Research Article:

EFFECT OF PHOSPHATE SOLUBILIZING BACTERIA AND PHOSPHORUS SOURCES ON SOIL PHOSPHORUS AVAILABILITY AND MAIZE YIELD

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ABSTRACT

Phosphorus is an important nutrient for maize; however, its availability in soil may be restricted due to binding to clay surfaces and precipitation with cations such as aluminium and iron at low pH and calcium and magnesium at high pH, ultimately affecting maize growth, development and yield. Phosphate solubilizing bacteria helps to improve soil phosphorus availability by transforming insoluble phosphorus to plant-available forms, thereby supporting improved crop growth and yield. To address this, a field experiment was conducted in Taukhel, Lalitpur, Nepal following a split-plot design with phosphate solubilizing bacteria inoculation and non-inoculation as the main plot factor and five phosphorus sources: control, rock phosphate, single super phosphate, bone meal and poultry manure as sub-plot factors, each replicated three times. Results showed no significant interaction between phosphate solubilizing bacteria and phosphorus sources. However, inoculation of phosphate solubilizing bacteria significantly increased thousand grain weight, grain yield, stover yield and soil available phosphorus by 2.1%, 11.6%, 9.7% and 13.4% respectively, compared with no inoculation. Similarly, among phosphorus sources, plots treated with poultry manure improved plant height, number of leaves, ear length, number of kernels per row, thousand grain weight, grain yield, stover yield and soil available phosphorus by 14.6%, 14.9%, 19.5%, 16.6%, 7.3%, 34.2%, 26.3% and 46.1% respectively, compared to control. The results of our study suggests that maize seed inoculation with phosphate solubilizing bacteria improved maize yield and soil available phosphorus in comparison to non-inoculated treatments. However, additional research is essential to understand combined effects of phosphate solubilizing bacteria with organic and inorganic fertilizers on soil nutrient availability and crop productivity.

Keywords: Bio-inoculants, organic fertilizers, sustainable agriculture, *Zea mays*

INTRODUCTION

Maize (*Zea mays* L.) ranks as the second most important cereal crop after rice and is a staple food for over 55% of people across the hilly areas of Nepal (Adhikari et al., 2022). It has a high nutrient requirement which makes proper nutrient management and a balanced nutrient supply crucial for its development and yield (Adekiya et al., 2020). A study conducted by Devkota et al. (2021) reported that the recommended fertilizer dose of 120:60:40 kg N: P_2O_5: K_2O ha^{-1} increased maize grain yield by 6.9% compared with farmers' fertilizer dose of 70:30:20

kg N: P_2O_5: K_2O ha^{-1}. Phosphorus (P) is a crucial mineral nutrient limiting plant growth and development (Haq et al., 2020). It falls second to nitrogen in importance (Greenway & Hughes, 2017) and cannot be manufactured by the plants, substituted, or fixed from the atmosphere like nitrogen (Adnan et al., 2022). Thus, its availability is crucial for achieving increased and sustained agricultural yields (Scervino et al., 2011). Phosphorus deficiency occurring in soil is a significant factor limiting maize growth and productivity (Gyaneshwar et al., 2006).

About 75-90% of applied phosphorus in soil becomes inaccessible for uptake by plants, thus causing P deficiency under both acidic and alkaline conditions (Shen et al., 2011; Baliah & Priya, 2017; Wang et al., 2022). This limited availability mainly occurs from formation of insoluble complexes due to adsorption on clay surfaces and precipitation through interaction with cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) at high pH levels and iron (Fe^{2+}) and aluminium (Al^{3+}) at low pH levels (Haq et al., 2020; Zafar et al., 2021). Thus, insufficient P availability directly affects maize growth, development and productivity. In order to address P deficiency and enhance yields, synthetic fertilizers are applied in phosphorus-deficient soils (Alori et al., 2017) which can increase maize production however; they are costly to produce, rely on nonrenewable sources and generate harmful byproducts (Abbas et al., 2013; Banerjee et al., 2014). Also, plants are able to utilize only 10-25 % of these inputs efficiently while the rest quickly forms insoluble complexes in the rhizosphere, thus not significantly improving crop yield (Haq et al., 2020; Wang et al., 2022).

