

Sustainable Management of Saline Soils Using Organic and Inorganic Amendments for Better Growth and Development of Wheat (*Triticum aestivum*) Plants

Waseem Hassan^{1*}, Saba Saleem², Muhammad Adil³, Muhammad Adnan Bukhari⁴, Amna Munir Leghari⁵, Muhammad Athar Khaliq², Zubair Aslam⁶, Safdar Bashir^{2,7*}

¹Department of Soil and Environmental Sciences, MNS-UAM, Pakistan

²Department of Soil and Environmental Sciences, Ghazi University, Dera Ghazi Khan, Pakistan

³College of Environmental Science and Engineering, Yangzhou University, Yangzhou, 225217, China

⁴Department of Agronomy, The Islamia University of Bahawalpur, Pakistan

⁵Department of Horticulture, University of Sargodha, Pakistan

⁶Department of Agronomy, University of Agriculture Faisalabad, Pakistan

⁷Department of Soil and Water Systems, University of Idaho, Moscow 83844, ID, United States of America

*Correspondence: sbashir@uidaho.edu (S.B); waseem.hassan@mnsuam.edu.pk (W.H)

ABSTRACT

Globally, salinity of soil has been experienced on almost one billion hectares of land, resulting in a major challenge on growth of plant and agricultural yields. To enhance crop performance and restore saline soils, integrated agronomic methods, sustainable management practices, and soil remediation strategies are essential. A study was carried out in a completely randomized design (CRD) with the objective to determine the effect of a combination of bentonite, compost, and gypsum on the yield of wheat, in addition to the rehabilitation of salinized soil. Overall, five treatments with three replications, viz., T0 (control), T1 (recommended N, P, and K fertilizer), T2 (94% compost + 1% gypsum + 5% bentonite), T3 (75% compost + 3% gypsum + 5% bentonite), and T4 (50% compost + 5% gypsum + 5% bentonite), were used. In comparison to the control and NPK treatments, the T4 showed the greatest improvement in wheat crop growth metrics, including plant biomass (56%), number of leaves (26%), plant height (61%), leaf length (48%), leaf width (21%), root length (47%), and shoot length (58%). Meanwhile, T3 increased spike length (82%), spikelets (46%), and 1000-grain weight (82%). Under saline circumstances, compost containing gypsum and bentonite significantly enhanced soil physiochemical characteristics, crop production, and chlorophyll content.

Keywords: Salinity, Bentonite, Compost, Gypsum, Wheat

1. INTRODUCTION

One of the most urgent issues with the sustainability of agriculture in Pakistan is the soil salinity, which has been caused by centuries of irrigating with canals and poor-quality damage to the soil, which leads to the deposition of soluble salts in the soil profile of the Indus Basin Irrigation System. In Pakistan, salinity and sodicity cover about 6.3 million hectares of land,

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which is nearly 20 percent of the total irrigated land, which seriously limits the yield of major crops including wheat (Qadir et al., 2006).

Saline soils change soil physical, chemical, and biological characteristics, decrease the soil permeability, nutrients, and microbial activity, and hamper the root elongation, leaf area extension, and photosynthesis of crops (Qadir et al. 2017). This degradation does not merely hinder the growth of the plants, but it is also a threat to the food security in salt-infested parts of Punjab and Sindh.

Salinity in the wheat-based cropping systems of Pakistan decreases the rate of germination, the number of tillers, and the weight of 1000 grains by 40-60 percent, mostly attributed to the osmotic stress, ionic toxicity, and nutrient imbalances (Saqib et al. 2017). The management of these saline soils must be sustainable, and this is only achievable through a combination of organic and inorganic soil amendments that will restore the degraded land and

recover the soil fertility. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is the most popular and efficient source of calcium, and it substitutes the sodium ions in the soil exchange complex and enhances the soil structure and permeability (Laghari et al. 2025). Calcium contained in the gypsum softens scattered clay particles, hence enhancing the rate of infiltration and decreasing surface crusting. Application of gypsum in salty soils of Sindh and southern Punjab has been known to boost the yield of wheat, length of spikes, and biomass accumulation.

Bentonite is a montmorillonite-based (high) clay mineral which is of interest in recent years as amendment mineral due to its capacity to expand water retention in the soil and its capacity to exchange cations. This phenomenon of swelling and shrinking enables the soil to be in a position to absorb moisture over long durations, which is most helpful in the development of wheat under salty environment where water stress is worsened by osmotic imbalances. Research has shown that the use of bentonite lowers the percentage of exchangeable sodium and enhances the availability of nutrients, especially potassium and magnesium that are vital to enzymatic activity and grain filling (Qadir et al. 2007). Bentonite is used in the arid areas of Pakistan where rainfall is not constant; this aids in keeping the soil moist around the rhizosphere to enhance root length, height of the shoot, and development of spikelets.

