



Synergistic Effects of Compost and Plant Growth-Promoting Rhizobacteria for Enhancing Maize Growth and Yield

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Article Info

Keywords:

Lead contamination, Plant growth-promoting rhizobacteria (PGPR), Zeolite, Sorghum, Phytoremediation, Heavy metal toxicity

Date:

Received: 10 January 2023

Accepted: 17 July 2023

Published: 15 December 2023

Volume: 04 (02), 2023



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Abstract

Maize (*Zea mays* L.) is one of the most significant cereal crops globally, contributing substantially to the agricultural output. Enhancing maize yield is crucial for food security, and sustainable practices such as using compost and plant growth-promoting rhizobacteria (PGPR) can play a vital role. This study investigates the effects of compost, with and without PGPR, on the growth and yield of maize. The experiment utilized varying compost application rates (400, 600, and 800 kg ha⁻¹) with and without PGPR. Results demonstrated that the combination of compost at 800 kg ha⁻¹ with PGPR significantly outperformed other treatments. Notably, this combination enhanced plant height by 34%, SPAD chlorophyll value by 48%, shoot length by 18%, root length by 18%, fresh shoot weight by 17%, fresh root weight by 47%, cob fresh weight by 50%, dry shoot weight by 54%, dry root weight by 40%, cob dry weight by 26%, grain number by 81%, 1000 grain weight by 22%, grain nitrogen by 182%, shoot nitrogen by 231%, and soil nitrogen by 1100% compared to the control. Lower compost application rates also showed improvements but were less pronounced. In conclusion, the use of compost, especially when combined with PGPR, significantly enhances maize growth and yield. This sustainable approach reduces the need for chemical fertilizers while improving soil health and crop productivity. These findings underscore the importance of integrating organic amendments and beneficial microbes into agricultural practices to achieve higher yields and sustainability.

Introduction

Agriculture is the backbone of our economy, sustaining a significant portion of the population directly or indirectly. It contributes approximately 24% to the GDP, employs half of the labor force, and is the primary source of foreign exchange revenue (Govt. of Pakistan, 2023). Among cereal crops, maize (*Zea mays* L.) is particularly important, providing high yields second only to wheat and rice. This crop is crucial in addressing the food demands of a rapidly growing global population, especially in countries like Pakistan, where food security is a

major concern (Memon et al., 2012). In Pakistan, maize contributes 2.1% to the total agricultural value and 0.4% to the GDP during 2013-2014. The chemical composition of dry maize seeds includes approximately 10.4% moisture, 6.8-12% protein, 4% lipid, 1.2% ash, 2% fiber, and 72-74% carbohydrate (Kulp, 2000).

The production of maize in Pakistan is expected to reach 9.24 million tons from 1.61 million hectares for the 2022-23 season, marking a 21.02% increase in area and a 28.86% increase in production compared to previous targets. Globally, maize is cultivated on approximately 197 million hectares, with

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significant areas in Asia, sub-Saharan Africa (SSA), and Latin America (FAOSTAT, 2021). With an annual yield surpassing 1 billion metric tons, maize is one of the principal staple cereals worldwide (García-Lara and Serna-Saldivar, 2019). It is primarily used for poultry and cattle feed (65%), human consumption (35%), and as a raw material in various industries, including starch, oil, protein, alcoholic beverages, sweeteners, cosmetics, and biofuel production (Serna-Saldivar, 2018).

In Pakistan, the import value of maize was calculated at \$72 million in 2021, reflecting a 28% increase from 2020. This rise in imports, driven by the growing population, underscores the need for enhanced food security. The value of maize exports in 2020 was \$14.3 million, making Pakistan the 51st largest global exporter of maize, while imports amounted to \$50.2 million, positioning Pakistan as the 74th largest global importer of maize. This trade imbalance highlights the necessity of increasing domestic maize production to meet local demand and reduce reliance on imports.

Intensified agricultural practices, including irrigation and fertilization, have been adopted to meet the rising demand for maize. However, these practices often lead to soil degradation and a decline in soil organic matter (SOM), which is critical for maintaining soil health and fertility. Sustainable intensification programs aim to enhance crop yields while minimizing the environmental impact of agriculture. Rebuilding SOM can improve soil fertility, water and nutrient retention, drainage, aeration, and reduce erosion (Saleem et al., 2023). However, Pakistani soils typically have lower-than-ideal organic matter concentrations due to climatic conditions, farming practices, and economic factors.