Currently, solubilization of insoluble phosphorus has become crucial for sustainable agriculture, inciting the need to explore all the possible alternatives to improve fertilization efficiency and optimize P availability for plant growth using environmentally safe methods (Khoshru et al., 2023). As highlighted by Khan et al. (2009), if made bio- available through appropriate means, reserved P in soil has the potential to support optimal plant productivity over 100 years. Therefore, enhancement of P fertilizer efficiency and bioavailability of phosphorus in soil is very crucial. Phosphate solubilizing bacteria (PSB) are a subset of Plant Growth-Promoting Rhizobacteria (PGPR), which positively influence plant growth, yield and soil health through several mechanisms including improved nutrient availability, producing phytohormones, supporting biocontrol activity, strengthening plant resistance and releasing enzymes such as phosphatases and phytases, as well as compounds such as organic acids, inorganic acids and siderophores (Alori et al., 2017; Suleman et al., 2018). Their application either through soil or seed inoculation is an effective alternative to improve phosphate solubilization and plant yields, thereby helping to reduce the gap between maize production and demand (Abbas et al., 2013; Baliah & Priya, 2017). Various bacteria including *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, *Pseudomonas*, and *Klebsiella* have been reported to solubilize phosphate and produce phytohormone in maize plants (Sharma et al., 2013). Phosphate solubilizing bacteria has also demonstrated significant potential in improving agronomic yield of various cereals and other crops (Saharan & Nehra, 2011).

Although the effect of PSB has been explored in maize in previous studies of Nepal, there is still a need for more site-specific information regarding their effect on maize growth and phosphorus availability as well as on the potential benefits of integrating PSB with other phosphorus sources. Since phosphorus availability and PSB performance may vary depending on soil type, climate and management practices, such site-specific evaluation is necessary before recommending their use to farmers. As reported by Pokharel, (2018), 40% of soil samples collected from farmer's field in Godawari Municipality, Lalitpur ranged from very low to low phosphorus classes, while 30% were classified as medium, highlighting phosphorus limitation in the area and the need for improved nutrient management practices. Therefore, this study aims to examine P supply and maize yield through application of PSB alone and its combination with various P sources such as rock phosphate (RP), single super phosphate (SSP), bone meal (BM) and poultry manure (PM), under the soil and climatic conditions of Taukhel, Lalitpur, Nepal. This research can contribute to improving soil phosphorus availability and enhancing phosphorus use efficiency in maize. Furthermore, the findings of this research may also serve as a stepping stone towards supporting sustainable agriculture in Nepal by reducing agrochemical use, lowering production costs and enhancing sustainable farming for farmers via the means of effective bio-inoculants.

RESEARCH METHODS

Experimental details

The field experiment was conducted in an agricultural field during the summer season of 2023 in Taukhel, Lalitpur district of Bagmati province, Nepal. The research site lies at an elevation of 1408m above the sea level with latitude of 27.6082^{0}N and longitude of 85.3547^{0}E. This region has a monsoon-influenced humid subtropical climate.