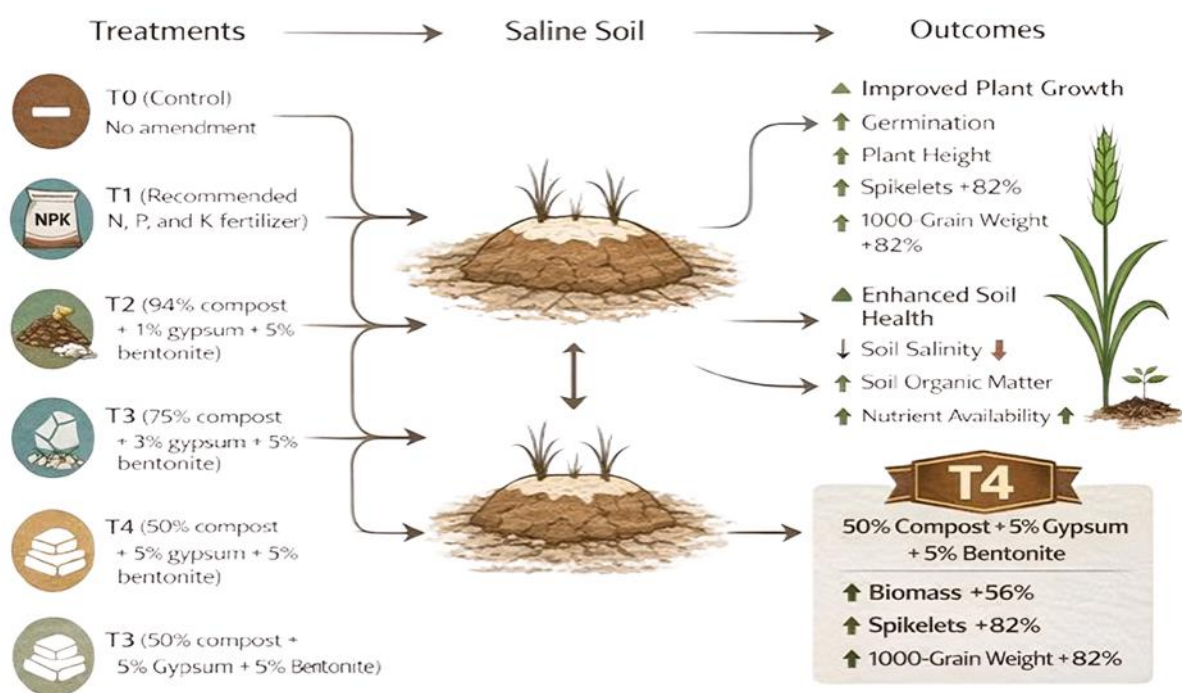
Complementary benefits are the organic amendments, including compost of kitchen waste, farmyard manure, or crop residues, which benefit soil biological activity and organic carbon. Compost serves as a source of macro- and micronutrients and increases the soil aggregation as well as the population of microorganisms, which are critical to nutrient cycling and soil resilience (Farooq et al. 2018). Compost and biogas slurry have been found to enhance the carbon and enzymatic activity of microorganism growth in saline soils (Faisalabad and Multan) and, consequently, enhance the soil structure and porosity (Tabbassum et al. 2022). In addition, the application of compost reduces the harmful impact of sodium due to the complexation of ions using humic compounds and buffering of variations in pH.

Sustainable management practices involving the combination of organic and inorganic amendments show synergistic impacts on enhancing saline-sodic soils. A study with rice-wheat rotations conducted in Punjab revealed that the exploitation of the gypsum in combination with organic matter (biogas slurry/compost) had a vital impact on reducing soil pH

and electrical conductivity and enhancing water infiltration and crop production (Saqib et al. 2017). On the same note, Sindh studies have indicated that the addition of wheat straw and gypsum enhanced the soil organic matter, which is water stable.

Key variables of soil health aggregates and mean weight diameter (Laghari et al. 2025). These changes in soil structure are directly converted into an increase in plant physiological performance, including leaf area index, spike length, and 1000-grain weight, which are key indicators of wheat productivity.