Increasing soil organic matter is essential for preserving soil quality, and compost serves as an effective organic fertilizer due to its rich nutrient content and organic waste. Compost improves soil productivity by enhancing nutrient availability, water retention, and soil structure, promoting seed germination and root development (Haile, 2017). The application of composted organic material to agricultural fields can address soil fertility issues, boosting crop yields and resilience to pests and diseases (Oldfield et al., 2019). Composting also helps recycle agricultural and organic waste, reducing the environmental footprint of farming activities.

Plant growth-promoting rhizobacteria (PGPR) are beneficial soil bacteria that can significantly enhance plant growth and yield by reducing the need for chemical fertilizers. These bacteria improve plant growth through various mechanisms, including phosphate solubilization, phytohormone synthesis, nitrogen fixation, and the biological control of harmful microorganisms (Safdar et al., 2022). PGPR can also induce systemic resistance in plants, helping them to fend off pathogens and pests. Research indicates that PGPR, in combination with compost, promotes nutrient uptake and transport during abiotic stress, contributing to improved crop growth and yields (Hafez et al., 2021).

The combined use of compost and PGPR represents a sustainable strategy for improving soil health and crop productivity while minimizing environmental impact. Compost enhances soil fertility and PGPR diversity, creating favorable conditions for plant growth. Inoculating crops with beneficial bacteria offers an eco-friendly approach to enhancing crop

output under adverse conditions (Osman et al., 2021). PGPR influences plant growth through direct mechanisms, including hormone production, nitrogen fixation, and nutrient solubilization, as well as indirect methods by suppressing plant pathogens like fungi and bacteria (Yupeng et al., 2018).

Compost, composed of decomposed organic materials, undergoes rapid breakdown under regulated, aerobic conditions, transforming potentially hazardous components into a stable state beneficial for soil quality and plant growth (Duong, 2013). Apart from its soil-enhancing properties, compost offers additional benefits such as diverting landfill waste, pathogen and weed seed removal, decomposing harmful residues, erosion control, and providing nutrients for soil re-vegetation (Okhumata and Iyabode, 2022).

Compost as an organic fertilizer is a valuable resource for improving soil quality and agricultural productivity. However, the individual use of compost may not be sufficient to meet nutrient demands, potentially affecting farm profitability and crop yields. Integrating biological and mineral fertilizers is a soil management strategy that can reduce resource surplus and minimize environmental impacts (Hernández et al., 2016). A field trial conducted on mungbean showed that the combined application of compost and PGPR resulted in higher yields compared to compost alone (Ipsita Das and Singh, 2014). Compost application with PGPR showed higher NPK content in soil compared to compost alone. Every treatment was more efficient than the control, with the combined use of compost and PGPR showing the best results (Das et al., 2014).

Therefore, this study aims to evaluate the effect of compost and PGPR, both alone and in combination, on the growth and yield of maize. The specific objectives are:

To assess the impact of different compost levels on the growth and yield of maize.

To evaluate the combined effect of PGPR and compost on the growth and yield of maize.

By understanding the synergistic effects of compost and PGPR, this research contributes to the development of sustainable agricultural practices that can improve crop yields, and soil health, and reduce the reliance on chemical fertilizers. The findings of this study will provide valuable insights for farmers and policymakers, promoting more efficient and environmentally friendly farming methods.

Materials and Methods

A pot study was conducted at the wirehouse of the Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad, to evaluate the role of plant growth-promoting rhizobacteria (PGPR) and compost on the growth and yield of maize (*Zea mays* L.). The study employed a completely randomized design (CRD) with three replications for each treatment.

Soil Preparation

The soil used in this study was collected from the Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad. The soil was thoroughly mixed, air-dried at room temperature, ground, and sieved through a 2.5 mm mesh. The prepared soil was then used to determine various chemical and physical parameters.

Physicochemical Analysis of Soil

Table 1 Pre-analysis of the Soil and compost

Parameter	Soil	Compost
Sand (%)	38.5	-
Silt (%)	34.4	-
Clay (%)	27.1	-
Textural Class	Sandy clay loam.	-
pH _s	7.75	7.4
EC _e (dS m ⁻¹)	1.63	6.26
Organic matter (%)	0.16	60
Available Phosphorus (mg kg ⁻¹)	7.28	-
Extractable potassium (mg kg ⁻¹)	158.3	-
Total Nitrogen (%)	0.056	-

The soil parameters were analyzed using standard methods:

Texture Analysis: Conducted using the hydrometer method. Forty grams of dry soil were mixed with 40 ml of 2% sodium hexametaphosphate solution, shaken, and readings were taken after 4 minutes and 2 hours, adjusted for temperature.

Saturation Percentage: Calculated by drying a saturation paste and using the formula (wet soil mass–dry soil mass)/dry soil mass×100(wet soil mass–dry soil mass)/dry soil mass×100.

pH: Measured from the saturated soil paste using a pH meter after one hour of saturation.