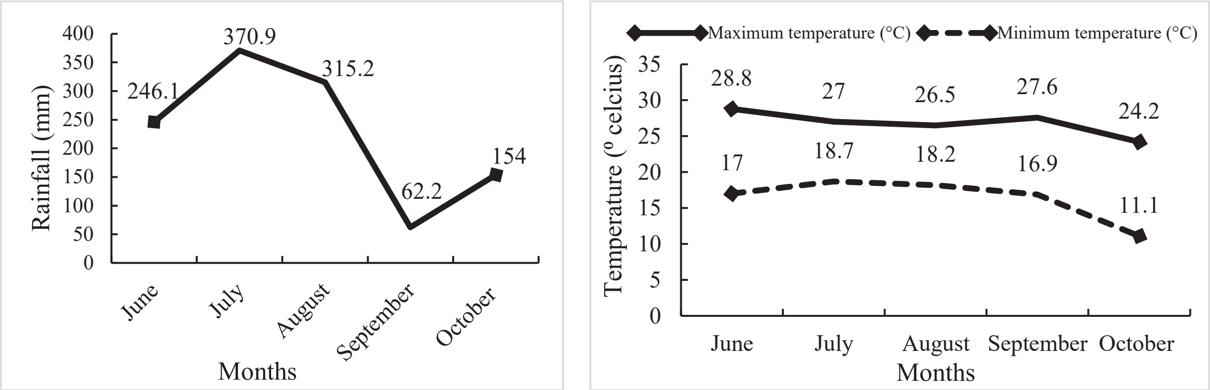

Fig. 1. Agro-meteorological data of the experimental location during the research period (Source: Department of Hydrology and Meteorology, 2023)

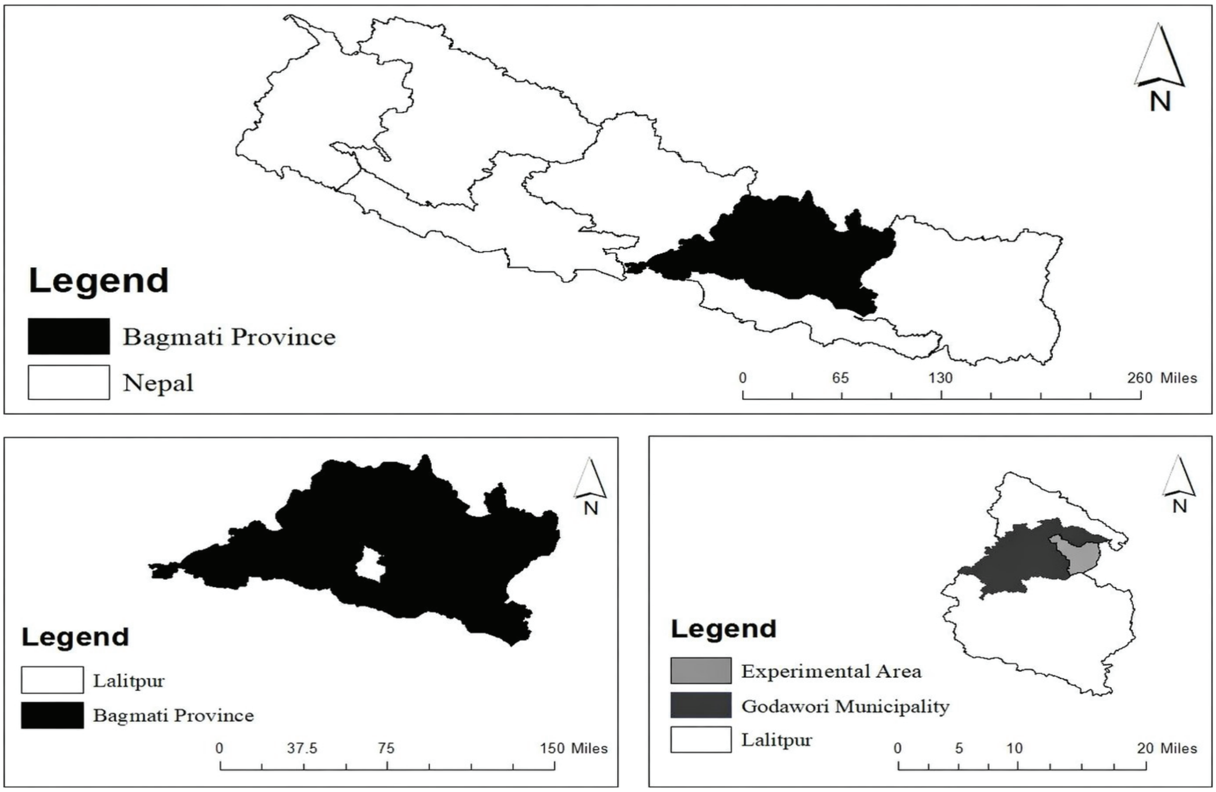

Fig. 2. Geographical map of the study area

A factorial experiment was conducted employing a split-plot design with main plot factor at two levels and sub plot factor at five levels in three replications resulting in a total of 30 plots. The total area of the experimental field was 370m^2 with an individual plot area of 9m^2 (3.6m × 2.5m). Main plot factor included: no inoculation of phosphate solubilizing bacteria (I_0) and inoculation of phosphate solubilizing bacteria (I_1) whereas sub plot factor included: control (P_0), addition of phosphorus through rock phosphate (P_1), addition of phosphorus through single super phosphate (P_2), addition of phosphorus through bone meal (P_3) and addition of phosphorus through poultry manure (P_4).