The other aspect of utilizing organic-inorganic amendment mixes is also very important in environmental sustainability. Oversupply of chemical fertilizer will only intensify the problem of soil degradation and decline in the microbial diversity, but organic amendments will reshape waste into long-term fertility of the soil (Khan et al. 2025). The incorporation of gypsum, bentonite, and compost does not only help in alleviating the sodicity problem in soils but also helps in converting the waste in a circular manner into a productive input that helps ensure food security under the harsh conditions. As salinity in the Pakistani irrigated land is increasingly posing a challenge in Pakistan, particularly in Sindh and South Punjab, there is a need to embrace the adaptive approach of managing the soils so as to ensure immediate yield as well as long-term sustainability. The compost, gypsum, and bentonite mix will provide a viable, environmentally sustainable, and affordable remedy to repair salty soils and improve the performance of wheat. The purpose of the current study is to determine the sustainability of saline soils in Pakistan by using the combined application of organic (compost created by waste products in the kitchen) and inorganic (gypsum and bentonite) amendments. In particular, it aims at evaluating their respective and synergistic impact on soil physicochemical and biological characteristics and their consequent impact on the growth parameters, i.e., plant biomass, number of leaves, plant height, leaf length, leaf width, root length, shoot length, spike length, spikelets, and 1000-grain weight of wheat. The hypothesis of the study was that the joint usage of compost, gypsum, and bentonite will raise the physical, chemical, and biological properties of soils as well as the improved soil conditions in Pakistan. Moreover, the combined amendment strategy will guarantee the reclamation of salty soils in a sustainable manner and bring to the table long-term agricultural sustainability. The schematic illustration for the complete investigation is given below in figure.



Sustainable management of saline soils and wheat growth using organic and inorganic amendments.

MATERIAL AND METHODS

Experimental Site

The pot experiment was conducted at the Research Area of the Department of Soil and Environmental Sciences, Ghazi University, Dera Ghazi Khan, Pakistan, during the Rabi season of 2022–2023. Soil

was collected from a farm in the Choti Zareen Zone, Dera Ghazi Khan. Table 1 shows the physicochemical qualities of the soil that was used in this study. The bentonite, gypsum and compost amendments used in the experiment were bentonite, gypsum and compost the chemical compositions of which are shown in Table 2.

Table 1. Physiochemical Properties of soil investigated in this study

Texture	pH	EC (dS m ⁻¹)	OM (%)	P(mg Kg ⁻¹)	K (mg Kg ⁻¹)	Required Gypsum (6’’depth) (Ton/acre)
Loam	8.59	21.11	0.21	4.49	97	0.68

Table 2. Chemical composition of compost and bentonite

Nutrient	Total N %	CaO %	Total P ₂ O ₅ %	MgO %	Total K ₂ O %
Compost	1.64%	ND	1.10%	ND	1.10%
Bentonite	0.60%	0.59%	ND	2.16%	1.10%

*Not Detected (ND)

Compost Preparation

Shredded newspaper and kitchen waste, such as vegetable waste and eggshells, were used to make compost. To eliminate smell, green materials such as leaves were added (Figure 2a). It was kept in a sunny position with holes of air flowing at the bottom and

sides of the compost bin. Continuous stirring of the pile was done to enhance its decomposition rate (Figure 2b). The compost should not to be too dry, and too wet, water can be added when necessary. After a few weeks or months, the compost will be dark, crumbly, and ready to use (Figure 2c).

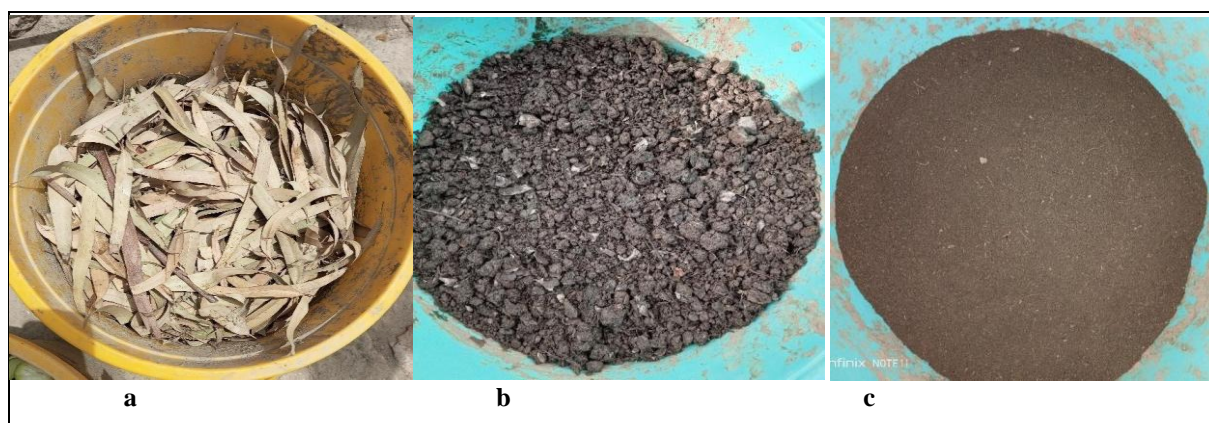


Fig. 2 Compost preparation process step by step

Experimental Setup and Amendments

The experiment was carried out in plastic pots (25 × 30 cm) provided with drainage holes at the bottom. Each pot was filled with 10 kg of saline loam soil. The study was arranged in a Completely Randomized Design (CRD) consisting of five treatments with three replications per treatment. The wheat variety Fakhare-Bakhar was sown at a rate of ten seeds per pot. Soil

amendments were applied 10 days prior to sowing according to soil weight, as presented in Table 3. A total of 5 g of the amendment mixture (0.05% of soil weight) was added to each pot and thoroughly mixed with the soil. NPK fertilizer was applied at sowing at a rate of 100:50:50 kg ha⁻¹ (N: P: K). Irrigation was carried out every three days to maintain adequate soil moisture throughout the experimental period.