Electrical Conductivity (EC): Determined from the soil paste extract using a digital conductivity meter.

Organic Matter: Measured by the Walkley-Black method, involving oxidation-reduction titration with ferrous ammonium sulfate.

Available Phosphorus: Extracted with 0.5 M NaHCO₃, developed with ascorbic acid, and measured using a spectrophotometer.

Extractable Potassium: Determined using 1N ammonium acetate and a flame photometer.

Total Nitrogen: Analyzed by Kjeldahl digestion, distillation, and titration with 1N H₂SO₄.

Selection of Plant Growth-Promoting Rhizobacteria (PGPR) Inoculant

The pre-isolated and pre-characterized S5 PGPR inoculant was obtained from the Soil Microbiology and Biochemistry Laboratory at the Institute of Soil and Environmental Sciences, University of Agriculture Faisalabad.

Inoculum Preparation

The inoculant was prepared using the S5 PGPR strain in autoclaved Luria Bertani (LB) broth media. The media were sterilized at 121°C and 15 psi for 30 minutes. The flask

containing the inoculated broth was incubated at 28°C for three days. The inoculum was then used for seed coating.

Seed Inoculation

Maize seeds were soaked in water and surface-sterilized with 65% sodium hypochlorite (NaOCl) or mercuric chloride (HgCl₂) for 10 minutes, followed by three rinses with sterilized deionized water. After sterilization, the seeds were inoculated with the prepared inoculum and sown in pots after 30 minutes.

Pot Study

The pot experiment was designed to assess the effects of compost and the combined use of PGPR with compost on maize growth and yield. Compost was applied at rates of 400, 600, and 800 kg ha⁻¹. Each pot was filled with 12 kg of soil, and NPK nutrients were added at rates of 250, 145, and 92 kg ha⁻¹, respectively, using urea, DAP, and SOP fertilizers. Six maize seeds were planted per pot, and after germination, two seedlings per pot were maintained by thinning. Pots were placed in the wirehouse under ambient temperature and light conditions. The experiment followed a completely randomized design (CRD) with three replications for each treatment, including individual applications of PGPR and combinations with different levels of compost. Irrigation was applied as needed, and pest and disease control was managed through spraying. Data on shoot length and chlorophyll content (SPAD value) were collected 30 days after planting. Manual hoeing was performed weekly to control weeds. Plants were harvested at maturity, and growth and yield parameters, including plant height, root and shoot lengths, fresh and dry weights of roots, shoots, and cobs, grain number per plant, and 1000-grain weight, were measured.

Nitrogen Determination

Samples of roots, shoots, and grains were oven-dried at 70°C until a consistent weight was achieved. The samples were then ground using a Wiley mill and stored in polyethylene bags for further analysis. Total nitrogen content was determined using

the Kjeldahl method following digestion procedures outlined in the ICARDA manual (Estefan et al., 2013).

Statistical Analysis

Data were analyzed using ANOVA with the statistical software Statistix 8.1. Tukey's Honestly Significant Difference (HSD) test was used to compare treatment means at a 5% probability level. Graphs representing the parameters mean, and standard errors ($\pm$ SE) were prepared using MS Excel.

Results

The study demonstrated that the combined application of compost and plant growth-promoting rhizobacteria (PGPR) significantly enhanced maize growth and yield parameters compared to the control. Treatments involving higher compost levels and PGPR showed notable improvements in shoot and root lengths, fresh and dry weights of shoots and roots, chlorophyll content, nitrogen content in grains, shoots, and soil, as well as overall cob weight and grain number. The integrated use of compost and PGPR proved to be the most effective strategy, highlighting the importance of sustainable soil management practices in boosting maize productivity and improving soil health.

enhanced these growth parameters, with improvements ranging from 14% to 38%. PGPR application alone also resulted in significant improvements in plant height, shoot length, fresh weight, dry weight, root length, root fresh weight, and root dry weight by 7% to 33% compared to the control. The combination of compost and PGPR yielded the best results, underscoring the importance of integrated soil management practices in enhancing plant growth and productivity.

Chlorophyll SPAD Value

Figure 1 shows that the combined application of compost and PGPR significantly improved the SPAD chlorophyll value of maize compared to all other treatments. The maximum enhancement in SPAD chlorophyll value was 48% in T8, where 800 kg ha⁻¹ of compost was combined with PGPR, compared to the uninoculated untreated control. Subsequent best treatments were T7 and T6, with combined applications of 600 kg ha⁻¹ and 400 kg ha⁻¹ of compost with PGPR, showing increases of 45% and 40%, respectively. Compost application without PGPR also showed better responses than the control, with T5, T4, and T3 treatments (800, 600, and 400 kg ha⁻¹ of compost, respectively) resulting in SPAD value increases of 39%, 35%, and 31%.

