limited (Kohli et al. 2023; Abu El-Fotoh et al., 2025). It also strengthens cell walls and promotes deeper root growth, allowing better access to nutrients bound in clay particles. Combined application of boron and nitrogen enhances vegetative growth and overall plant development (Al-Mharib et al., 2021). In boron-deficient conditions, sensitive crops such as cotton may show reduced boll retention and lower yields, while foliar application during flowering and boll development improves boll setting and lint yield (Wahid et al., 2020). Additionally, boron enhances fiber quality by improving sugar transport and cell wall strength, leading to higher cotton productivity when applied with nitrogen (Cordeiro et al., 2024).

Boron sources, such as boric acid applied as a foliar spray, when combined with nitrogen fertilizers like urea, ammonium nitrate, or soil-applied nitrogen, significantly improve cotton productivity, boll retention, and fiber quality in heavy clay soils. This positive effect is due to the synergistic interaction between boron and nitrogen, which enhances nutrient use efficiency and supports better reproductive development compared to applying each nutrient alone (U.S. Borax, 2025). However, limited research has investigated how different nitrogen sources (urea, ammonium sulfate, or ammonium nitrate) interact with various boron sources (such as boric acid, sodium borate, or potassium borate) in influencing cotton performance under heavy clay soil conditions.

Based on these findings, it is hypothesized that foliar application of boron combined with nitrogen fertilizers such as urea, ammonium sulfate, and ammonium nitrate can help overcome the limitations of clay soils. This approach is expected to enhance plant growth, boll retention, yield, and fiber quality in cotton. Therefore, integrating boron with different nitrogen sources may represent an effective micronutrient strategy for maximizing cotton performance under heavy soil conditions.

MATERIAL AND METHODS

Crop Management and Experimental Design

The field experiments were carried out in the summer of 2024 and 2025 at the Sakha Agricultural Research Station in Kafr El-Sheikh Governorate, Egypt (30°56' N and 31°05' E). In the two seasons, winter wheat (*Triticum aestivum* L.) was used as the previous crop. The field was tilted two weeks prior to planting and leveled using a laser. The experiment followed a split-plot design with five replications for each of the 12 treatment combinations across both seasons. The main plots were assigned one of the three nitrogen fertilizer sources (urea, ammonium sulfate, or ammonium nitrate) applied to the soil, while the subplots received one of three boron sources (boric acid, sodium borate, or potassium borate) as a foliar spray.

Each experimental plot had eight ridges, 6 m long and spaced 70 cm apart, giving a total area of 33.6 m², while the net subplot area was 25.2 m². The cotton cultivar Giza 97 (Egyptian long-staple type) was obtained from the Cotton Research Institute and sown at a rate of 60 kg/ha. Planting took place on May 15 in 2024 and May 25 in 2025. Seedlings were thinned after emergence (two weeks after sowing), leaving two plants per hill before the first irrigation. Harvesting for both seasons occurred on September 26 (first picking) and November 1 (second picking). While harvested on Oct. 18 in 2025 and Nov. 15 in 2025 as first and second pickings, respectively.

Prior to the initiation of the experiment, soil samples from the surface layer (0-15, 15-30, 30-45 and 45-60 cm) were collected from the experimental field for analysis of their physical and chemical properties, following the procedures described by Dane and Topp (2020) and Sparks et al. (2020). The resulting data are illustrated in Tables 1 and 2.

Table 1. Mean values of selected physical soil properties at the experimental site prior to planting during the two growing seasons

Sampling sector depth, cm	Particle size distribution, %			Texture classes
	Sand	Silt	Clay	
0- 15	21.57	24.63	53.80	clayey
15- 30	19.32	23.21	57.47	clayey
30- 45	17.85	22.42	59.73	clayey
45- 60	16.65	21.51	61.84	clayey
Mean	18.85	22.94	58.21	-

Table 2. Mean values of selected chemical soil properties at the experimental site prior to planting during the two growing seasons

Sector depth (cm)	Ec, dS/m	PH	Soluble cautions, meq/ l (soil paste extract)				Soluble anions, meg/l (soil paste)			
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Co^{-}_{3}	Hco^{-}_{3}	Cl^{-}	So_4^{--}
0- 15	3.29	8.04	9.07	6.17	15.23	0.72	0.00	8.52	12.46	10.21
15- 30	3.11	8.26	7.31	5.35	15.82	0.63	0.00	7.84	12.63	8.64
30- 45	2.93	8.39	6.11	5.52	1 5.60	0.58	0.00	8.45	12.80	6.56
45- 60	2.84	8.52	6.28	5.85	14.84	0.33	0.00	8.30	12.67	6.33
Mean	3.04	8.31	7.19	5.72	15.37	0.57	0.00	8.28	12.64	7.93

Where: SO_4^{--} was calculated by the difference between soluble cautions and anions.

Soli fertilization and pests' management

Phosphorus fertilizer in the form of calcium superphosphate (15.5% P_2O_5) was incorporated into the soil during field preparation at a rate of 22.5 kg P_2O_5 per feddan. Following thinning, potassium fertilizer was applied as potassium sulfate (48% K_2O) at a rate of 24 kg K_2O per feddan. All pesticide treatments were carried out in accordance with the recommendations issued by the Egyptian Ministry of Agriculture for cotton cultivation.