Table 3. Description of experimental treatments

Treatment	Description
T ₀	Control (no amendments)
T ₁	NPK fertilizer only (100:50:50 kg ha ⁻¹ of N:P:K)
T ₂	94% compost + 1% gypsum + 5% bentonite
T ₃	75% compost + 3% gypsum + 5% bentonite
T ₄	50% compost + 5% gypsum + 5% bentonite

Analysis of Soil Properties

Following harvesting of the wheat, samples were taken on soil in each pot and analyzed. The soil texture was measured by using the hydrometer method and the pH and electric conductivity (EC) were measured following the standard procedures. Chemical methods were used to estimate available phosphorus (P) and potassium (K) and determine the content of organic matter (OM) based on standard procedures (Hassan et al., 2022a; Hassan and David, 2018). The standard guidelines were used to determine the Gypsum Requirement (GR) and Sodium Adsorption Ratio (SAR), which is used to determine the salinity and amendment requirements of the soil.

Plant Analysis

The harvest of wheat plants, their drying and nutrient analysis as well as agronomic characteristics were

examined. The concentration of potassium (K) was measured with the help of a flame photometer, nitrogen (N) was measured by using the digestion and titration techniques (Hassan et al., 2025). During the vegetative period, the content of chlorophyll was counted. The most important agronomic parameters such as plant biomass, the number of leaves, plant height, length and width of the leaves, root, and shoot length, spike length, the number of spikelets, and 1000-gram weight of the plant were determined in accordance with the conventional methods (Hassan et al., 2025).

Statistical Analysis

Data were analyzed by the use of SPSS version 26. The Shapiro-Wilk test was used to examine the data normality and Levene test was used to determine the homogeneity of variances. One-way ANOVA was

used to determine the treatment differences and then the Least Significant Difference (LSD) test was done at a significance level of 0.05. Microsoft Excel was used to calculate descriptive statistics in the form of mean, standard deviation. Three replications were done in every treatment and the results are represented in terms of mean plus standard deviation. Pearson correlation was conducted to test the relationship between each of the wheat growth parameters and the influence of organic and inorganic amendments.

RESULTS

Seed Germination

Soil amendments greatly increased germination rates in saline conditions ($P < 0.05$), as depicted in Figure 1 (a and b). T4 had the highest improvement at 26%, followed by T3 at 21% compared to the control. T1 and T2 also boosted germination rates, but to a lesser extent. The combination of bentonite, gypsum, and compost was the most effective under saline conditions, while the recommended NPK amendment did not significantly impact crop growth.

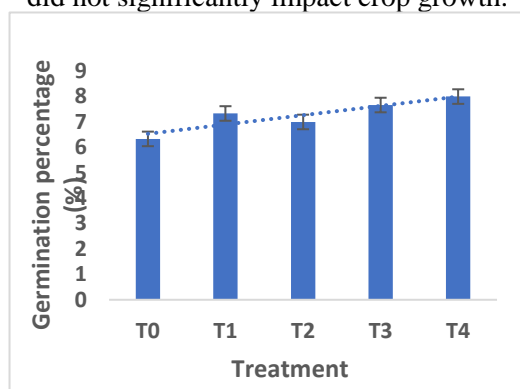


Figure 1. Impact of various combinations of organic and inorganic amendments on germination percentage.

Plant Height

The height of wheat plants is a crucial indicator of plant health and yield. Significant differences in plant height were observed among treatments and the control group after using various organic-inorganic mixtures and chemical fertilizers (Fig. 2).

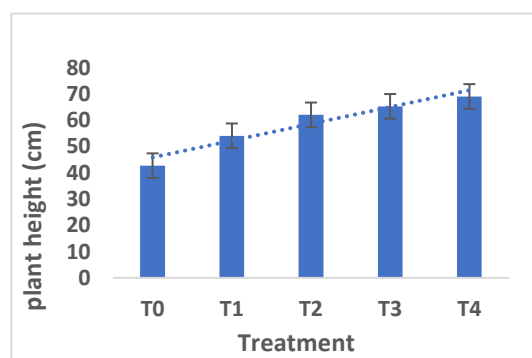


Fig 2. Impact of various combinations of organic and inorganic amendments on plant height.

T4 resulted in the tallest plants at 61%, followed by T3 at 52% and T2 at 45%. In contrast, using the recommended NPK fertilizer did not yield favorable results for plant height.