Table 2. Effect of PGPR and Compost alone and in combination on shoot attributes of maize (average of three replications)

Treatments	Shoot length (cm)	Shoot fresh weight (g)	Shoot dry weight (g)
Control	165.67 d	266.67 c	112 e
PGPR	184.67 bc	276.67 c	120 e
Compost 400 kg/ha	179.33 c	270 c	125 de
Compost 600 kg/ha	182.67 bc	283.33 bc	141.67 c
Compost 800 kg/ha	185 bc	290 a-c	136. 67 cd
PGPR+Compost 400 kg/ha	187 b	291.33 a-c	148.33 bc
PGPR+Compost 600 kg/ha	189.33 ab	306.67 ab	158.33 ab
PGPR+Compost 800 kg/ha	196 a	311.67 a	168.33 a

The mean values in a column having similar letters do not differ significantly at $p=0.05$ according to Tucky's HSD test.

Growth Parameters of Maize

Tables 2 and 3 illustrate the significant enhancements in plant growth parameters with the use of 800 kg ha⁻¹ of compost combined with plant growth-promoting rhizobacteria (PGPR) compared to the control. This treatment resulted in substantial increases in shoot length (18%), fresh shoot weight (17%), dry shoot weight (50%), root length (18%), root fresh weight (47%), and root dry weight (54%). The application of 600 kg ha⁻¹ of compost with PGPR also outperformed the control, showing notable improvements in plant growth parameters by 27% to 49%.

Using 800 kg ha⁻¹ of compost alone led to significant increases in plant height, shoot length, fresh and dry weight, root length, root fresh weight, and root dry weight by 21% to 54% compared to the control. Similarly, 600 kg ha⁻¹ of compost significantly

PGPR inoculation alone increased the SPAD chlorophyll value by 26% over the control.

Nitrogen Contents

Table 4 indicates that the use of 800 kg ha⁻¹ of compost with PGPR significantly improved grain nitrogen, shoot nitrogen, and soil nitrogen contents by 182%, 231%, and 1100%, respectively, compared to the control. The 600 kg ha⁻¹ compost with PGPR treatment also showed significant improvements, increasing grain nitrogen, shoot nitrogen, and soil nitrogen by 164%, 145%, and 333%, respectively. The application of 400 kg ha⁻¹ compost with PGPR enhanced grain nitrogen, shoot nitrogen, and soil nitrogen by 139%, 56%, and 358%, respectively. Using 800 kg ha⁻¹ of compost alone improved grain nitrogen, shoot nitrogen, and soil nitrogen by 120%, 46%, and 283%, respectively. Similarly, 600 kg ha⁻¹ and 400 kg ha⁻¹

Table 3. Effect of PGPR and Compost alone and in combination on root attributes of maize (average of three replications)

Treatments	Root length (cm)	Root fresh weight (g)	Root dry weight (g)
Control	55 d	152.33 d	71.05 d
PGPR	58 cd	173 cd	94.67 c
Compost 400 kg/ha	57.667 cd	200 a-c	70.71 d
Compost 600 kg/ha	58.333 cd	210 ab	99.67a-c
Compost 800 kg/ha	59.667 bc	218.33 ab	96.33 bc
PGPR+Compost 400 kg/ha	62.667 ab	210 ab	105.67 ab
PGPR+Compost 600 kg/ha	64 a	195.33 bc	102.67 a-c
PGPR+Compost 800 kg/ha	65 a	223.33 a	109.67 a

The mean values in a column having similar letters do not differ significantly at $p=0.05$ according to Tucky's HSD test.

Table 4. Effect of PGPR and Compost alone and in combination on Mineral content of maize. (average of three replications)

Treatments	Grain nitrogen	Shoot nitrogen	Soil nitrogen
Control	4.11 c	7.285 e	2.242 e
PGPR	5.324 bc	9.807 c-e	3.642 e
Compost 400 kg/ha	8.313 a-c	7.846 de	5.23 de
Compost 600 kg/ha	8.593 ab	9.06 c-e	5.791 c-e
Compost 800 kg/ha	9.06 ab	10.648 cd	8.593 b-d
PGPR+Compost 400 kg/ha	9.807 a	11.395 c	10.274 b
PGPR+Compost 600 kg/ha	10.834 a	17.839 b	9.714 bc
PGPR+Compost 800 kg/ha	11.582 a	24.097 a	26.899 a

The mean values in a column having similar letters do not differ significantly at $p=0.05$ according to Tucky's HSD test.

compost applications without PGPR also increased these parameters significantly. PGPR application alone improved grain nitrogen, shoot nitrogen, and soil nitrogen by 30%, 35%, and 50%, respectively. Overall, the best response regarding nitrogen content in grain, shoot, and soil was obtained with 800 kg ha⁻¹ compost combined with PGPR.