Experimental Design and Treatments

The study evaluated 12 treatment combinations derived from three nitrogen fertilizers: urea (46.5% N) at 130 kg/feddan, ammonium nitrate (33.5% N) at 179.1 kg/feddan, and ammonium sulfate (20.5% N) at 285.7 kg/feddan. Each nitrogen source was applied in two equal splits: the first before the initial irrigation after sowing and the second before the following irrigation. These were combined with three foliar boron sources: boric acid (0.68 g L^{-1}), sodium borate (0.55 g L^{-1}), and potassium borate (1.2 g L^{-1}), which were sprayed at 70, 90, and 110 days after sowing using equal volumes. One feddan is approximately 0.42 hectares (4200.83 m²). The experiment followed a split-plot design with five replications to ensure statistical reliability, with nitrogen and boron sources applied either individually or in combination.

Plant height and fruiting branches number

Ten plants were randomly chosen from the central five furrows (or beds) of each subplot (10 plants per subplot) to evaluate the recorded traits, including final plant height (cm) and the number of fruiting branches per plant.

Chlorophyll content

At 120 days following sowing, the fourth fully developed leaf from the top of the main shoot was removed and placed in 5 mL of dimethylformamide to extract pigments. The concentrations of chlorophyll a, chlorophyll b, and total chlorophyll (expressed in µg per cm^2) were measured using the procedure outlined by Moran (1982).

Nutrients content

Prior to nutrient analysis, dried cotton plant samples were digested by a wet digestion method using a mixture of sulfuric and perchloric acids. Total nitrogen was quantified using the Kjeldahl procedure, phosphorus was determined by spectrophotometric analysis and potassium was measured by flame photometry following the methodology reported by Walinga et al. (2013).

Yield and Yield Components

For each treatment, fully opened bolls were hand-picked thrice to estimate the cotton yield. The harvested seed cotton was then ginned to estimate both seed and lint yields. In the first and second picking, 100 fully matured bolls were hand-picked to estimate the average weight per boll and lint percentage. Average boll weight was calculated by dividing the total weight of seed cotton of the 100 bolls by their number per boll. Lint percentage was calculated by dividing the lint weight obtained from the same 100 bolls by their corresponding seed cotton weight. Seed cotton yield per feddan (kantar) was determined by weighing the seed cotton harvested from two pickings in each subplot with a size of 25.2 m^2 and by then expressing the weight in kantar per feddan. It should be noted that one kantar equal 157 kg.

Statistical Analysis

The data were processed using Microsoft Excel software version 2024. The graphs were produced using GraphPad prism software version 10.4.0. The analysis of variance test was carried out using CoStat software. The split plot technique for the statistical analysis design was adopted following Snedecor and Cochran (1980) work. When significant results were obtained, LSD test at a probability significance level of 0.05 based on Waller and Duncan (1969) guidelines.

RESULTS AND DISCUSSION

Plant height and number of fruiting branches

The results shown in Figure 1 demonstrate that, compared to urea, ammonium sulfate (AS) and ammonium nitrate (AN) significantly increased plant height and the number of fruiting branches per plant in both growing seasons, with AN producing the largest gains. Combining foliar boron sources with nitrogen fertilizers further enhanced these traits. Among the boron treatments, boric acid and potassium borate resulted in higher plant height and fruiting branch numbers than sodium borate under all nitrogen sources. The highest values of both plant height and fruiting branch number were recorded with the combined application of potassium borate and ammonium nitrate in both seasons.

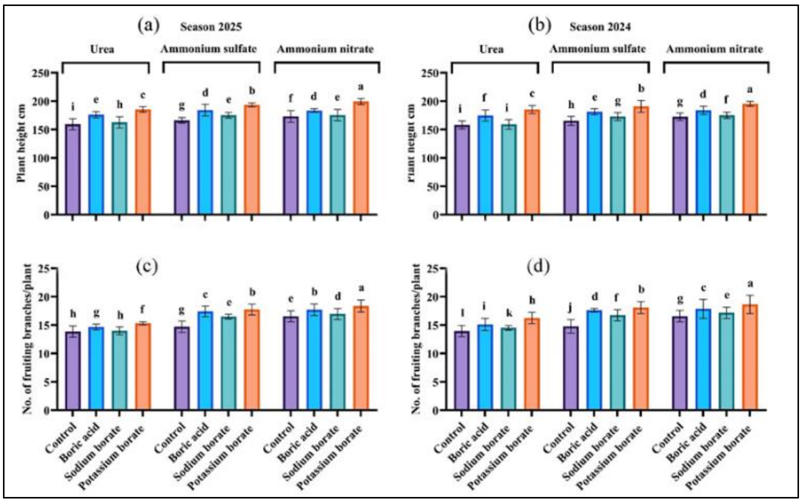

Figure 1. Illustrates how different nitrogen fertilizer treatments urea (130 kg per feddan), ammonium sulfate (285.7 kg per feddan), and ammonium nitrate (179.1 kg per feddan) combined with foliar-applied boron sources (boric acid at 0.68 g/L, sodium borate at 0.55 g/L, and potassium borate at 1.2 g/L) influenced cotton plant height [(a) and (b)] and the number of fruiting branches per plant [(c) and (d)] across the 2024 and 2025 growing seasons. Treatments that differ significantly at $p < 0.05$ are denoted by different letters above the bars, as determined by Duncan's multiple range test.