Root Length

The application of different combinations of inorganic and organic soil amendments significantly ($P < 0.05$) enhanced root length (Fig. 3). T4 (50% compost, 5% gypsum, and 5% bentonite) produced the highest increase (47%) compared with the control, whereas T1 (recommended NPK) resulted in the lowest increase (16%). Root length was effectively improved under saline soil conditions by the combined use of organic and inorganic amendments.

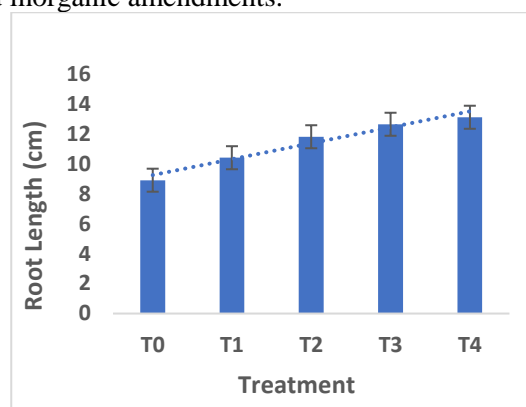


Figure 3. Impact of various combinations of organic and inorganic amendments on root length.

Chlorophyll Content

Chlorophyll content was significantly improved by the incorporation of organic and inorganic amendments in saline soil. T4 (75% compost, 3% gypsum, and 5% bentonite) produced the highest increase (42%), followed by T3 (50% compost, 5% gypsum, and 5% bentonite) with a 36% increase. The recommended NPK treatment produced the lowest chlorophyll content.

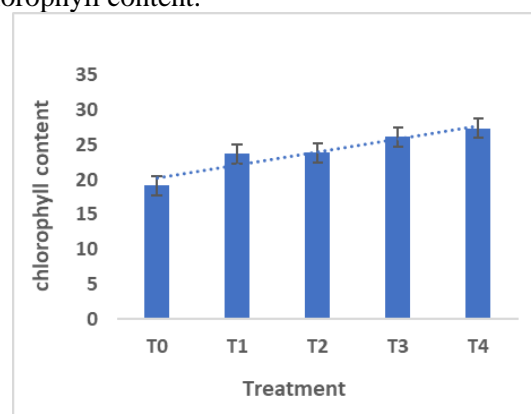


Fig. 4. Impact of various combinations of organic and inorganic amendments on chlorophyll content.

Spike Characteristics

Spike traits, including spike length and the number of spikelets per spike, increased significantly ($P < 0.05$) under soil amendment treatments. T3 (75% compost,

3% gypsum, 5% bentonite) produced the highest increases, with 82% in spike length and 46% in the number of spikelets, while T4 (50% compost, 5% gypsum, 5% bentonite) showed a 61% increase in spike length and a 37% increase in spikelets (Fig. 5 A

and B). The combination of compost, gypsum, and bentonite in the suggested proportions was most effective under saline conditions, whereas the recommended NPK treatment produced the lowest values.

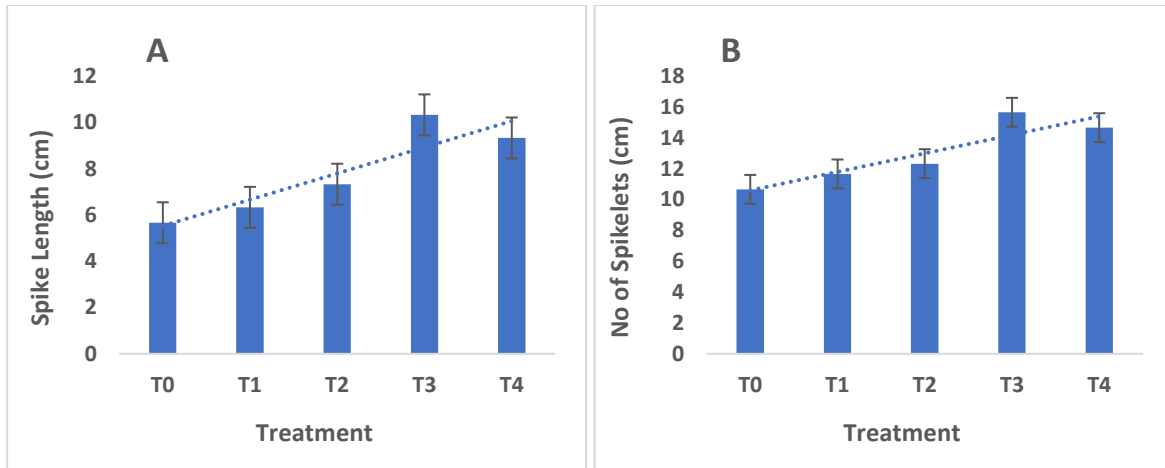


Figure 5: Impact of various combinations of organic and inorganic amendments on spike length (A) and number of spikelet (B).