Yield Parameters of Maize

Table 5 demonstrates that the use of 800 kg ha⁻¹ of compost with PGPR significantly enhanced cob fresh weight, cob dry weight, grain number per spike, and 1000-grain weight by 40%, 26%, 81%, and 22%, respectively, compared to the control. The treatment with 600 kg ha⁻¹ of compost with PGPR also showed significant improvements, enhancing these parameters by 39%,

9%, 61%, and 16%, respectively. The application of 400 kg ha⁻¹ of compost with PGPR improved cob fresh weight, cob dry weight, grain number per spike, and 1000-grain weight by 20%, 7%, 52%, and 11%, respectively. Using 800 kg ha⁻¹ of compost alone increased these parameters by 37%, 19%, 46%, and 7%, respectively, compared to the control. Similarly, 600 kg ha⁻¹ and 400 kg ha⁻¹ compost applications without PGPR showed substantial improvements. PGPR application alone resulted in increases of 13%, 12%, 27%, and 0%, respectively, compared to the control. The best response in terms of cob fresh weight, cob dry weight, grain number per spike, and 1000-grain weight was observed with the combined application of 800 kg ha⁻¹ compost and PGPR. Inoculation with bacterial consortia

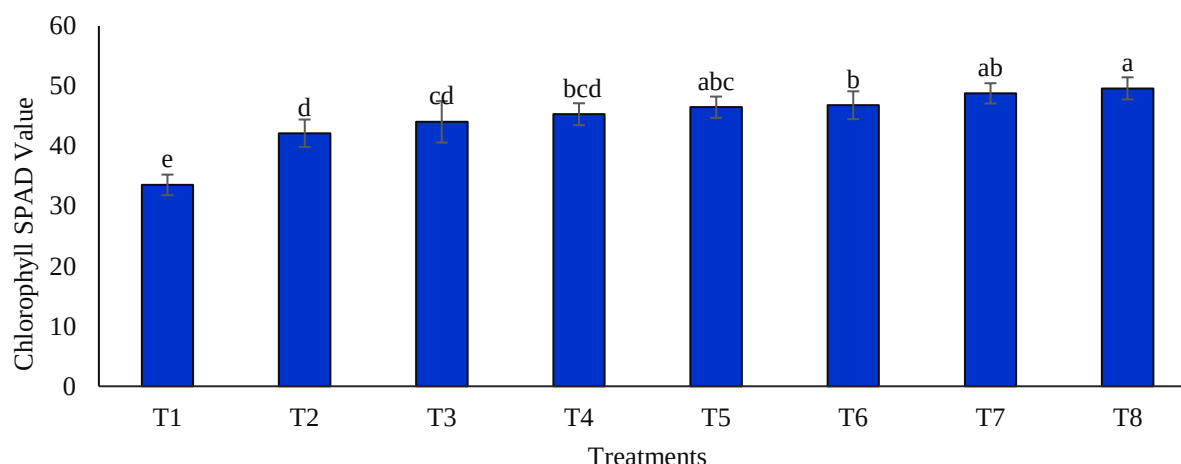
Table 5. Effect of PGPR and Compost alone and in combination on Yield parameters of maize. (average of three replications)

Treatments	Cob fresh weight (g)	Cob dry weight (g)	Grain no per spike	1000 grain weight (g)
Control	109.67 d	94 c	181.33 c	285.79 e
PGPR	124 c	105 a-c	230 d	286.65 e
Compost 400 kg/ha	145 ab	108.5 ab	229.33 c	292.72 de
Compost 600 kg/ha	146.67 a	111.67 ab	231.67 c	299.51 c-e
Compost 800 kg/ha	150 a	112.21 ab	264 bc	306.27 cd
PGPR+Compost 400 kg/ha	131.67 bc	101 bc	275 bc	317.11 bc
PGPR+Compost 600 kg/ha	152 a	102.67 bc	292.67 ab	330.5 b
PGPR+Compost 800 kg/ha	153.67 a	118 a	328.67 a	348.78 a

The mean values in a column having similar letters do not differ significantly at $p=0.05$ according to Tucky's HSD test.

significantly influenced cob weight, with the highest fresh cob weight observed in the consortium of four strains, showing a notable increase compared to the control.

roots (RFW), and dry weight of roots (RDW) also exhibit strong positive correlations. Cob fresh weight (CFW) and cob dry weight (CDW) are highly correlated with the number of grains