Chlorophyll content

As shown in Figure 2, ammonium nitrate (AN) and ammonium sulfate (AS) significantly increased chlorophyll a, b, and total levels compared with urea in both seasons, with AN consistently yielding the highest pigment concentrations. Foliar application of boron sources alongside nitrogen fertilizers further enhanced chlorophyll content compared to nitrogen alone. Among these combinations, potassium borate with any nitrogen source produced the greatest increase in chlorophyll a, b, and total, followed by boric acid, which also improved chlorophyll levels across all nitrogen treatments.

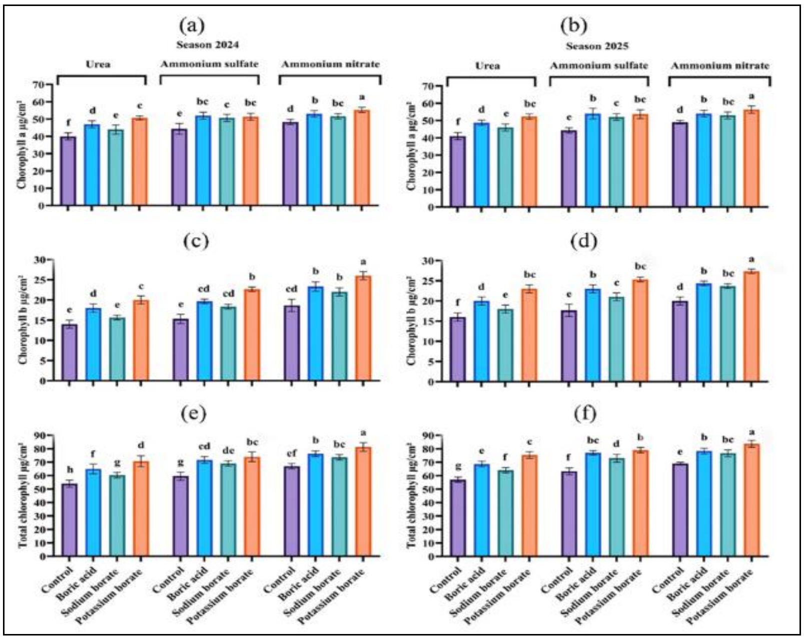

Figure 2. Effect of nitrogen fertilizers; urea (130 kg/feddan), ammonium sulfate (285.7 kg/feddan), and ammonium nitrate (179.1 kg/feddan) in combination with foliar boron sources, namely boric acid (0.68 g/L), sodium borate (0.55 g/L), and potassium borate (1.2 g/L), on chlorophyll pigments content; (a) and (b): chlorophyll a, (c) and (d): chlorophyll b and (e) and (f) total chlorophyll in cotton leaves during the 2024 and 2025 growing seasons. Statistical differences among treatments ($p < 0.05$) are indicated by distinct letters above the bars, in accordance with Duncan's multiple range test.

Number of open bolls and boll weight

Figure 3 shows that nitrogen fertilizers, especially ammonium sulfate (AS) and ammonium nitrate (AN), significantly increased the number of open bolls per plant and average boll weight compared to urea, with AN consistently giving the highest values in both seasons. Further enhancements were observed when foliar boron sources were combined with any nitrogen treatment. Among the boron sources, boric acid and potassium borate applied in combination with AS or AN resulted in the highest boll number and boll weight, with the greatest increases recorded under the combined potassium borate + ammonium nitrate treatment in both seasons.

Nutrients content

Figure 4 shows that ammonium sulfate (AS) and ammonium nitrate (AN) significantly increased nitrogen, phosphorus, and potassium concentrations compared with urea in both seasons. Foliar application of boron sources with any nitrogen fertilizer further enhanced nutrient content. The highest N, P, and K levels were achieved with potassium borate combined with each nitrogen source, followed by boric acid, which also improved nutrient levels across all nitrogen treatments.