Azotobacter (3×10^8 cfu/ml) species was used as the phosphate solubilizing bacteria in the experiment. The inoculum was obtained from Biomandu Organic Private Limited, Kathmandu, Nepal. Similarly, rock phosphate (30% P_2O_5) was used as the natural phosphorus source, bone meal (2% N, 22% P_2O_5) and poultry manure (1.8% N, 1.5% P_2O_5, 0.9% K_2O) were used as the organic phosphorus sources and single super phosphate (16% P_2O_5, 12% S) was used as the inorganic phosphorus source in the experiment (Chaturvedi, 2006; Dhakal et al., 2019; Emam & Dewdar, 2015; Klock & Taber, 1996). Rock phosphate, single super phosphate and bone meal were obtained from nearby agro-vet and poultry manure was obtained from National Animal Science Research Institute, Khumaltar, Lalitpur, Nepal. Manakamana-4 variety of maize was used to examine the effect of the experimental materials on several parameters.

Soil sampling and laboratory analysis

The soil of the study area was analyzed at the beginning and end of the experiment. Before the initiation of the experiment, a composite soil sample was prepared, collected and was taken for further analysis of soil pH, total nitrogen, available phosphorus, available potassium, and organic matter. Following the experiment, soil samples were collected from each respective plot and were taken for further analysis of soil pH and available phosphorus.

Soil texture analysis was conducted by Hydrometer Method (Bouyoucos, 1927) and soil pH by 1:2.5 Potentiometric Method (FAO, 2021). Similarly, soil organic matter was analysed by Walkley-Black Method (Walkley & Black, 1934), Total Soil Nitrogen by Micro Kjeldahl Method (Jackson, 1973), Available Phosphorus by Modified Olsen's Bicarbonate Method (Olsen et al., 1954) and Available Potassium by using Flame Photometric Method (Barnes et al., 1945).

Initial physio-chemical properties of the experimental site

The study area had clay-loam soil (30% silt, 40% sand and 30% clay) with pH in the moderately acidic range (5.8).

Table 1. Initial soil chemical properties of the experimental site

Soil Property	Observed value	Low range	Medium range	High range	Interpretation
Organic Matter (%)	2.81	<2.5	2.5-5	>5	Medium
Total Nitrogen (%)	0.14	<0.1	0.1-0.3	>0.3	Medium
Available P_2O_5 (kg ha^{-1})	43.1	<31	31-55	>55	Medium
Available K_2O (kg ha^{-1})	195	<110	110-280	>280	Medium

Note: Low, medium and high ranges were classified for the hill region according to Digital Soil Map Management Procedure (MoALD, 2023)

Seed inoculation, fertilizer application and crop management

Maize seed inoculation was carried out at the rate of 10 ml bacterial solution in 100 ml of water per kg of seeds 24 hours before sowing following the manufacturer's application guidelines. Fertilizer was applied according to the recommended application rate of N, P_2O_5 and K_2O i.e. 120:60:40 kg ha^{-1} (Agriculture Information and Training Centre, 2023). Nitrogen and potassium were supplied to all plots through urea and muriate of potash respectively for agronomic practices. Phosphorus was added through rock phosphate (200 kg ha^{-1}), single super phosphate (375 kg ha^{-1}), bone meal (273 kg ha^{-1}) and poultry manure (4000 kg ha^{-1}) respectively. 50% of the recommended dose of nitrogen along with 100% of the recommended dose of phosphorus and potassium were broadcast uniformly and incorporated into the soil during the final field preparation prior to sowing of seeds. Remaining half dose of urea was applied in two split doses: the first at 30 days after sowing and the second at 60 days after sowing, with each application top-dressed and incorporated into the soil during earthing up. Line sowing of maize was carried out with row spacing of 60 cm and plant spacing of 25 cm between the seeds. A total population of 60 plants were maintained in each plot with 10 plants in each row. Harvesting and threshing was done manually.

