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RESEARCH ARTICLE

Smart bio-mineral integration to enhance sorghum productivity in gypsiferous soils

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Abstract

This study aimed to evaluate the effects of bacterial biofertilizers (*Azotobacter* and *Bacillus*) integrated with phosphate mineral fertilizer (DAP), while keeping nitrogen fertilizer (urea) constant across all treatments, on the growth and yield of sorghum (*Sorghum bicolor* L.) cultivated in gypsiferous soils in Iraq. This study was conducted in 2025 in a gypsiferous soil region of Iraq, where nutrient limitations particularly nitrogen and phosphorus reduce sorghum productivity. The site conditions reflect the broader challenges facing cereal cultivation in degraded soils. Therefore, the experiment provided a realistic platform to assess the effectiveness of integrating biofertilizers with mineral fertilizers in improving crop performance under such conditions. The field experiment was conducted in a randomized complete block design (RCBD) with ten treatments and three replications. Measurements included plant height, leaf number, chlorophyll content, days to 50 % flowering, 1000-grain weight, grain number per head, grain yield per plant and grain yield per hectare. Results showed that the treatment combining compost with biofertilizer achieved the highest plant height (295.3 cm), chlorophyll content (57.3 SPAD) and grain yield (5.69 t ha^{-1}). It also recorded superior yield components, including the greatest 1000-grain weight and seed number per head, reflecting a marked improvement in both vegetative vigour and reproductive efficiency. The findings suggest that the integration of mineral fertilizer and bacterial inoculants is an effective strategy to improve sorghum productivity in gypsiferous soils, addressing a research gap given the scarcity of such studies under Iraqi conditions.

Keywords: biofertilizer; crop performance; gypsiferous soils; *sorghum bicolor*; yield components

Introduction

Sorghum (*Sorghum bicolor* L.) is a strategic field crop in arid and semi-arid regions due to its high adaptability to harsh environmental conditions such as drought and salinity, in addition to its significant role in food security and livestock feed (1–3). In Iraq, the growing importance of sorghum is attributed to the expanded use of marginal lands that were previously underutilized, alongside the marked decline in the productivity of major traditional crops particularly wheat and barley due to recurrent drought events, elevated soil salinity and severe nutrient depletion. These combined constraints have driven the search for crops with greater tolerance to environmental stresses, making sorghum a strategic option for enhancing agricultural productivity in degraded environments.

Gypsiferous soils cover large areas of agricultural land in Iraq and are characterized by high calcium sulfate ($CaSO_4 \cdot 2H_2O$) content, low organic matter and limited availability of essential nutrients, particularly nitrogen and phosphorus (4–6). These properties inhibit nutrient uptake and reduce plant growth and productivity, posing a major obstacle to sustainable agricultural production. These challenges emphasize the necessity of developing fertilization approaches capable of improving nutrient bioavailability in gypsum-rich environments. Addressing this limitation is crucial for boosting crop productivity and achieving more efficient use of degraded soils.

Phosphate mineral fertilizer (DAP) is widely applied to improve soil fertility and crop growth, but its efficiency in gypsiferous soils is limited due to rapid phosphorus fixation and reduced availability (7–9). Urea was equally applied across all treatments as a uniform nitrogen background, making the effects of DAP and bacterial biofertilizers the primary factors under investigation. Thus, evaluating whether DAP can perform better when combined with biological sources of nutrients represents a central component of the research hypothesis. This approach may offer an alternative pathway to counteract nutrient losses typically observed in gypsum-rich soils.

Biofertilizers, particularly bacterial inoculants such as *Azotobacter* and *Bacillus*, play a crucial role in improving crop growth and productivity by fixing atmospheric nitrogen, solubilizing insoluble phosphorus and producing plant growth regulators. Recent studies have reported that integrating biofertilizers with mineral fertilizers increased grain productivity by 15–25 % in cereal crops, including sorghum (10–13). These potential benefits suggest that microbial inoculants may compensate for the low nutrient efficiency in gypsiferous soils. Accordingly, assessing the interaction between biofertilizers and mineral fertilizers forms a key objective of the current investigation.