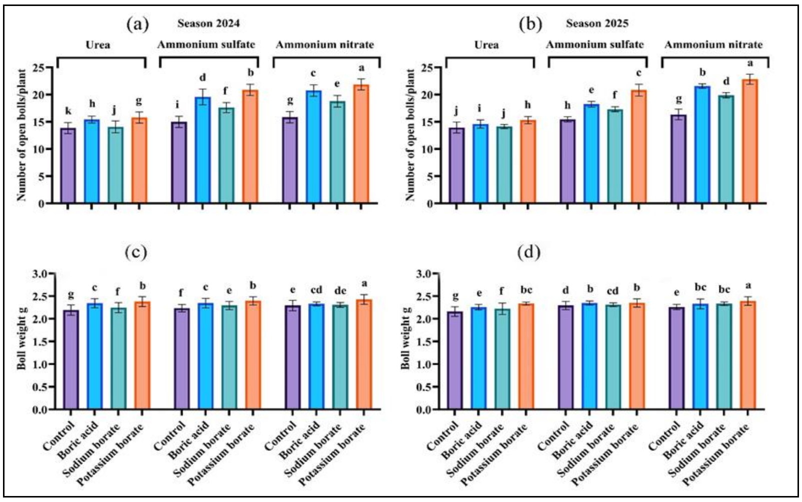

Figure 3. Illustrates how different nitrogen fertilizer treatments urea (130 kg per feddan), ammonium sulfate (285.7 kg per feddan), and ammonium nitrate (179.1 kg per feddan) combined with foliar-applied boron sources (boric acid at 0.68 g/L, sodium borate at 0.55 g/L, and potassium borate at 1.2 g/L) influenced number of open bolls/plant [(a) and (b)] and average boll weight [(c) and (d)] across the 2024 and 2025 growing seasons. Treatments showing significant differences ($p < 0.05$) are indicated by different letters above the bars, as determined by Duncan's multiple range test.

Lint and earliness percentage

Figure 5 shows that among nitrogen sources, ammonium nitrate (AN) gave the highest lint percentage in the first season, while ammonium sulfate (AS) was superior in the second season. Across both seasons, the highest lint percentage was achieved when potassium borate was applied with AN.

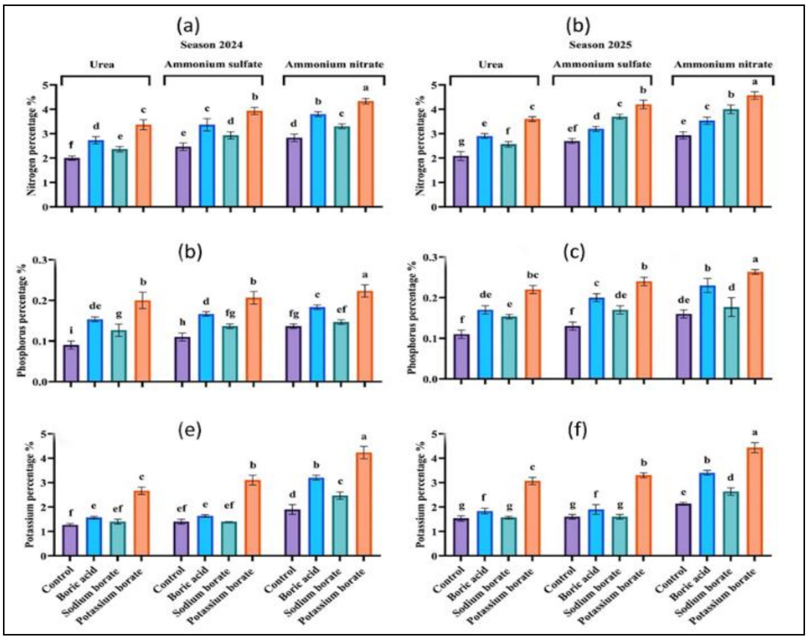

Figure 4. Effect of nitrogen fertilizers; urea (130 kg/feddan), ammonium sulfate (285.7 kg/feddan), and ammonium nitrate (179.1 kg/feddan) in combination with foliar boron sources, namely boric acid (0.68 g/L), sodium borate (0.55 g/L), and potassium borate (1.2 g/L), on nutrients %; (a) and (b): nitrogen, (c) and (d): phosphorous and (e) and (f) potassium in cotton leaves during the 2024 and 2025 growing seasons. Statistical differences among treatments ($p < 0.05$) are indicated by distinct letters above the bars, in accordance with Duncan's multiple range test.

Regarding earliness, AN significantly improved this trait in both seasons compared with other nitrogen sources. In the first season, maximum earliness occurred with sodium borate plus urea or AS and potassium borate plus AN, while in the second season, the highest earliness values were observed with sodium borate plus AS and potassium borate plus AN.

