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RESEARCH ARTICLE

Synergistic organic-bio-mineral fertilization as a breakthrough strategy to maximize maize productivity in gypsiferous soils

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Abstract

Gypsiferous soils are characterized by low nutrient availability and structural limitations that often restrict crop productivity. Therefore, developing integrated nutrient-management strategies is essential to enhance plant performance under such challenging conditions. This study evaluated the efficiency of integrated fertilization with compost, biofertilizers and diammonium phosphate (DAP) in improving the growth and yield of maize (*Zea mays* L.) grown in gypsiferous soils under sprinkler irrigation. The field experiment was conducted during the 2024 growing season, using a randomized complete block design (RCBD) with 10 treatments (T_1–T_{10}) and 3 replications. Results showed that the integrated treatment combining compost, biofertilizers and DAP (T_4) produced the tallest plants (163.4 cm), the largest flag leaf area (493.8 cm^2) and the earliest flowering (55 days to 50 % male anthesis) compared with the control (128.9 cm, 404.3 cm^2 and 59.3 days, respectively). Moreover, this treatment recorded the highest yield components: 17.33 rows per cob, 195.5 g grain yield per plant and a total yield of 10.43 t ha^{-1}, whereas the control recorded 14.33 rows per cob, 115.6 g per plant and 6.16 t ha^{-1}. These findings confirm that integrating compost and biofertilizers with DAP represents a sustainable and efficient strategy to improve maize productivity in saline -gypsiferous soils under sprinkler irrigation.

Keywords: biofertilizers; compost; DAP; gypsiferous soils; maize; sprinkler irrigation

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide due to its critical role in food security, livestock feed and the food and oil industries, covering more than 190 million hectares globally (1). Notwithstanding the worldwide increase in maize production, growing maize in arid and semi-arid regions remains constrained by several factors. These include soil and water salinity and low soil fertility, particularly in gypsiferous soils. Gypsiferous soils-characterized by high gypsum ($CaSO_4 \cdot 2H_2O$) content are extensively distributed across Iraq and severely limit nutrient availability and root development (2, 3). Soil gypsum is a multifaceted medium, not only because of its physical properties (e.g., poor structure, low organic matter levels and high susceptibility to compaction), but also because of soil salinity and sulfated status. These limitations are associated with crop growth and reduce water-use efficiency and nutrient utilization (4, 5). Recent literature highlights that the sustainable management of these soils involves integrated systems that combine mineral, organic and biological fertilizer applications to ensure both soil fertility and productivity (6).

As an essential phosphate fertilizer in intensive farming systems, diammonium phosphate (DAP) can supply phosphorus (P) for root growth and energy formation and enhance nitrogen (N) use efficiency (7). Nonetheless, in gypsiferous soils, the efficacy of DAP is frequently compromised by increased phosphate precipitation and decreased availability, which hinders plant uptake (8). Thus, combining DAP with organic materials, such as compost and biofertilizers, has been a viable way to alleviate these constraints (9). Compost improves soil fertility by increasing organic matter, enhancing cation exchange capacity (CEC), improving aeration and water retention and mitigating salinity impacts by stimulating microbial activity (10, 11). Biofertilizers such as *Azotobacter* and *Bacillus* fix atmospheric N, release organic acids that solubilize unavailable phosphates and produce phytohormones, all of which stimulate growth and improve plant tolerance to environmental stresses (12, 13). However, despite these advantages, gypsiferous soils remain severely constrained by low nutrient availability and weak soil structure, which continue to limit maize productivity under sprinkler irrigation systems. A recent study has emphasized that integrating organic and bio-mineral amendments is essential to overcome these persistent limitations and sustain crop growth under arid conditions (14).

Field studies in Iraq have shown that integrating organic, biological and mineral fertilizers improves maize growth and yield under saline and heat-stress conditions (15). Other studies have reported that integrated fertilization under sprinkler or drip irrigation enhances water and nutrient use efficiency and significantly increases productivity compared with sole reliance on chemical fertilizers (16). Recent investigations on vermicompost have revealed its richness in essential nutrients and trace elements and its ability to improve soil physical and chemical properties while mitigating salinity stress (17). Vermicompost application has been shown to significantly enhance maize growth and yield in gypsiferous soil under sprinkler irrigation (17). Against this background, the present experiment was conducted to test the integrative effects of compost and biofertilizers along with DAP on the growth and yield attributes of maize grown in gypsiferous soil under sprinkler irrigation (18). These findings are expected to provide a scientific foundation for developing sustainable fertilization strategies for saline gypsiferous soils in Iraq.