Data collection

Data collection was carried out from the inner four rows. Ten sample plants were selected randomly from the inner four rows in each individual plot and the plant growth and yield attributing parameters were measured at the time of maturity. Stover yield was measured at the time of harvest from net plot area i.e. 4.2 m^2 and was left for drying for a few days until constant weight was obtained. The final weight was recorded in kg ha^{-1} and was later expressed in mega gram (Mg ha^{-1}). Grain yield was calculated from net plot area i.e. 4.2 m^2 in kg ha^{-1} at 15% moisture content from the following formula:

$$Grain\ yield\ (\frac{kg}{ha}) = \frac{F.W.\left(\frac{kg}{plot}\right) \times (100 - HMP) \times S \times 10000}{(100 - DMP) \times NPA}$$

where,
F.W. = Fresh weight of ear in kg per plot at harvest
HMP = Grain moisture percentage at harvest
DMP = Desired moisture percentage i.e 15%
NPA = Net harvest plot area, m^2
S = Shelling coefficient i.e 0.8

The value of grain yield in kg ha^{-1} was later converted and expressed in Mg ha^{-1}.

Data analysis

Data analysis was performed using R-Studio version 4.2.2, for all the parameters. Analysis of variance was conducted for split-plot design using agricolae package. Mean comparison of treatments were performed using Duncan's Multiple Range Test (DMRT) at 5% level of significance (Gomez & Gomez, 1984). MS Excel and Word program were used for generating tables.

RESULTS AND DISCUSSION

Effect of phosphate solubilizing bacteria and phosphorus sources on soil pH and available phosphorus

Phosphate solubilizing bacteria as well as different phosphorus sources exhibited no significant difference on soil pH but both factors exhibited significant difference on available phosphorus. Inoculation of phosphate solubilizing bacteria promoted soil available P by 13.4% compared to the non-inoculated treatment. Similarly, application of poultry manure resulted in a 46.1% increase in soil available P compared with control. Interaction of phosphate solubilizing bacteria and phosphorus sources showed no significant difference on soil pH and available phosphorus. Our findings correspond with the findings of Panhwar et al. (2013) who also reported no significant difference in soil pH but reported significant difference in solubilization of phosphorus with the application of phosphate solubilizing bacteria. Agbede et al. (2008), Zaluszniewska and Nogalska (2022) and Sarangi and Jena (2020) reported increased levels of available phosphorus in soil with application of PM and BM with slightly less value of P derived from SSP and RP and a decline in untreated control.

Table 2. Effect of phosphate solubilizing bacteria and phosphorus sources on soil pH and available phosphorus

Treatments	Soil pH	Available Phosphorus (kg P_2O_5 ha^{-1})
Phosphate solubilizing bacteria		
Without PSB	5.93 ± 0.03	47.96^{b} ± 2.41
With PSB	5.87 ± 0.05	54.46^{a} ± 3.22
P value	NS	*
LSD (=0.05)	0.04	3.15
CV%	1.07	7.94
Phosphorus sources		
Control	5.78 ± 0.03	40.72^{b} ± 3.27
Rock Phosphate	5.92 ± 0.07	48.18^{ab} ± 4.73
Single Super Phosphate	5.78 ± 0.04	49.40^{ab} ± 4.52
Bone Meal	6.00 ± 0.06	58.25^{a} ± 3.12
Poultry Manure	6.00 ± 0.04	59.50^{a} ± 3.57
P value	NS	*
LSD (=0.05)	0.19	12.65
CV%	2.76	20.19
Interaction of PSB × P sources		
P value	NS	NS
LSD (=0.05)	0.28	17.89
CV%	2.76	20.19
Grand mean	5.90	51.21