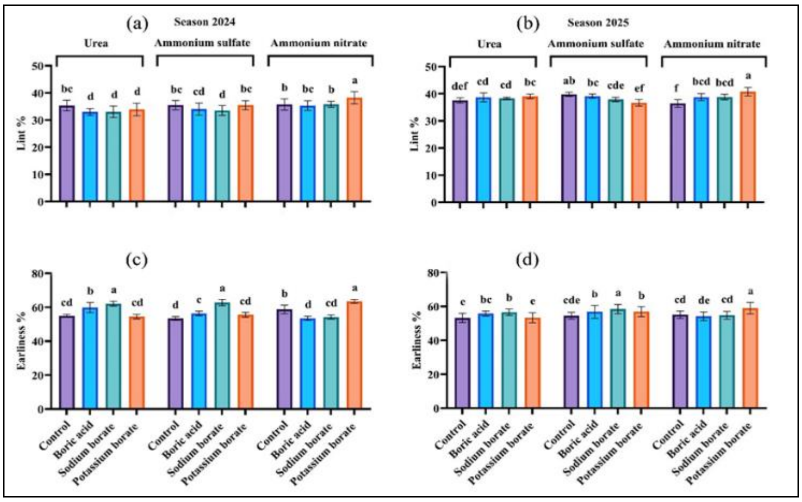

Figure 5. Presents the effects of nitrogen fertilizer forms urea (130 kg feddan^{-1}), ammonium sulfate (285.7 kg feddan^{-1}), and ammonium nitrate (179.1 kg feddan^{-1}) applied in combination with foliar boron sources, including boric acid (0.68 g L^{-1}), sodium borate (0.55 g L^{-1}), and potassium borate (1.2 g L^{-1}), on lint percentage [(a) and (b)] and earliness percentage [(c) and (d)] of cotton during the 2024 and 2025 growing seasons. Statistical differences among treatments ($p < 0.05$) are indicated by distinct letters above the bars, in accordance with Duncan's multiple range test.

Seed index and seed cotton yield

Figure 6 shows that ammonium sulfate (AS) and ammonium nitrate (AN) significantly increased seed index and seed cotton yield compared with urea in both seasons, with AN consistently producing the highest values. Foliar application of boron sources alongside nitrogen fertilizers further enhanced these traits. The highest seed index and seed cotton yield were achieved with potassium borate combined with AS or AN, with the combination of potassium borate and AN giving the overall maximum responses in both seasons.

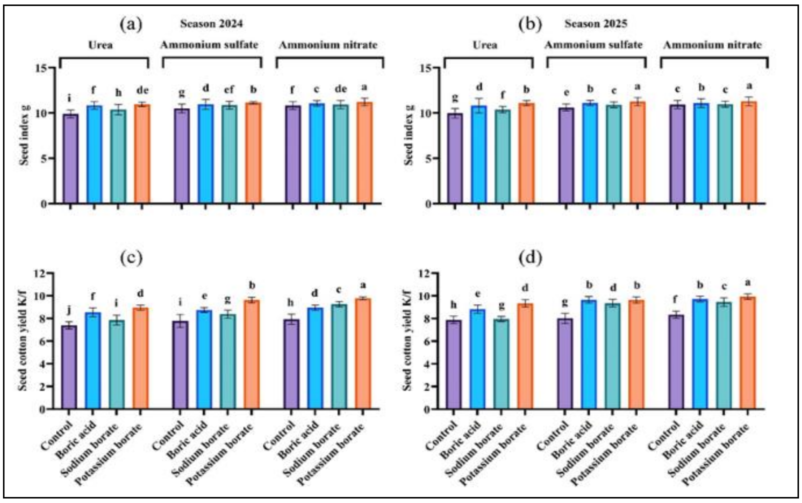

Figure 6. Presents the effects of nitrogen fertilizer forms urea (130 kg feddan^{-1}), ammonium sulfate (285.7 kg feddan^{-1}), and ammonium nitrate (179.1 kg feddan^{-1}) applied in combination with foliar boron sources, including boric acid (0.68 g L^{-1}), sodium borate (0.55 g L^{-1}), and potassium borate (1.2 g L^{-1}) on seed index [(a) and (b)] and seed cotton yield [(c) and (d)] of cotton during the 2024 and 2025 growing seasons. Statistical differences among treatments ($p < 0.05$) are indicated by distinct letters above the bars, in accordance with Duncan's multiple range test.

The results showed that ammonium nitrate (AN) and ammonium sulfate (AS) significantly increased plant height and the number of fruiting branches compared with urea in heavy clay soils. These effects are attributed to the sulfur supplied by AS and the balanced ammonium and nitrate forms provided by AN, which promote vigorous vegetative growth and reproductive development (Abdel-Tawab et al., 2021; El-Waraky et al., 2025). AS enhances growth and boll development through its sulfur component, although long-term use may lead to soil acidification, emphasizing the need for proper soil management (Bufogle et al., 1998). Chlorophyll content was higher with AN than urea, as ammonium-based fertilizers supply readily available nitrogen, while sulfur from AS further supports chlorophyll synthesis (Abd El-Salam et al., 2003). Overall, improvements in plant height and fruiting branch number are closely linked to increased chlorophyll content and photosynthetic efficiency.

Cotton plants fertilized with ammonium nitrate (AN) generally produced more bolls than those receiving urea due to its dual nitrogen forms (NH_4^+ and NO_3^-), which provide a continuous nitrogen supply that stimulates vegetative growth and fruiting branch formation. Nitrate promotes root development and photosynthesis, while ammonium supports amino acid and protein synthesis, together enhancing boll retention and reducing shedding (Chen et al., 2019; Shams et al., 2025). AN also often increases boll weight by improving chlorophyll content, photosynthetic efficiency, and nutrient levels, including nitrogen, phosphorus, and potassium. Enhanced assimilate production supports carbohydrate allocation to developing bolls, promoting boll filling and fiber development. Its ability to maintain nitrogen availability under soil fluctuations further sustains boll growth during stress periods (Fageria and Baligar, 2005; Chen et al., 2019).