**Figure 1. Effect of PGPR and Compost alone and in combination on chlorophyll SPAD value of maize. (average of three replications)**

Control (T1); PGPR (T2); Compost 400 kg/ha (T3); Compost 600 kg/ha (T4); Compost 800 kg/ha (T5); PGPR+Compost 400 kg/ha (T6); PGPR+Compost 600 kg/ha (T7); PGPR+Compost 800kg/ha(T8)

Correlation analysis

The correlation matrix graph illustrates the relationships between various growth and yield parameters of maize in the study (Figure 2). Positive correlations are represented by red circles, with the size and intensity indicating the strength of the correlation. Parameters such as shoot length (S. Length), fresh weight of shoots (SFW), and dry weight of shoots (SDW) show strong positive correlations with each other, suggesting that increases in one parameter are likely associated with increases in the others. Similarly, root length (R. Length), fresh weight of

and 1000-grain weight, indicating that these yield components are closely linked. Notably, nitrogen content in grains (N Grain) and shoots (S. N) are positively correlated with SPAD value and plant height (P. Height), reflecting the importance of nitrogen in plant growth and chlorophyll content. Overall, the strong positive correlations among these parameters suggest that the combined application of compost and PGPR effectively enhances multiple aspects of maize growth and yield.

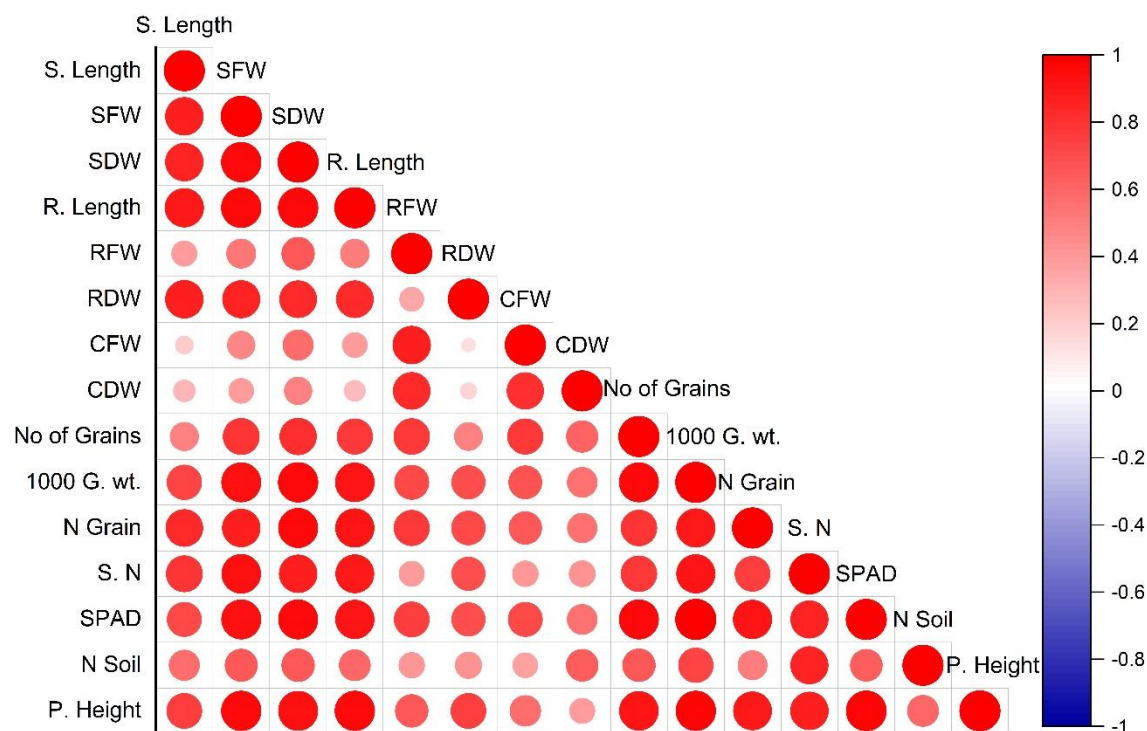


Figure 2. Correlation between different parameters

PC Analysis

The principal component analysis (PCA) biplot illustrates the relationships between different treatments (T1 to T8) and various growth and yield parameters of maize (Figure 3). The first principal component (PC1) explains 74.14% of the variance, while the second principal component (PC2) accounts for 13.76% of the variance. Treatments T8, T7, T6, and T5 are closely associated with positive growth parameters such as cob fresh weight (CFW), root fresh weight (RFW), number of grains, 1000 grain weight, nitrogen content in grains (N Grain) and soil (N Soil), SPAD value, plant height (P. Height), shoot dry weight (SDW), shoot fresh weight (SFW), and root length (R. Length). This indicates that these treatments had a positive influence on these parameters. In contrast, treatments T1, T3, T4, and T5 are less associated with these positive outcomes. Notably, T2 is positioned furthest from the favorable growth parameters, suggesting it had the least positive impact on maize growth and yield. Overall, the PCA biplot effectively demonstrates that treatments involving higher compost levels and PGPR combinations (particularly T8) significantly enhance maize growth and yield.