Materials and Methods

Experimental site

The field experiment was conducted during the 2024 growing season at the Agricultural Field of the Center for Biotechnologies and Environmental Research, University of Fallujah (≈33.355° N, 43.783° E), a site characterized by gypsiferous soils with moderate to high salinity and a dry climate with hot summers (≈43 °C), cold winters (≈5 °C) and low seasonal rainfall.

Soil characteristics

Pre-sowing soil samples (0–30 cm) revealed a sandy loam texture, with 65 % sand, 23 % silt and 12 % clay. The soil had an electrical conductivity (EC) of 4.32 dS m^{-1}, pH of 7.21 and low organic matter content. Additional soil chemical and biological characteristics are presented in Table 1. Irrigation water applied via sprinkler irrigation had an EC of 3.0 dS m^{-1} and its chemical composition is presented in Table 2.

Experimental design

The experiment was laid out in an randomized complete block design (RCBD) with 10 treatments (T_1–T_{10}) and 3 replications. Each plot measured 6 m^2 and was planted with the maize cultivar "Baghdad" at 75 × 20 cm spacing, corresponding to a planting density of 66666 plants ha^{-1}.

Treatments

The list of treatments and their combinations of compost and biofertilizers (*Azotobacter* and *Bacillus*) is summarized in Table 3.

Table 1. Physicochemical and biological properties of the soil sample

Parameter	Value	Unit
Gypsum	180.6	g kg^{-1}
Lime	5.43	g kg^{-1}
Clay	120	g kg^{-1}
Silt	230	g kg^{-1}
Sand	650	g kg^{-1}
EC	4.32	dS m^{-11}
pH	7.61	-
Organic Matter	3.31	g kg^{-1}
Phosphorus	5.4	mg kg^{-1}
Nitrogen	30.5	mg kg^{-1}
Total Microorganisms	3.023	Log CFU g^{-1}

Table 3. Description of organic-bio fertilizer integration treatments applied in the experiment

No	TREAT
T_1	Control
T_2	Compost 100 %
T_3	Bio 100 % (50 % *Azotobacter* + 50 % *Bacillus*)
T_4	Compost 25 % + Bio 75% (50 % *Azotobacter* + 50 % *Bacillus*)
T_5	Compost 75 % + Bio 25% (50 % *Azotobacter* + 50 % *Bacillus*)
T_6	Compost 75 % + Bio 25 % (25 % *Azotobacter* + 75 % *Bacillus*)
T_7	Compost 25 % + Bio 75 % (75 % *Azotobacter* + 75 % *Bacillus*)
T_8	Compost 75 % + Bio 75 % (75 % *Azotobacter*)
T_9	Compost 75 % + Bio 25 % (75 % *Azotobacter* + 25 % *Bacillus*)
T_{10}	Compost 75 % + Bio 75 % (40 % *Azotobacter* + 60 % *Bacillus*)

Compost was applied at a rate of 5 g $plant^{-1}$, while biofertilizers were inoculated at 15 mL $plant^{-1}$, containing *Azotobacter* and *Bacillus* strains. Mineral fertilizer included DAP (225 g m^{-2}) and urea (46 % N), which were applied in three split doses at sowing, the 6–8 leaf stage and pre-tasseling.

Data collection

Growth traits measured were plant height, number of leaves, flag leaf area and days to 50 % flowering, whereas yield traits included number of rows per cob, number of grains per row, 500-grain weight, grain yield per plant and total grain yield (t ha^{-1}).

Statistical analysis

Data normality was tested using the Shapiro-Wilk test and variance homogeneity was examined before performing the two-way ANOVA. Statistical analyses were carried out using GenStat software and treatment means were compared using the LSD test at the 5 % significance level (19–24).

Results and Discussion

Table 4 shows significant variation among fertilization treatments for plant height, leaf number and flag leaf area. The integrated fertilization treatment (T4: DAP + Compost + Biofertilizer) yielded the highest plant height (163.4 cm), which was markedly higher than the control (128.9 cm). This superiority can be attributed to the complementary roles of the applied inputs: compost enriched the soil with organic matter and improved its structure, thereby enhancing water retention and mitigating the adverse effects of salinity; biofertilizers such as *Azotobacter* and *Bacillus* contributed by solubilizing insoluble phosphates and producing phytohormones (auxins and gibberellins), which promoted root branching and nutrient uptake; while DAP supplied readily available P and N, which are fundamental for cell division and vegetative growth (6, 25). Collectively, these interactions created a favorable rhizosphere environment that supported stronger shoot development.