Although many studies have examined the effects of mineral fertilizers or biofertilizers individually, research addressing their integration in gypsiferous soils is very limited, particularly under Iraqi conditions (14, 15). Therefore, this study was conducted to fill this research gap by evaluating the impact of combining mineral fertilizer (DAP) with bacterial inoculants (*Azotobacter* and *Bacillus*) on the growth and yield of sorghum cultivated in gypsiferous soils. The main hypothesis of this study is that integrating DAP with microbial inoculants will markedly enhance nutrient availability, vegetative growth and yield compared with using each fertilizer source alone. This hypothesis further assumes that microbial activity can mitigate the nutrient losses typically associated with gypsum-rich soils.

Materials and Methods

The field experiment was conducted during the fall growing season of 2025 at the research field of the Center for Biotechnologies and Environmental Research, University of Fallujah, located in Al-Anbar Province, Fallujah District (33.355° N, 43.783° E), an area characterized by gypsiferous soils. Soil samples (0–30 cm depth) were collected and analyzed for their physico-chemical properties (Table 1). The soil contained 177.4 g kg^{-1} calcium sulfate with a pH of 7.27, electrical conductivity (EC) of 4.42 dS m^{-1}, organic matter of 3.42 g kg^{-1}, available phosphorus of 5.76 mg kg^{-1} and available nitrogen of 32.76 mg kg^{-1}. Soil texture was sandy loam and the irrigation water had an EC of 3.0 dS m^{-1} (Table 2).

The sorghum cultivar "Bahooth 70", approved by the Iraqi Ministry of Agriculture, was used in the experiment due to its suitability to local conditions. The experiment was arranged in a randomized complete block design (RCBD) with three replications. Ten treatments were applied (Table 3), involving different combinations of mineral fertilizer (DAP), bacterial inoculants (*Azotobacter* and *Bacillus*) and compost. DAP was applied at a rate of 120 kg P_2O_5 ha^{-1}. *Azotobacter* and *Bacillus* inoculants were used in this study; *Azotobacter* was applied as a free-living nitrogen fixer supported by the *nif* gene at a concentration of 10^6 CFU g^{-1}, whereas *Bacillus* was applied as an efficient phosphate-solubilizing bacterium at 10^7 CFU g^{-1}. The microbial inoculants were applied using a seed-coating technique at a rate of 10 g inoculant per kg of seed delivering approximately 1×10^8 CFU g^{-1}. Compost was incorporated at rates of 5, 10 and 15 t ha^{-1} and was characterized by 42 % organic matter, a pH of 6.4 and a C:N ratio of 16:1. Urea was equally applied across all treatments as a uniform nitrogen background, making the effects of DAP and bacterial biofertilizers the primary factors under investigation.

Measurements included plant height, leaf number, chlorophyll content (SPAD), days to 50 % anthesis, 1000-grain weight, grain number per head and grain yield per plant and per hectare. Plant height and leaf number were recorded at the late vegetative stage (50 days after sowing). SPAD readings were taken from the uppermost fully expanded leaf, with three readings per leaf and the average of three plants per replicate. Data were analyzed using analysis of variance (ANOVA) and means were compared using the least significant difference (LSD) test at the 5 % probability level.

Table 1. Physicochemical and biological properties of the soil sample (2025)

Parameters	Value	Unit
Gypsum ($CaSO_4 \cdot 2H_2O$)	177.4	g kg^{-1}
Calcium carbonate ($CaCO_3$)	5.86	g kg^{-1}
Clay	125	g kg^{-1}
Silt	223	g kg^{-1}
Sand	652	g kg^{-1}
Electrical conductivity (EC)	4.42	dS m^{-1}
Soil pH	7.27	-
Organic matter (OM)	3.42	mg kg^{-1}
Available phosphorus (P)	5.76	mg kg^{-1}
Available nitrogen (N)	32.76	mg kg^{-1}
Total microorganisms (TM)	3.034	log CFU g^{-1}