The results indicate that ammonium nitrate (AN) and ammonium sulfate (AS) outperform urea in terms of lint percentage, seed index, seed cotton yield, and crop earliness. Urea is less efficient due to high nitrogen losses through volatilization, whereas nitrogen from ammonium salts is more readily available, enhancing yield and fiber quality. Ammonium salts promote overall plant growth and accelerate early development by improving nutrient uptake. Nitrate ions (NO_3^-) stimulate early growth, while ammonium ions (NH_4^+) support protein synthesis and seed formation. Additionally, the sulfur component in ammonium sulfate synergistically enhances enzyme activity and fiber strength (Abdel-Tawab et al., 2021).

The findings also showed that foliar application of boron sources significantly improved all evaluated growth and yield traits. Boron plays a key role in pollen viability, pollen germination, and successful fertilization, thereby enhancing boll formation. It also facilitates the translocation of carbohydrates from leaves to developing bolls, supporting boll growth. Furthermore, when combined with nitrogen fertilizers, boron improves nitrogen use efficiency, leading to increased plant productivity (Dordas, 2006).

The combined application of potassium borate and ammonium nitrate (AN) produced the greatest improvements in cotton growth and productivity. All boron sources boric acid, sodium borate, and potassium borate enhance cotton growth, boll retention, seed cotton yield, and fiber quality (Howard et al., 2000). However foliar application provided more consistent benefits due to higher nutrient availability and uptake efficiency (Wahid et al., 2020; El-Beltagi et al., 2024b). Potassium borate is particularly effective because its dual supply of boron and potassium improves assimilate translocation, boll weight, and fiber quality, whereas sodium borate releases boron more slowly, favoring long-term availability rather than rapid crop response (Howard et al., 2000; Vera-Maldonado et al., 2024; El-Beltagi et al., 2025a, b). The combination of potassium borate with AN enhances the synergistic interaction of nitrogen, boron, and potassium, leading to better boll retention, higher seed cotton yield, and improved fiber quality, making it an efficient nutrient management strategy (Kommineni and Bhandari 2024). The observed improvements in lint percentage, seed index, and seed cotton yield were closely linked to enhanced growth traits - such as plant height, number of fruiting branches, boll number per plant, chlorophyll content, and overall nutrient status all of which collectively increase photosynthetic efficiency and assimilate production to support higher yields.

Figure 7 shows that in heavy clay soils, ammonium sulfate (AS) and ammonium nitrate (AN) outperformed urea in enhancing cotton growth and productivity. Among the nitrogen sources, AN was the most effective, increasing plant height, number of fruiting branches, chlorophyll content, nutrient uptake, number of open bolls, boll weight, seed index, and total seed cotton yield. Foliar application of boron sources - boric acid, sodium borate, and potassium borate - further improved all measured parameters compared to nitrogen alone, with the greatest gains observed when potassium borate was combined with AN in both growing seasons.

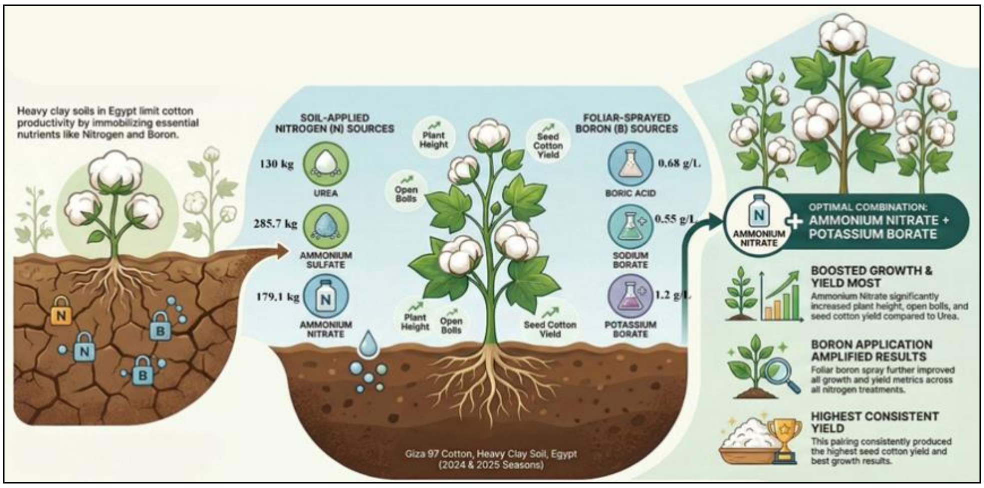

Figure 7. Graphical abstract depicting the beneficial effects of nitrogen fertilizers, namely ammonium sulfate (285.7 kg/fedd.) and ammonium nitrate (179.1 kg/fedd.), compared with urea (130 kg/fedd.) under heavy clay soil conditions. The figure also highlights the additional enhancement in all evaluated growth and yield-related traits such as plant height, number of fruiting branches, number of open bolls per plant, boll weight, and seed cotton yield resulting from the combined application of nitrogen fertilizers with boron sources, including boric acid (0.68 g/L), sodium borate (0.55 g/L), and potassium borate (1.2 g/L).