Discussion

This study demonstrates the significant positive effects of integrating compost and plant growth-promoting rhizobacteria (PGPR) on maize growth and yield. The combined use of compost and PGPR not only enhances various growth

parameters such as shoot and root lengths, fresh and dry weights, and chlorophyll content but also improves nutrient uptake, particularly nitrogen and phosphorus. These findings highlight the potential of sustainable agricultural practices to improve crop productivity while maintaining soil health. The integration of organic amendments like compost with beneficial microbes offers a viable alternative to traditional chemical fertilizers, reducing environmental impact and promoting long-term soil fertility. This discussion explores the underlying mechanisms and implications of these findings, drawing comparisons with previous research and emphasizing the importance of sustainable soil management practices in modern agriculture.

In this study, the effects of plant growth-promoting rhizobacteria (PGPR) strains on maize production were evaluated. The results indicated that PGPR strains significantly promote growth during the initial stages when seedlings are vulnerable to environmental stresses. Previous studies, such as those by Dashti (1996) on soybean and Beneduzi et al. (2008) on rice, have shown similar findings where PGPR inoculation resulted in substantial growth enhancement during early development. Dobbelaere et al. (2001) observed improved sprouting, flowering, and initial development in maize with *Azospirillum brasilense*, which also enhanced nitrogen uptake efficiency.

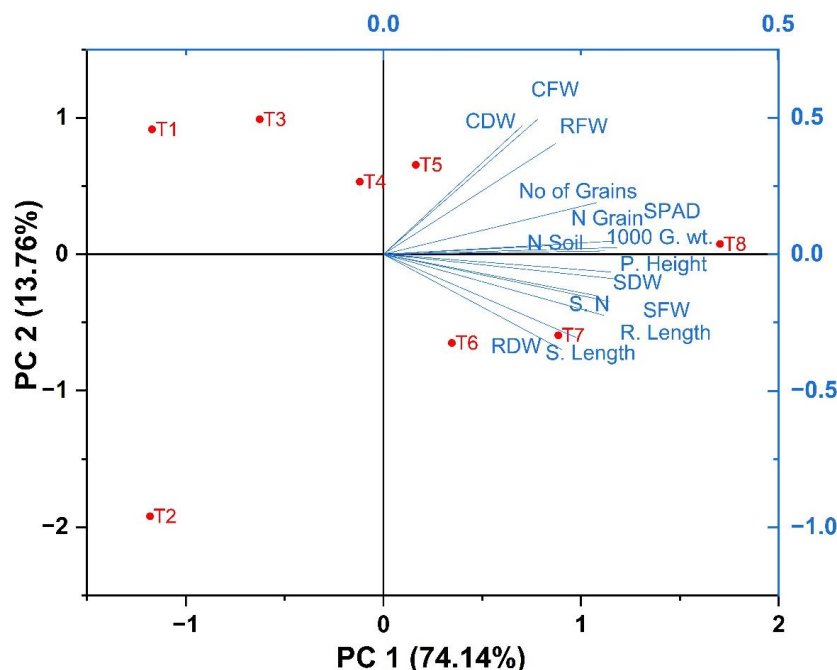


Figure 3. PC analysis between different parameters

Cakmakci et al. (2006) reported that sugar beet plants treated with PGPR showed increased root weight, foliage, and sugar content during early growth stages. However, Piao et al. (2005) found that rice plants treated with *Azotobacter* did not show significant growth promotion during early stages but exhibited notable improvements in biomass and foliage number after 60 days. These enhancements can be attributed to the production of plant hormones, vitamins, improved nutrient uptake, and inhibition of plant ethylene, as well as inorganic phosphate solubilization (Cakmakci, 2006; Puente, Li, and Bashan, 2004).

Tejera et al. (2005) demonstrated that *Azospirillum*-produced encouraging elements improve sugarcane growth, while Hoberg, Marschner, and Lieberei (2005) found that certain PGPR isolates produce organic acids that solubilize inorganic phosphorus. Woodard and Bly (2000) noted that maize plants treated with *A. brasilense* had higher dry shoot weight and grain yield. Similarly, Dobbelaere et al. (2002) and Kizilkaya (2008) found that PGPR inoculation in wheat and maize enhanced root growth, grain yield, and nitrogen content. Nandakumar et al. (2001) suggested that PGPR treatment improves photosynthetic capacity due to increased chlorophyll content.