Results

Significant differences were observed among the treatments for all vegetative growth traits, including plant height, leaf number, chlorophyll content and days to 50 % anthesis, indicating that the integration of compost and biofertilizers had a substantial influence on sorghum performance under gypsiferous soil conditions (Table 4). Among the treatments, the superior performance of treatment T8 may be due to the stronger role of *Azotobacter* in gypsiferous soils, where its high nitrogen-fixing ability and production of growth-promoting hormones enhance vegetative growth and chlorophyll synthesis. In contrast, the contribution of *Bacillus* through phosphorus solubilization is comparatively less influential under nitrogen-limited conditions. This likely explains why T8 achieved the tallest plants, highest chlorophyll content and earliest anthesis. These results highlight the capacity of *Azotobacter* to enhance nutrient uptake and photosynthetic activity, thereby accelerating the transition from vegetative to reproductive stages.

By contrast, the control treatment (T1) exhibited the weakest growth, with the lowest plant height (224.3 cm), minimum chlorophyll content (44.30 SPAD) and the latest anthesis (78.3 days), reflecting the severe nutrient limitations of gypsiferous soils when left unfertilized. Intermediate responses were recorded in treatments such as T6 and T7, which improved chlorophyll levels (54.54 and 55.29 SPAD respectively) and leaf number compared to the control, though they were still inferior to T8. Interestingly, while T10 produced the highest leaf number (16 leaves per plant), this did not translate into superior plant height or chlorophyll content, suggesting that leaf proliferation alone was insufficient to maximize photosynthetic efficiency without balanced nutrient dynamics.

Overall, the results emphasize that the combined application of compost and *Azotobacter*-rich biofertilizer (T8) not only promoted more robust vegetative growth but also shortened the time to anthesis, which is advantageous in stress-prone environments like gypsiferous soils, where early flowering can secure yield before the onset of severe water or nutrient stress. This finding confirms the pivotal role of microbial inoculants in improving crop adaptation and growth performance under marginal soil conditions.

Table 2. Physico-chemical properties of irrigation water samples (2025)

Sample name	Texture	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	Gypsum (%)	NaCl (%)	TDS (mg/ L)	pH	EC (dS m^{-1})
EXP Site	Sandy loam	17.3	24.8	57.8	18.3	4.0	19.0	1019.7	2.03	3.0

Table 3. Experimental treatments for sorghum under gypsiferous soils

Treatment	Description
T1	Control (no fertilizer)
T2	Compost 100 %
T3	50 % *Azotobacter* + 50 % *Bacillus*
T4	Compost 25 % + Bio 75 % (50 % *Azotobacter* + 50 % *Bacillus*)
T5	Compost 75 % + Bio 25 % (50 % *Azotobacter* + 50 % *Bacillus*)
T6	Compost 25 % + Bio 75 % (25 % *Azotobacter* + 75 % *Bacillus*)
T7	Compost 75 % + Bio 25 % (25 % *Azotobacter* + 75 % *Bacillus*)
T8	Compost 25 % + Bio 75 % (75 % *Azotobacter*)
T9	Compost 75 % + Bio 25 % (75 % *Azotobacter* + 25 % *Bacillus*)
T10	Compost 50 % + Bio 50 % (75 % *Azotobacter* + 25 % *Bacillus*)

Table 4. Effect of fertilization treatments on vegetative traits of sorghum under gypsiferous soil conditions

Treatment	Plant height (cm plant^{-1})	Leaf number per plant	Days to 50 % anthesis	Leaf chlorophyll content (SPAD)
T1	224.3	10.33	78.33	44.30
T2	269	12	77	45.99
T3	248.7	13	72	46.05
T4	271.3	14	69.67	43.27
T5	277.3	13	71	45.40
T6	269	16.33	76	54.54
T7	257.7	14.67	70.67	55.29
T8	295.3	14	66	57.31
T9	256.7	13	73	55.95
T10	277.3	16	72.67	55.21
LSD 5 %	14.5	2.00	5.51	1.57

As shown in Table 5, significant differences were observed among treatments for yield and its components. Treatment T8 (25 % compost + 75 % biofertilizer with 75 % *Azotobacter*) recorded the highest values across all traits, including 1000-grain weight (38.67 g), grain number per head (2894), grain yield per plant (106.8 g plant^{-1}) and grain yield per hectare (5.69 t ha^{-1}). This superiority can be explained by the dual effect of compost in improving soil structure and water retention and *Azotobacter* in enhancing nitrogen fixation, phosphorus solubilization and phytohormone production, which together stimulated better grain filling and higher reproductive efficiency.