CONCLUSIONS

Compared with urea, the application of ammonium sulfate and ammonium nitrate had a dramatic effect on improvement in cotton crop growth and yield-related traits. Further improvement in all the studied characteristics was obtained by foliar treatment with boron source like boric acid, sodium borate, and potassium borate along with the various studied nitrogen sources. The greatest enhancement in crop growth and production traits was found when the application of potassium borate through foliar treatment was done along with ammonium nitrate. This treatment showed a strong synergistic effect, indicating its superiority in improving cotton performance under the studied conditions.

FUNDING

This study was supported by Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia under GRANT KFU254667.

ACKNOWLEDGEMENTS

We thank the Deanship of Scientific Research, Vice Presidency for Graduate Studies and Scientific Research, King Faisal University, Saudi Arabia (KFU254667), for supporting this research work.

REFERENCES

Abd El-Salam, E.S., EI-Menshawi, M.E., EI-Kashlan, M.K., 2003. *Effect of some nitrogen sources, nitrogen doses and time of splitting on yield and quality of Egyptian cotton under soil salinity.* Journal of Plant Production, 28(6): 4361-4373. https://doi.org/10.21608/jpp.2003.244641

Abdel-Tawab, R.M., Mahrous, N.M., El-Ssadi, S.A., 2021. *Comparative effect of different mineral nitrogen fertilizer sources on productivity and quality of some Egyptian cotton cultivars.* Journal of Plant Production, 12(3): 269-277. https://doi.org/10.21608/jpp.2021.157373

Abu El-Fotoh, H.M., El-Kalawy, S., El-Sheref, G.F., 2025. *Impact of soil applied molasses and foliar spraying with magnesium and boron on sugar beet yield and quality under nitrogen fertilization regime under clay soils.* Menoufia Journal of Soil Science, 10(10): 171-197. https://doi.org/10.21608/mjss.2025.426294.1038

Al-Mharib, M.Z., Alrawi, M., Naser, A.R., Alwan, A.M., Farhan, M.J., 2021. *Effect of foliar spray with magnesium and boron on growth and yield of broad bean*. International Journal of Agricultural & Statistical Sciences, 17(1): 1787-1792. https://connectjournals.com/03899.2021.17.1787

Bufogle, Jr.A., Bollich, P.K., Kovar, J.L., Lindau, C.W., Macchiavellid, R.E., 1998. *Comparison of ammonium sulfate and urea as nitrogen sources in rice production.* Journal of Plant Nutrition, 21(8): 1601-1614. https://doi.org/10.1080/01904169809365507

Chen, J., Liu, L., Wang, Z., Sun, H., Zhang, Y., Bai, Z., Song, S., Lu, Z., Li, C., 2019. *Nitrogen fertilization effects on physiology of the cotton boll-leaf system*. Agronomy, 9(6): 1-16. https://doi.org/10.3390/agronomy9060271

Cordeiro, L.F.D.S., Malenowtch, J.V.C., Cordeiro, C.F.D.S., Detoni Filho, J.A.C., Furlani Junior, E., Ferrari, S., 2024. *Improving cotton yield and fiber quality in different tropical soils with boron fertilization*. Agronomy Journal, 116(3): 1540-1550. https://doi.org/10.1002/agj2.21553?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

Dane, J.H., and Topp, C.G., 2020. *Methods of soil analysis, Part 4: Physical methods*. John Wiley & Sons.

Dordas, C., 2006. *Foliar boron application affects lint and seed yield and improves seed quality of cotton grown on calcareous soils*. Nutrient Cycling in Agroecosystems, 76(1): 19-28. DOI 10.1007/s10705-006-9037-7

El-Beltagi, H.S., El-Waraky, E.A., Almutairi, H.H., Al-Daej, M.I., El-Nady, M.F., Shehata, W.F., Belal, E.B., El-Mogy, M.M., El-Mehasseb, I., Metwaly, M.M.S., 2024a. *Morphophysiological and biochemical responses of cotton (Gossypium barbadense L.) to nano zinc (ZnO-NPs) and Azospirillum sp. under water deficit stress conditions*. Journal of Plant Nutrition, 10: 1-22. DOI: 10.1080/01904167.2024.2402882

El-Beltagi, H.S., Alwutayd, K.M., Rasheed, U., Sattar, A., Ali, Q., Alharbi, B.M., Al-Hawas, G.H, Abbas, Z.K., Darwish, D.B.E., Mahmoud, S.F., Al-Shaqhaa, M.A., Abou El-Yazied, A., Hamada, M.M.A., 2024b. *Sole and combined foliar application of silicon and putrescine alleviates the negative effects of drought stress in maize by modulating the morpho-physiological and antioxidant defence mechanisms*. Plant, Soil and Environment, 70: 26-39. DOI: 10.17221/423/2023-PSE

El-Beltagi, H.S., El-Waraky, E.A., Al-Daej, M.I., El-Naqma, K.A., Rezk, A.A., Zoghdan, M.G., El-Mogy, M.M., El-Nady, M.F., Ismail, A.M., Metwaly, M.M.S., 2025a. *Coupling effects of silicon and calcium foliar application and potassium soil fertilization on growth and yield production of cotton plants under drought stress conditions*. Silicon, 17: 2225-2245. DOI:10.1007/s12633-025-03333-4