100-Grain Weight, and No of Grains per Plant

The study demonstrated significant improvements ($P < 0.05$) in 100-grain weight, and number of grains per plant when compost, gypsum, and bentonite were combined under saline conditions (Fig. 6 A and B). T4 (50% compost + 5% gypsum + 5% bentonite) showed the highest increase in grain yield at 39%, followed by T3 (75% compost + 3% gypsum + 5% bentonite) with

a 31% increase (Fig. 3 A and B). T3 also exhibited the best results for 100-grain weight, with an 82% increase and an average weight of 3.94 g. In comparison, the recommended NPK fertilizer only led to a 17% improvement in grain weight and had no significant impact on yield. These results indicate that the use of a combination of compost, gypsum and bentonite is better instead of NPK fertilizer.

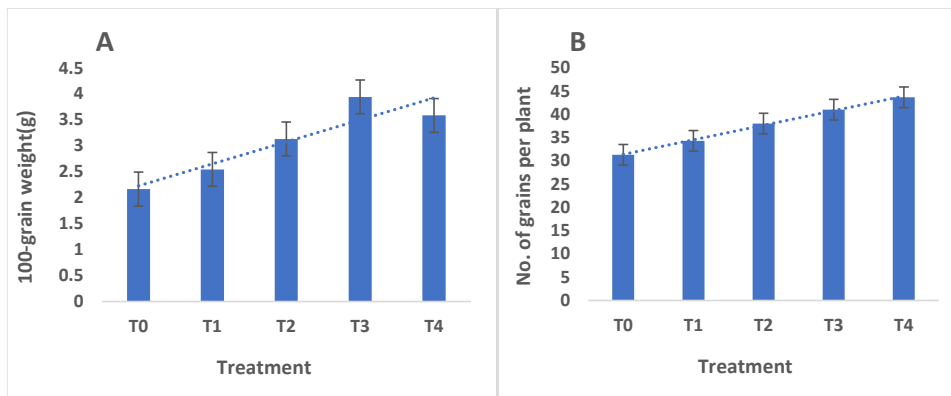


Figure 6: Impact of various combinations of organic and inorganic amendments on 100-grain weight (A), grains per plant (B).

Total biomass

The total biomass of the wheat is an important area of measure of the growth and productivity in the plants (Fig. 7). Application of various organic and inorganic amendments led to significant increase in the total biomass of wheat, the combination of T3 (75 percent compost, 3 percent gypsum, 5 percent bentonite) and T4 showed the greatest growth respectively. This specific mixture was the most successful at enhancing

fresh and dry weight under salty conditions and indicates its ability to promote growth under harsh conditions.

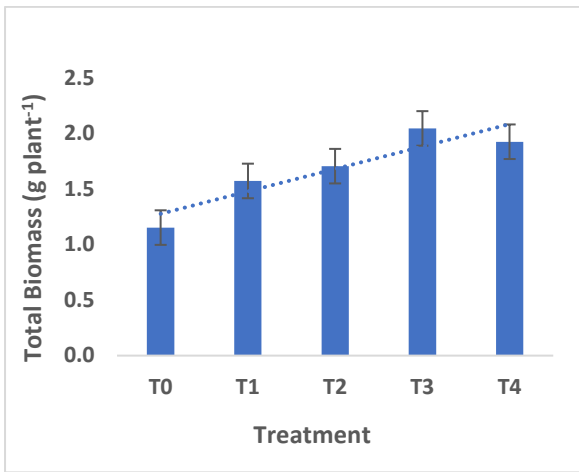


Figure 7. Impact of various combinations of organic and inorganic amendments on plant biomass.

N and K uptake

The experiment showed that the amendments of soils had a great effect in increasing the level of potassium and nitrogen in wheat plants as shown in Fig. 8 (A and B). T3 (75 percent compost, 3 percent gypsum, 5 percent bentonite) gave the greatest potassium increase (85 percent) followed by T4 (50 percent compost, 5 percent gypsum, 5 percent bentonite) with an 81 percent increase. T3 has also demonstrated maximum increment of nitrogen (85%), and secondly T 4 (77%). Finally, introduction of compost, gypsum and bentonite in certain proportions significantly enhanced the nutrient content of plants especially potassium and nitrogen.

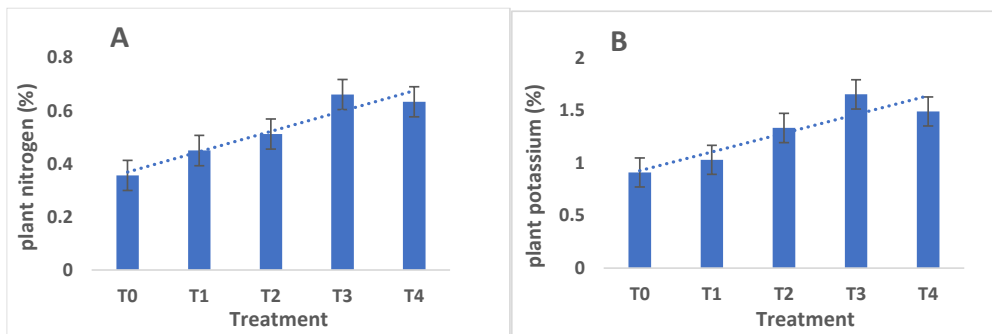


Figure 8: Impact of various combinations of organic and inorganic amendments on plant nitrogen (A) and plant potassium (B).