The use of compost and nitrogen fertilizer significantly improved the nutrient status of the soil, consistent with the findings of Curtis and Claassen (2005) and Farrell and Jones (2009). Adeniyi and Ojeniyi (2003) and Larney et al. (2008) observed that while inorganic inputs provide immediate nutrients, compost combined with nitrogen fertilizer enhances plant growth at later stages. The positive effects of compost are attributed to its provision of a readily available carbon and nitrogen source for soil microorganisms, improved soil structure, reduced erosion, and increased soil water-holding capacity (Adebayo et al., 2011). Studies by Gitari and Friesen (2001) and Makinde (2007) also showed higher yields in maize

and wheat with combined N fertilizer and compost application compared to using either alone.

Enhanced biological production with compost application is due to increased plant growth, height, vegetative yield, leaf area, and grain production. Improved nitrogen availability from mineral fertilizers also contributes to better crop growth, as confirmed by Ganjali et al. (2013) and Naderi and Ghadiri (2010). Akanbi and Togun (2002) found that various levels of compost, alone or with urea, significantly influenced maize plant height and shoot production.

Organic fertilizers, including compost, enhance nutrient use efficiency, which in turn promotes maize growth (Nevens and Reheul, 2003; Naveed et al., 2008). This might be due to the slow nutrient release from compost, reducing leaching losses, particularly for nitrogen, and the beneficial effects of *Azotobacter* and phosphate-solubilizing bacteria. Singh et al. (2006) and Suke et al. (2011) suggested that the production of vitamins and growth-stimulating substances like gibberellic acid and indole acetic acid by microorganisms contributes to enhanced plant growth and yield.

In this experiment, PSR inoculation improved maize growth, production, and phosphorus uptake when used with compost. The compatibility of substrate and nutrient availability are crucial for positive plant-microbe interactions in organic inputs (Arif et al., 2016). Research by Kaur and Reddy (2015) and Shahzad et al. (2014) supports the enhanced plant production with PSR and phosphorus-enriched compost. PSR bacteria act as efficient fertilizers, increasing crop dry matter and phosphorus nutrition in P-deficient soils (Krey et al., 2013; Noumavo et al., 2013).

Root production can be enhanced in nutrient-rich areas, increasing root surface area and nutrient uptake efficiency (Postma et al., 2014; Hammond et al., 2009). PSR application generally improves root growth, length, fresh and dry weight, and branching, increasing nutrient uptake (Egamberdieva and Kucharova, 2009; Pereira and Castro, 2014). Root length density affects the ability to absorb moisture and nutrients, impacting total production (Ning et al., 2015). Beneficial bacteria in roots engage in associative interactions, enhancing plant growth even in nutrient-deprived conditions (Drogue et al., 2012; Song et al., 2015).

This study highlighted the benefits of combined compost and chemical fertilizer application, supplemented with PGPR, for maize growth and yield. Improved oil content in sunflower seeds due to PGPR and nitrogen-enhanced compost application was also noted, consistent with findings by Jalilian et al. (2012), Zheljaskov et al. (2008), and Dordas and Sioulas (2008). Enhanced oil quality was attributed to increased unsaturated fatty acids, corroborating studies by Ahmad and Abdin (2000), Akbari et al. (2011), and Mohammadi and Rokhzadi (2012).

Conclusion

This study demonstrates that the combined application of compost and plant growth-promoting rhizobacteria (PGPR) significantly enhances maize growth and yield parameters compared to traditional fertilization methods. The treatments involving higher levels of compost (800 kg ha⁻¹) in conjunction with PGPR resulted in the most substantial improvements in plant height, shoot and root lengths, fresh and dry biomass, chlorophyll content, and nutrient uptake, particularly nitrogen and phosphorus. The findings indicate that integrating compost with PGPR not only boosts crop productivity but also improves soil health by increasing organic matter and microbial activity. These sustainable agricultural practices reduce the reliance on chemical fertilizers, minimize environmental impacts, and contribute to long-term soil fertility and crop resilience. This research underscores the potential of using organic amendments and beneficial microbes to enhance agricultural sustainability and food security, advocating for broader adoption of such practices in maize cultivation and other crops.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to express their sincere gratitude to the Soil Microbiology and Biochemistry Laboratory, University of Agriculture, Faisalabad, for providing the necessary space and resources to conduct this research. Their support and facilities were invaluable to the successful completion of this study.

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