El-Beltagi, H.S., El-Waraky, E.A., El-Mogy, M.M., El-Nady, M.F., Ismail, A.M., Belal, E.B., Al-Daej, M.I., El-Khateeb, N.M., Hamed, L., Metwaly, M.M.S., 2025b. *Microbial-priming of seeds with plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi for improving cotton (Gossypium barbadense L.) growth, yield and water productivity under drought stress*. Biologia, 80: 779-803. https://doi.org/10.1007/s11756-025-01865-z

El-Waraky, E.A., El-Beltagi, H.S., El-Nady, M.F., Al-daej, M.I., Belal, E.B., Shehata, W.F., Hadid, M.L., Salem Metwaly, M.M., 2025. *Responses of Gossypium barbadense L. cotton plants to biofertilizers under different levels of nitrogen fertilization*. Polish Journal of Environmental Studies, 34(1): 631-643. https://doi.org/10.15244/pjoes/186578

Fageria, N.K., and Baligar, V.C., 2005. *Enhancing Nitrogen Use Efficiency in Crop Plants*. Advances in Agronomy, 88: 97-185. https://doi.org/10.1016/S0065-2113(05)88004-6

Howard, D.D., Essington, M.E., Gwathmey, C.O., Percell, W.M., 2000. *Buffering of foliar potassium and boron solutions for no-tillage cotton production*. Journal of Cotton Science, 4(4): 237-244.

Khan, A., Tan, D.K.Y., Afridi, M.Z., Luo, H., Tung, S.A., Ajab, M., Fahad, S., 2017. *Nitrogen fertility and abiotic stresses management in cotton crop: a review*. Environmental Science and Pollution Research, 24(17): 14551-14566. https://doi.org/10.1007/s11356-017-8920-x

Kohli, S.K., Kaur, H., Khanna, K., Handa, N., Bhardwaj, R., Rinklebe, J., Ahmad P., 2023. *Boron in plants: Uptake, deficiency and biological potential*. Plant Growth Regulation, 100(2): 267-282. https://doi.org/10.1007/s10725-022-00844-7

Kommineni, V., and Bhandari, A.B., 2024. *Effects of potassium application on growth, yield, and quality of dryland cotton*. Agronomy Journal, 116(6): 3222-3230. https://doi.org/10.1002/agj2.21664?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

Moran, R., 1982. *Formulae for determination of achlorophyllous pigments extracted with N, N-Dimetheylformamide*. Plant Physiology, 69: 1376-1381. https://doi.org/10.1104/pp.69.6.1376

Qin, Y., Feng, W., Zheng, C., Chen, J., Wang, Y., Zhang, L., Nie, T., 2025. *Evaluation of soil quality and balancing of nitrogen application effects in summer direct-seeded cotton fields based on minimum dataset*. Agronomy, 15(8): 1-23. https://doi.org/10.3390/agronomy15081763

Shams, A., Armin, M., Jamimoeini, M., 2025. *Cotton physiological and agronomic response to nutrient systems in different planting methods*. Egyptian Journal of Agronomy, 47(3): 547-556. https://doi.org/10.21608/agro.2024.308718.1480

Snedecor, G.W., and Cochran, W.G., 1980. *Statistical methods, 7th edition*. Iowa State University Press, Ames.

Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., 2020. *Methods of soil analysis, part 3: Chemical methods (Vol. 14)*. John Wiley & Sons.

U.S. Borax, 2025. *Boron applications for improved cotton yields*. Agronomy Note, 5/2025. https://agriculture.borax.com/USBorax/media/assets/agronomy-notes/boron-cotton.pdf?ext=.pdf

USDA, United States Department of Agriculture, 2024. *World Agricultural Production*. Available online: https://apps.fas.usda.gov/psdonline/circulars/production.pdf (accessed on 15 Febraury 2024).

Vera-Maldonado, P., Aquea, F., Reyes-Díaz, M., Cárcamo-Fincheira, P., Soto-Cerda, B., Nunes-Nesi, A., Inostroza-Blancheteau, C., 2024. *Role of boron and its interaction with other elements in plants*. Frontiers in Plant Science, 15, 1332459. doi: 10.3389/fpls.2024.1332459

Wahid, M.A., Saleem, M., Irshad, S., Khan, S., Cheema, M.A., Saleem, M.F., Tung, S.A., 2020. *Foliar feeding of boron improves the productivity of cotton cultivars with enhanced boll retention percentage*. Journal of Plant Nutrition, 43(16): 2411-2424. https://doi.org/10.1080/01904167.2020.1783300?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

Walinga, I., Van Der Lee, J., Houba, V.J., Vanvark, W., Novozamsky, I., 2013. *Plant Analysis Manual*. Springer Science: 1-239.

Waller, R.A., and Duncan, D.B., 1969. *A Bayes Rule for the Symmetric Multiple Comparisons Problems*. Journal of the American Statistical Association, 64: 1484-1503. https://doi.org/10.1080/01621459.1969.10501073

Wright, D., Marois, J., Rich, J., 2003. *Cotton cultural practices and fertility management*. University of Florida, Gainesville, FL, http://edis.ifas.ufl.edu/AG200 (accessed on 20 April 2005).