NOTE: Means followed by the same letters within a column don't differ significantly ($p<0.05$); means followed by different letters indicates significant difference at 0.05 level (*), LSD= Least Significant Difference, CV= Coefficient of Variation, NS= Non Significant, Mean ± SEM (Standard Error of Mean)

An enhancement of available phosphorus in soil with the inoculation of phosphate solubilizing bacteria could be attributed to synthesis of low molecular weight organic acids. The hydroxyl and carboxyl groups present in organic acids is involved in phosphorus solubilization through chelation of phosphate bound-cations thereby making them available in soluble forms (Adnan et al., 2017). Furthermore, production of siderophores might have also involved in solubilization of phosphate (Sarikhani et al., 2019).

Improved soil phosphorus availability in plots with PM may be attributed to both the direct supply of phosphorus from the manure and the reduction of phosphorus fixation in the soil. Phosphorus release may have improved through the decomposition and mineralization of PM (Islam et al., 2021). Besides supplying phosphorus, PM can also help reduce phosphorus fixation in the soil through production and release of organic compounds that compete with phosphate for adsorption in acidic soils. This process may have reduced P adsorption on soil particles thereby keeping more P in the soil solution for plant uptake (Ojo et al., 2015, Poblete-Grant et al., 2020). Similarly, an improvement in soil available P in plots with BM might be due to the release of P from the hydroxyapatite (bone fraction) favored by the acidic condition of the soil. In soils with acidic pH, phosphorus compounds with low solubility produced from bone hydroxyapatite can be readily made available to plants, thus providing steady dissolution and promoting phosphorus availability. Thus, the use of BM may contribute to increased soil phosphorus levels particularly under acidic soil conditions (Jeng et al. 2006; Zwetsloot et al., 2016).

Effect of phosphate solubilizing bacteria and phosphorus sources on plant height, leaves number, ear length, ear diameter, kernel rows per ear and kernels per row

Phosphate solubilizing bacteria exhibited no significant difference on plant height, number of leaves, ear length, ear diameter, number of kernel rows per ear and number of kernels per row. However, phosphorus sources exhibited significant differences on plant height, number of leaves, ear length and number of kernels per row whereas no significant difference was observed on ear diameter and number of kernel rows per ear. The highest values of the observed parameters were obtained with poultry manure application compared with control, with increase of 14.6% in plant height, 14.9% in number of leaves, 19.5% in ear length and 16.6% in number of kernels per row. Similarly, interaction of phosphate solubilizing bacteria and phosphorus sources showed no significant difference on the observed parameters. Our results are consistent with the findings of Abbasi and Yousra, (2012) who also reported no significant effect of bacteria alone in increasing vegetative parameters of wheat. Afzal et al. (2005) also found no significant difference on spike length, spikelets per spike and grains per spike in wheat with inoculation of phosphate solubilizing bacteria. Agbede et al. (2017) reported a positive response in plant height with PM application in acidic soil.

Table 3. Effect of phosphate solubilizing bacteria and phosphorus sources on plant height, leaves number, ear length, ear diameter, kernel rows per ear and kernels per row