In addition, integrated fertilization significantly increased leaf number and flag leaf area, with leaf number rising by 24.9 % and flag leaf area by 22.2 % compared with the control. The largest flag leaf area (493.8 cm^2) was observed under T_4, compared with 404.3 cm^2 in the control, reflecting an expanded photosynthetic surface and, by inference, a higher carbon assimilation potential. Compost is known to enhance aeration and microbial activity,

Table 2. Physicochemical properties of irrigation water samples (2025)

Sample Name	Texture	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	Gypsum (%)	NaCl (%)	TDS (mg/L)	pH	EC (dS/m)
EXP Site	Sandy Loam	17.3	24.8	57.9	18.3	4.0	19.0	1019.7	7.4	9.0

Table 4. Vegetative growth traits of maize

TREAT	Plant height (cm)	Number of leaves per plant	Flag Leaf Area (cm^2)	Number of days to 50 % male flowering	Number of days to 50 % female flowering	Main Ear Height (cm)
T_1	128.9	10.67	404.3	59.33	70	51.42
T_2	151.0	12.33	469.8	57.00	66.33	64.34
T_3	156.1	13.00	468.3	56.33	66.00	60.80
T_4	163.4	13.33	493.8	55.00	64.67	67.12
T_5	142.4	12.67	476.8	56.00	65.67	55.84
T_6	161.1	12.67	472.8	55.67	66.00	63.27
T_7	155.0	12.33	477.5	54.33	64.67	60.42
T_8	151.1	13.33	446.1	56.33	66.00	63.59
T_9	138.3	12.33	450.8	56.67	67.00	62.15
T_{10}	144.6	12.67	460.2	56.67	68.33	58.88
LSD 5 %	17.67	1.11	35.97	2.162	2.304	6.08

which may contribute to improve leaf development. In contrast, biofertilizers contributed through N fixation and phytohormone secretion, both of which stimulated leaf expansion. Moreover, integrated fertilization shortened the time to 50 % flowering, with T_4 reaching anthesis in 55 days compared with 59.3 days in the control, indicating a more efficient source-sink relationship and improved physiological maturity due to balanced nutrient availability (26).

The results in Table 5 clearly demonstrated the positive impact of integrated fertilization on cob formation and grain filling in maize (27, 28). The number of rows per cob increased significantly from 14.3 in the control (T_1) to 17.3 in the integrated treatment (T_4). This improvement can be attributed to enhanced P availability, as P plays a central role in reproductive development and kernel set. Similarly, the weight of 500 grains increased from 126.03g in T_1 to 120.1 g in T_4, reflecting more efficient assimilate partitioning and suggesting improved grain filling under integrated management. Grain yield per plant also significantly increased from 115.6 g in the control to 195.5 g in T_4, leading to a total grain yield of 10.43 t ha^{-1}, compared with the control (6.16 t ha^{-1}). These results emphasize the value of dynamic nutrient management, in that DAP served as a readily available source of P, compost improved CEC and decreased P fixation and biofertilizers maintained active emergent microbial populations (29, 30) all of which positively influenced nutrient flow.

The observed improvement in growth and yield can be attributed to the synergistic effects of compost and biofertilizers, which enhance soil structure, increase nutrient availability and promote root physiological activity. Compost improves soil aeration and moisture retention, while biofertilizers accelerate nutrient mineralization and stimulate phytohormone production, collectively strengthening plant tolerance under saline-gypsiferous conditions. These mechanisms scientifically justify the recorded increases in maize performance and support the integrative fertilization approach as an effective strategy for improving crop productivity in challenging environments.

Besides nutrient supply, the beneficial impact may be attributed to enhanced soil-plant interactions under gypsiferous and salinized conditions. Compost was beneficial in decreasing soil pH and increasing CEC, alleviating sodicity and increasing the availability of calcium (Ca) and magnesium (Mg). Biofertilizers capable of producing exopolysaccharides may help mitigate Na^+ toxicity by promoting a more balanced ionic environment in gypsiferous soils. These processes, together, resulted in improved photosynthetic efficiency and better grain filling under stress (31).