Correlation among wheat growth, yield, and nutrient traits

Correlation heatmap of relationships between wheat growth, yield, and nutrient traits measured in saline soil during soil amendment treatments (Fig. 9). Most

traits were found to be positively related, which showed coordinated enhancement of plant growth, yield components, biomass and nutrient uptake with the combined treatments of compost, gypsum and bentonite.

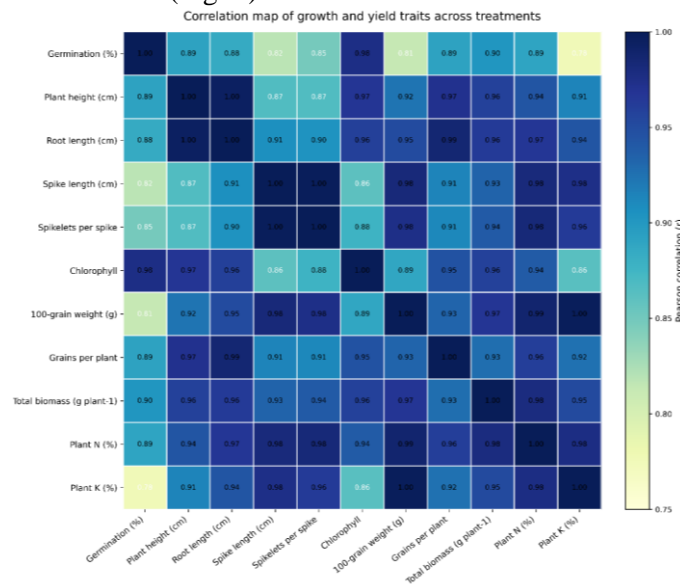


Figure 9. Correlation heatmap showing associations among wheat growth, yield, and nutrient traits across soil amendment treatments under saline conditions. Values represent Pearson correlation coefficients calculated from treatment means.

DISCUSSION

The effectiveness of the reclamation strategies to reduce salinity stress affects crop productivity in salt-affected soils using a strong dependence on the physicochemical properties of the soils. Salinity inhibits the germination of wheat seed because of the osmotic stress it causes on wheat seed, the impairment of water uptake, and the ionic toxicity that develops as a result of Na⁺ being taken up in excess. In this experiment, the use of compost, gypsum, and bentonite together gave significant enhancement in the germination as compared with that of the control and that of the NPK fertilizer, which indicates the efficacy of combined soil amendment approaches. Organic additions, including compost, enhance the aggregation, microbial activity, and water retention of soils, providing a good environment of seed imbibition and the development of seedlings (Arshad et al., 2024; Sabah, 2020; Zaghoul et al., 2024). Gypsum neutralizes the saline soils by providing calcium ions that substitutes the exchangeable sodium, which increases the soil structure, permeability, and early root development (Mamun et al., 2019; Bello et al., 2021; Murtaza et al., 2017). Bentonite also adds to water retention and cation exchange capability, alleviating salt stress levels in the partiality of germinating seeds (Mi et al., 2020; Bouiadjra et al., 2025). T3 (75% compost + 3% gypsum + 5% bentonite) and T4 (50% compost + 5% gypsum + 5% bentonite) created the optimum germination environments under salty soils as a result of the synergistic effect of these amendments. The increased plant height (Fig. 2) was noted in the treatments with combined amendments and T4 increased the height the most. Compost led to increased nutrient availability and activity of microbes, gypsum provided an exchange of calcium and sodium on the exchange sites, and bentonite enhanced the retention of water and nutrient absorption (Gomez and Green, 2017; Soni et al., 2021; Chaganti and Crohn, 2015; Mi et al., 2017; Zhang et al., 2025). These changes in the soil characteristics favored the development of the root resulting in high plant height during salinity pressure. Root growth is one of the most important parameters of wheat in saline environment since salinity limits the growth in roots by causing osmotic stress and sodium toxicity. In the current experiment, the use of compost, gypsum, and bentonite had a significant effect on the enhancement of root length (Fig. 3), whereas Treatment 4 (50% compost + 5% gypsum + 5% bentonite), and Treatment 3 (75% compost + 3% gypsum + 5% bentonite) had the best increase of 47 and 41 percent, respectively, as compared to the control. Compost enhanced the structure of the soils, microbial activity, and the availability of nutrients,