Treatments	Plant height (cm)	Number of leaves	Ear length (cm)	Ear diameter (cm)	Number of kernel rows per ear	Number of kernels per row
Phosphate solubilizing bacteria						
Without PSB	214.7 ± 4.61	12.0 ± 0.24	18.4 ± 0.54	3.8 ± 0.11	13.2 ± 0.16	32.3 ± 0.70
With PSB	218.4 ± 4.66	12.6 ± 0.24	19.0 ± 0.44	3.9 ± 0.13	13.4 ± 0.18	34.1 ± 0.78
P value	NS	NS	NS	NS	NS	NS
LSD (=0.05)	12.6	0.31	0.7	0.1	0.3	1.7
CV%	7.6	3.3	5.1	5.8	3.3	6.8
Phosphorus Sources						
Control	199.1^{b} ± 5.10	11.4^{c} ± 0.22	16.9b ± 0.62	3.6 ± 0.28	12.8 ± 0.22	30.2b ±1.26
Rock Phosphate	213.2^{ab} ± 4.16	12.1^{bc} ± 0.31	17.8^{ab} ± 0.39	3.8 ± 0.22	13.2 ± 0.15	32.5^{ab} ± 0.69
Single Super Phosphate	216.3^{ab} ± 3.98	12.1^{bc} ± 0.24	18.9^{ab} ± 0.54	3.8 ± 0.11	13.2 ± 0.12	32.8^{ab} ± 1.16
Bone Meal	226.3^{a} ± 6.28	13.0^{ab} ± 0.39	19.6^{a} ± 0.75	4.0 ± 0.10	13.6 ± 0.32	35.1^{a} ± 1.10
Poultry Manure	228.1^{a} ± 9.19	13.1^{a} ± 0.39	20.2^{a} ± 0.80	4.0 ± 0.17	13.6 ± 0.38	35.2^{a} ± 0.67
P value	*	**	*	NS	NS	*
LSD (=0.05)	19.8	0.91	2.1	0.6	0.8	3.0
CV%	7.5	6.07	9.6	13.8	5.0	7.4
Interaction of PSB × P sources						
P value	NS	NS	NS	NS	NS	NS
LSD (=0.05)	28.1	1.3	3.1	0.9	1.1	4.2
CV%	7.5	6.0	9.1	13.8	5.0	7.3
Grand Mean	216.6	12.3	19.7	3.8	13.3	33.2

NOTE: Means followed by the same letters within a column don't differ significantly ($p<0.05$); means followed by different letters indicates significant difference at 0.05 level (*) and 0.01 level (**), LSD= Least Significant Difference, CV= Coefficient of Variation, NS= Non Significant, Mean ± SEM (Standard Error of Mean)

The better performance of PM on plant height, number of leaves, ear length and number of kernels per row may be attributed to the favorable soil conditions created by its application. Decomposition of organic materials from PM may enhance soil physical conditions such as aeration, water holding capacity, total porosity, root distribution and function while reducing soil bulk density. Besides improving soil physical conditions, PM may influence soil chemical properties by releasing organic compounds that reduce P adsorption on soil particles, thereby keeping more P in the soil solution (Ojo et al., 2015, Poblete-Grant et al., 2020). These improved soil conditions likely improved water uptake and supported better phosphorus status and supply in the soil making it more available for uptake by the plants (Adeleye et al., 2010; Agbede et al., 2017). This may have further promoted cell division, production and transfer of assimilates leading to improved plant growth and leaf development, as reflected in the increased plant height and number of leaves. The resulting increase in vegetative growth may have further contributed to the improvement of cob length and number of kernels per row (Shah et al., 2023).

Effect of phosphate solubilizing bacteria and phosphorus sources on thousand grain weight, grain yield and stover yield

Phosphate solubilizing bacteria exhibited significant differences on thousand grain weight, grain yield and stover yield. Higher values on the observed parameters were obtained in plots inoculated with phosphate solubilizing bacteria than the non-inoculated treatment, with increase of 2.1% in thousand grain weight, 11.6% in grain yield and 9.7% in stover yield. Phosphorus sources also exhibited significant differences on the observed parameters where highest values were obtained from PM application with increase of 7.3% in thousand grain weight, 34.2% in grain yield and 26.3% in stover yield, compared to control. However, interaction of phosphate solubilizing bacteria and phosphorus sources showed no significant difference on the observed parameters. Iqbal et al. (2019) also observed similar results of phosphate solubilizing bacteria on observed traits over no inoculation. Adesida et al. (2020) also found a similar increase in observed parameters in crops with the application of PM. Similarly, Haile et al. (2023) also noted high values of observed parameters with application of BM in tomato while Sarangi et al. (2020) observed low value in plots with RP compared to SSP.