Altogether, the study inferred that combined fertilization (DAP + Compost + Biofertilizer) exerted synergistic effects compared with sole nutrient sources. Diammonium phosphate (DAP) provided these nutrients at hand at the beginning, but compost and biofertilizers likely improved soil health and enhanced microbial activity, thereby sustaining fertility and productivity. This favourable association is likely responsible for the better growth, flowering precocity and yield of the maize crop under sprinkler irrigation in gypsiferous soils when integrated soil management is applied (32).

The highest plants (163.4 cm), the greatest flag leaf surface and the highest yield in grain (10.43 t ha^{-1} compared to 6.16 t ha^{-1} in the control) were achieved with combined treatment (T_4), which confirmed a higher effectiveness of plant nutrition combination over separate inputs. This benefit could be attributed to the synergetic contribution of composted enriched organic matter + enhanced water holding capacity and CEC + improved soil structure, biofertilizers (*Azotobacter* and *Bacillus*) + increased microbial activity modulating N fixation, solubilization of phosphate as well as phytohormone production stimulating root length and nutrient uptake, DAP supplying available P and N prerequisite for vegetative growth and reproductive organs. Together, these mechanisms may have helped alleviate salinity stress by supporting better ionic balance, without direct evidence of changes in Ca^{2+}, Mg^{2+} uptake, or Na^+ accumulation, which, in turn, supported higher photosynthetic efficiency, assimilate partitioning and grain filling. Therefore, integrated fertilization offers a scientifically validated and sustainable strategy to maximize maize productivity while improving soil health in stress-prone environments (33).

Table 5. Yield components and the yield of maize

TREAT	Number of rows per ear	Number of grains per row	Weight of 500 seeds (g)	Yield per plant (g)	Total Yield (t ha^{-1})
T_1	14.33	34.33	126.03	115.6	6.16
T_2	15.00	36.33	118.25	177.9	9.49
T_3	14.67	35.67	110.62	189.3	10.09
T_4	17.33	36.33	120.10	195.5	10.43
T_5	15.33	37.00	116.37	191.3	10.20
T_6	16.00	35.67	121.22	173.2	9.24
T_7	16.00	35.67	116.80	184.2	9.82
T_8	16.33	37.33	105.93	188.2	10.04
T_9	15.67	36.33	119.90	166.8	8.89
T_{10}	16.00	36.67	114.58	182.9	9.75
LSD 5 %	1.4	N.S	9.36	17.67	0.94

The inclusion of compost not only enhances crop productivity but also contributes to long-term soil sustainability by increasing organic matter and stimulating beneficial microbial activity. Expanding the use of biofertilizers and tailoring them to local microbial strains is essential to maximize their efficiency under Iraqi environmental conditions. Furthermore, future research should focus on integrating these practices with advanced approaches, such as foliar nutrition and nanofertilizers, which hold strong potential to improve nutrient use efficiency and maize resilience under saline stress (34).

Conclusion

The results of this study clearly demonstrated that integrating compost, biofertilizers and DAP produced significantly superior vegetative growth and yield traits of *Zea mays* compared to single nutrient sources. The combined treatment (T_4) consistently produced the tallest plants, the largest flag leaf area and the earliest flowering, indicating enhanced physiological efficiency under gypsiferous soil conditions. Yield attributes, such as number of rows per cob, 500-grain weight and grain yield per plant, also reached their highest values under integrated fertilization, resulting in a remarkable total yield of 10.43 t ha^{-1}, compared with 6.16 t ha^{-1} in the control. These improvements reflect the synergistic benefits of organic matter enrichment, improved nutrient solubility, microbial activation and better ionic balance under salinity stress. The findings confirm that integrated fertilization is more effective than applying mineral fertilizers alone. Therefore, this approach provides a sustainable and scientifically validated strategy for enhancing maize productivity and soil health in saline-gypsiferous environments. Further optimization of biofertilizer formulations and nutrient ratios is recommended to maximize long-term productivity.

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Authors' contributions

EJA and NAM designed the experiment and supervised the research. MSH conducted the field and laboratory experiments and collected the data, while SKK performed the statistical analysis and contributed to data interpretation. EJA and MSH drafted the initial version of the manuscript and NAM critically revised the manuscript and made important intellectual revisions. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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