which promoted the growth of roots (Gómez & Green, 2017). Gypsum relieved sodium toxicity and enhancing soil aggregation and permeability enabled the root to enter better and nutrient uptake (Mamun et al., 2019; Bello et al., 2021). Bentonite improved water-holding capacity and cation exchange capacity of the soil, stabilized the level of moisture and salt stress on the roots, further increased the elongation and absorption of nutrients (Mi et al., 2020; Bouiadjra et al., 2025). These findings confirm the earlier research that demonstrated that organic and inorganic amendments together enhance root growth in salty environments (Rop et al., 2019; Bah et al., 2020), which is due to the interaction between organic and inorganic amendments to promote the growth of roots and overall plant productivity in salty soils. The joint amendments greatly increased the level of chlorophyll (Fig. 4). T4 had witnessed 42 percent rise in chlorophyll and T3 had witnessed 35 percent rise indicating the role of compost, gypsum and bentonite in ensuring soil remained moist and has nutrients. The high capacity of cation exchange and water retention of bentonite facilitated the build-up of chlorophyll during salinity stress (Bouiadjra et al., 2025; Mi et al., 2020; Farghali and Tammam, 2025), and optimized nutrient uptake and minimized damage on chlorophyll caused by salinity through compost and gypsum (Amer et al., 2023). Grain yield and yield portions, such as spike length and No. of spikes (Fig. 5 A and B), 100-grain weight and grain per plant (Fig. 6 A and B) significantly increased in T3 and T4. The compost provided nutrients and stimulated microbial activity, gypsum alleviated sodium toxicity and aggrandated soil structure, and bentonite increased water retention and nutrient availability, which all formed good conditions of grain growth. Integrated organic-inorganic amendments have been successfully applied to improve spike characteristics, which was consistent with previous results obtained with treatment 3, where the maximum 100-grain weight was achieved (82%), and the spike characteristics were improved (Crusciol et al., 2019; Soni et al., 2021; El-Sharkawy et al., 2024; Amer et al., 2023; Mi et al., 2020; Bouiadjra et al., 2025).

Combined amendments also increased the total biomass (Fig. 7) of wheat. T3 was the one that produced the highest biomass, and then T4. These findings align with previous researchers that discovered that gypsum and organic amendments increase the amount of dry matter through the increased availability of nutrients and water uptake (Trivedi et al., 2017; Crusciol et al., 2019; Xie et al., 2019). Similarly, the peaks of nitrogen and potassium (Fig. 8 A and B) were also in T3 (85% increase), which can be explained by the fact that the level of nutrient was influenced by compost-mediated release,

the gypsum-mediated replacement of sodium, and mediated by bentonite i.e. nutrient retention (Gharbi et al., 2016; Bouiadjra et al., 2025; Mi et al., 2020; Amer et al., 2023; Alcár et al., 2018).

Correlation relationship (Fig. 9) indicates predominantly strong positive relationships among the measured growth, yield, and nutrient parameters across treatments. Same results were observed by Crusciol et al., (2019) and Xie et al., (2019) during their experiment under organic amendments and their effects on the cereal crops. Plant height, root length, grains per plant, total biomass, and tissue nutrient concentrations (plant N and plant K) were closely associated, indicating that treatments enhancing vegetative growth also improved nutrient uptake and yield formation. Bouiadjra et al., (2025) tested effects of organic and inorganic amendments on the growth, nutrients uptake and biomass of wheat plant and observed a significant correlation between the growth, development, nutrients and biomass traits. The correlation between reproductive properties, such as spike length and spikelets per spike and 100-grain weight and nutrient content showed that enhanced spike development was associated with enhanced grain yields (Amer et al., 2023). Chlorophyll content also exhibited positive correlations with most measured traits, reflecting enhanced physiological activity under favorable treatment conditions. Collectively, these results indicate that the treatments exerted a coordinated positive effect on plant growth, biomass accumulation, reproductive performance, and nutrient enrichment (El-Sharkawy et al., 2024). However, since the correlations were calculated using treatment means, they should be interpreted as overall treatment-level associations.

CONCLUSION

This analysis has proven that the joint application of the compost, gypsum and bentonite can be effectively used to take care of the soil properties and to stimulate growth and production of wheat under the salty environment. Integration of the amendments decreased sodium stress, enhanced nutrient availability and stimulated seed germination, root and shoot growth, height, area, biomass accumulation and significant yield determinants, including spike length, spikelets per spike, and 100-grains weight. The combination of organic and inorganic amendments with respect to individual applications was more effective probably because of their complements in terms of soil structure, water retention, and chemical properties, which jointly alleviate salinity stress. These results are positive although they were acquired under controlled conditions of pot. It is, therefore, recommended that extensive field experimentations on different agro-ecological regions should be carried

out to test the effectiveness, applicability as well as sustainability of these amendment strategies in the large-scale wheat production in the saline-soil.

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