Table 4. Effect of phosphate solubilizing bacteria and phosphorus sources on thousand grain weight, grain yield and stover yield

Treatments	Thousand grain weight (gm)	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})
Phosphate solubilizing bacteria			
Without PSB	286^{b} ± 3.03	4.3^{b} ± 0.15	6.2^{b} ± 0.18
With PSB	292^{a} ± 3.40	4.8^{a} ± 0.16	6.8^{a} ± 0.23
P value	*	*	*
LSD (=0.05)	2.4	0.22	0.28
CV%	1.1	6.4	5.6
Phosphorus sources			
Control	277.6^{b} ± 6.35	3.8^{d} ± 0.18	5.7^{b} ± 0.26
Rock Phosphate	285.3^{ab} ± 2.89	4.3^{cd} ± 0.10	6.3^{ab} ± 0.30
Single Super Phosphate	286.5^{ab} ± 3.72	4.5^{bc} ± 0.28	6.4^{ab} ± 0.22
Bone Meal	297.0^{a} ± 3.35	5.0^{ab} ± 0.19	7.1^{a} ± 0.32
Poultry Manure	298.6^{a} ± 4.37	5.1^{a} ± 0.15	7.2^{a} ± 0.30
P value	*	***	*
LSD (=0.05)	14.7	0.5	0.91
CV%	4.2	9.9	11.4
Interaction of PSB × P sources			
P value	NS	NS	NS
LSD (=0.05)	20.7	0.7	1.29
CV%	4.2	9.9	11.4
Grand mean	289	4.5	6.5

NOTE: Means followed by the same letters within a column don't differ significantly ($p<0.05$); means followed by different letters indicates significant difference at 0.05 level (*) and 0.001 level (***), LSD= Least Significant Difference, CV= Coefficient of Variation, NS= Non Significant, Mean ± SEM (Standard Error of Mean)

Through the use of phosphate solubilizing bacteria, root acquisition of P may have increased due to higher available P followed by delayed root and leaf senescence in the inoculated plants, enhancing the availability of assimilates thereby favoring the duration of grain filling and dry matter accumulation and finally increasing thousand grain weight, grain yield and stover yield (Mohammad, 2012; Sun et al., 2023).

Enhancement of yield attributing parameters upon application of PM could be associated with improved availability of phosphorus as observed in the present study, along with improved soil conditions that may have supported better phosphorus and water uptake by the plants. Greater P availability under PM application may have promoted vegetative growth, leading to increased production and transfer of assimilates as well as water uptake. These improvements may have favored cob development, kernel production, grain filling and biomass accumulation ultimately resulting in higher thousand grain weight, grain and stover yield (Masood et al., 2011; Shah et al., 2023; Sun et al., 2023). Similarly, contribution of BM to increased value of yield attributing parameters might be due to increased soil phosphorus availability resulting from its application. BM contains phosphorus mainly in organic and apatite forms, which is released gradually through decomposition and mineralization, which may have allowed plants to access and improve P nutrition during important growth stages (Nogalska et al., 2017; Stępień et al., 2021).

CONCLUSION

The findings of this study revealed that seed inoculation of phosphate solubilizing bacteria improved soil available phosphorus and maize yield compared to the non-inoculated treatments. The improvement was observed in soil available phosphorus by 13.4%, thousand grain weight by 2.1%, grain yield by 11.6% and stover yield by 9.7%. Among the phosphorus sources, poultry manure and bone meal performed better compared to single super phosphate and rock phosphate implying their potential to serve as effective organic sources of phosphorus fertilizers. Performance of rock phosphate was similar to single super phosphate, which means that it can be used as a low-cost alternative of phosphorus fertilizers. Overall, this study highlights the potential of combining PSB inoculation with different phosphorus sources to improve phosphorus use efficiency and maize productivity. More research needs to be done to evaluate the effect of phosphate solubilizing bacteria with wide variety of organic and inorganic phosphorus fertilizers under different soil and climatic conditions. Furthermore, future research should focus on its interaction with other beneficial microbes and its effect on physiological, biochemical and molecular responses of plants.

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AUTHOR CONTRIBUTIONS

AO: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft; **JJG:** Writing – review & editing, Supervision, Validation; **BPT:** Writing – review & editing, Supervision, Validation; **RBO:** Writing – review & editing, Supervision, Validation; **SP:** Software, Formal analysis, Writing – review & editing.

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.

ETHICAL APPROVAL AND PERMITS

Not applicable.

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