In contrast, the control treatment (T1) showed the lowest performance (grain yield 3.57 t ha^{-1}), reflecting the severe nutrient limitations of gypsiferous soils. Intermediate results were obtained in treatments such as T6 and T7, which improved yield components compared to the control but remained below T8, suggesting that *Bacillus* also contributed through phosphorus solubilization, though less effectively than *Azotobacter*.

Overall, the results confirm that the integration of compost with *Azotobacter*-rich biofertilizer provided the best nutritional balance, leading to increased kernel weight, higher seed number and improved total yield. This highlights the importance of microbial inoculants in maximizing sorghum productivity under marginal soil conditions.

Discussion

The results indicated that T8 produced the best vegetative growth response. This can be attributed to the role of *Azotobacter* and *Bacillus* in enhancing nitrogen and phosphorus uptake, as well as producing growth regulators such as auxins and gibberellins, which stimulated physiological growth and increased photosynthetic efficiency (16–18). These findings are consistent with an earlier study that reported significant improvements in cereals following bacterial inoculation (19).

Treatment T8 also excelled in all yield components. This improvement can be attributed to the nutritional balance achieved through the integration of DAP with bacterial inoculants, which enhanced phosphorus availability and nitrogen fixation, positively affecting grain development and yield (20, 21). Similar results in maize, supporting our findings.

The findings of this study are consistent with research published in various scientific journals, which emphasized that integrating biofertilizers with mineral fertilizers enhanced nutrient use efficiency and crop productivity in marginal soils (22, 23). Other studies also confirmed that combining compost and bacterial inoculants improved wheat and maize yields by 18–25 % compared to mineral fertilizers alone (24, 25).

Table 5. Effect of fertilization treatments on yield components and grain yield of sorghum under gypsiferous soil conditions

Treatment	1000-grain weight (g)	Seed number per head	Grain yield per plant (g plant^{-1})	Grain yield per hectare (t ha^{-1})
T1	26	2242	67	3.57
T2	31	2563	83.5	4.45
T3	32	2592	87.4	4.66
T4	29.67	2447	77.1	4.11
T5	31	2583	81.5	4.35
T6	31	2600	86.8	4.63
T7	32	2641	87.3	4.66
T8	38.67	2894	106.8	5.69
T9	35.67	2850	104.4	5.57
T10	32.67	2752	93.7	5.00
LSD 5 %	4.57	250.5	17.26	0.92

This study is among the first to investigate the integration of DAP and bacterial inoculants in gypsiferous soils under Iraqi conditions. Most previous studies focused on normal or saline soils, while research on gypsiferous soils remains limited. Thus, our findings fill an important knowledge gap and provide a scientific basis for sustainable sorghum fertilization in marginal soils.

Conclusion

The integration of DAP with bacterial inoculants (*Azotobacter* and *Bacillus*) proved more effective than using either alone in enhancing the growth and yield of sorghum in gypsiferous soils. Treatment T8 achieved the highest plant height, chlorophyll content and grain yield (5.69 t ha^{-1}). Incorporating biofertilizers with mineral fertilizers is recommended as a sustainable strategy for integrated nutrient management programmes to improve sorghum productivity in Iraq's marginal lands.

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Authors' contributions

NAM conceptualized the study, designed the experimental framework and supervised the research work. EJA conducted the experiments and prepared the first draft of the manuscript. SKK and MSH contributed to data collection, laboratory analyses, statistical analysis and interpretation of results. JSE reviewed and scientifically edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that there are no conflicts of interest regarding the publication of this research and that all procedures were carried out in accordance with academic integrity and ethical standards.

Ethical issue: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to refine limited sentence structures. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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